NUMERICAL SIMULATION OF DAMAGE PROPAGATION FOR A CHANNEL STRUCTURE MADE OF SHORT GLASS FIBER REINFORCED COMPOSITES

Xingsheng Li[1], T. Kurashiki[1], M. Zako[1], K. Kobayashi [2], T. Yamamoto [2], G. Yamada [2]
and T. Sakakibara [2]

[1] Graduate School of Engineering, Osaka University,
2-1, Yamadaoka, Suita, 565-0861 Japan
xingsheng@mit.eng.osaka-u.ac.jp
kurasiki@mit.eng.oasaka-u.ac.jp
zako@mit.eng.osaka-u.ac.jp
[2] Department of Science and Engineering, ITOCHU Techno-Solutions Corp.,
North Gate Building, 3-1-3, Umeda, Kita-ku, Osaka-shi, 530-0001 Japan
tatsuo.sakakibara@ctc-g.co.jp

Keywords: Injection molding, PP, μCT, Damage mechanics, FEM

ABSTRACT

An effective method which can evaluate the mechanical property and the damage behaviour of short glass fiber reinforced composites(SFRC) made by injection molding has been proposed. Two types channel-shaped structure which have centre gate injection molding and edge gate injection molding with polypropylene resin and glass fiber (vf=40%) have been prepared. From the 3-point bending test, it is recognized that the damage mode is depending on the gate position.

The purpose of this paper is to make clear the effect of the gate position of injection molding on the strength and damage pattern. The mechanical properties with nonlinear and anisotropy are obtained by tensile test and fiber orientations are measured by μCT. The formulations for the mechanical properties have introduced. On the other hand, channel-shaped structures have been produced by the injection molding with the different gate position. The fiber orientations at the local position have been observed by μCT. A FEM model has been prepared and the mechanical properties and the fiber orientation are applied as input data. The channel-shaped structures have been tested by 3-point bending test. The experimental results have been compared with the numerical simulation using nonlinear and anisotropic mechanical properties. As both results show good agreement, it is recognized that the proposed method is useful for the determination of gate position and the design of structure.

1 INTRODUCTION

Fiber reinforced composites are widely used in automobile components to reduce the weight. But the car makes up many components with complicated shape. For such parts, the main production process remains injection molding because complex shapes and the composed parts can be produced easily. The mechanical property of SFRC is depend on the length, the orientation and the dispersion of fiber. Phelps-Tucker anisotropic rotary diffusion model has demonstrated the ability to handle primary anisotropic fiber orientation [1], but it is still difficult to precisely predict fiber orientation for high fiber volume fraction. Homogenization technology is used to derives macroscopic composite properties for materials defined on the microscopic scale [2,3]. Mori-Tanaka homogenization is applied to obtain material properties on the pseudo-grain level. Voigt averaging is applied to pseudo-grains and the mechanical properties can be obtained as macroscopic level.

Kammoun et al. have proposed a micromechanical modelling of the progressive failure in short glass-fiber reinforced thermoplastics [2]. It is difficult to predict damage behaviour of SFRC, because the damage will occur at the microscopic level. Notta-Cuvier et al. have proposed a failure criterion based on a critical number of voids located in deboned areas [4]. Though these methods have some advantages, it is not easy to apply the simulation of the effect of the gate position on failure mode.

2 EVALUATION METHOD FOR DAMAGE PROPAGATION OF SFRC

2.1 Measurement of fiber orientation and Tensile test

Plate specimens (polypropylene and glass fiber vf=40%) are prepared by injecting molding. Figure 1 shows the direction of tensile specimens to injection direction. The Five specimens are prepared for 0˚, 45 ˚ and 90 ˚, respectively. The fiber orientation of specimen is measured by μCT (SMX-100) which is shown in Fig. 2. Figure 3 shows an example of the fiber orientation of sections though thickness direction. It is generally known for the injection molding with short fiber that the fiber is aligned along flow direction near the surface and is transversely aligned in the mid-plane. The specimen is considered as a sandwich structure that the thickness ratio of each layer measured are shown in Fig. 3.

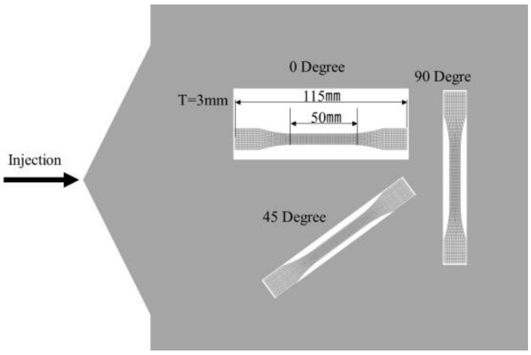


Fig. 1 Three types specimens for tensile tests.

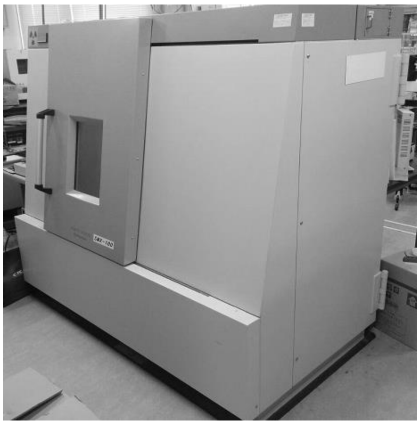


Fig. 2 Testing equipment of μCT

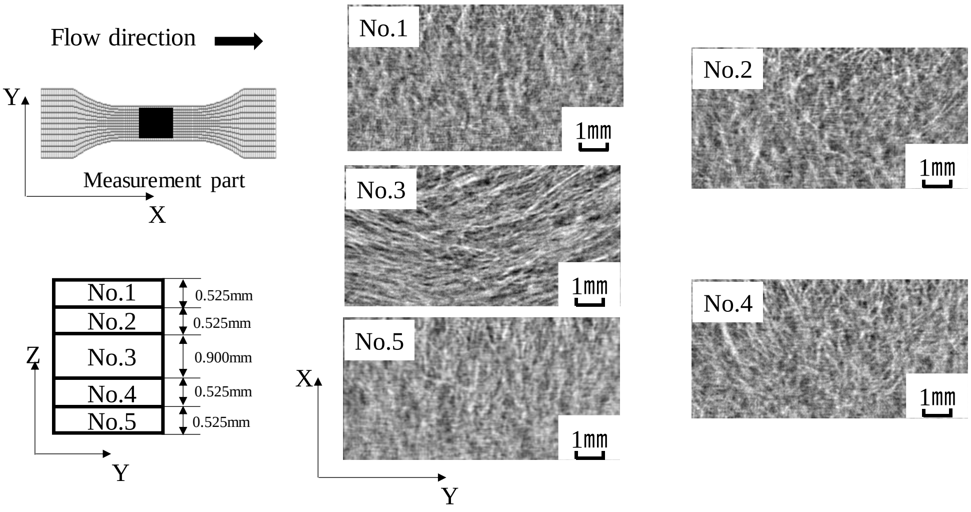


Fig. 3 μCT images of plate specimen

2.2 Identification of mechanical property

The nonlinear stress-strain relationship of SFRC is considered by using [5]:

$$E_i^* = E_i + \alpha_i e^{-n_i \sigma} \tag{1}$$

Where, E_i is the initial young's modulus, α_i and n_i are material coefficient, which are obtained from tensile test. The identified material parameters are shown in table 1. The superscripts T and C mean loading direction: T is tension and C is compression. The subscripts L, T and S mean the principal material axis: L represents longitudinal direction, T is transverse direction and S is shearing direction.

Table 1 The mechanical properties

E_L[MPa]		E_T[MPa]		E_{45}[MPa]	
1350		300		1000	
α_L[MPa]		α_T[MPa]		α_{45}[MPa]	
5325		6125		4100	
nL		nT		n45	
0.017		0.017		0.0205	
Stress_criteria	Strain_criteria	Stress_criteria	Strain_criteria	Stress_criteria	Strain_criteria
Flt[MPa]	Flt[%]	Ftt[MPa]	Ftt[%]	Ftt[MPa]	Flt[%]
108	1.86	59.2	1.39	59.2	1.39
Fcl[MPa]	Fcl[%]	Fct[MPa]	Fct[%]	Fct[MPa]	Fct[%]
216	3.71	118.4	2.78	118.4	2.78
Fs[MPa]	Fs[%]	Fs[MPa]	Fs[%]	Fs[MPa]	Fs[%]
61	1.86	61	1.86	61	1.86

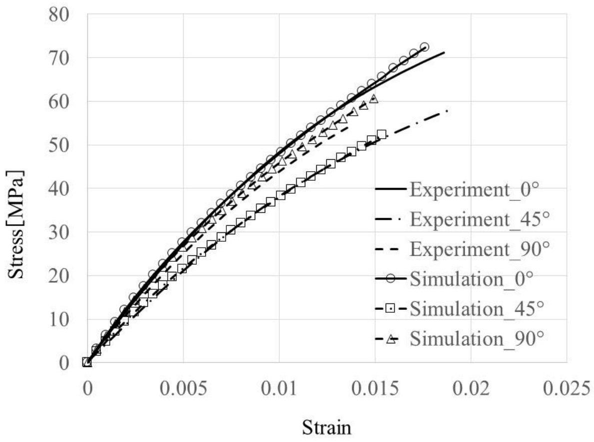


Fig.4 The comparison of experimental result with the simulation ones under tensile condition based on stress damage criterion

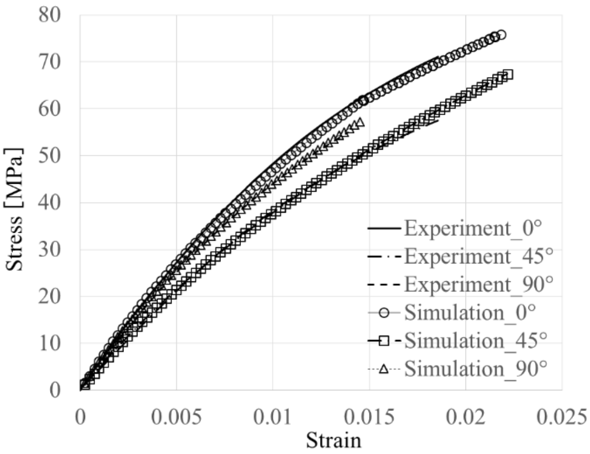
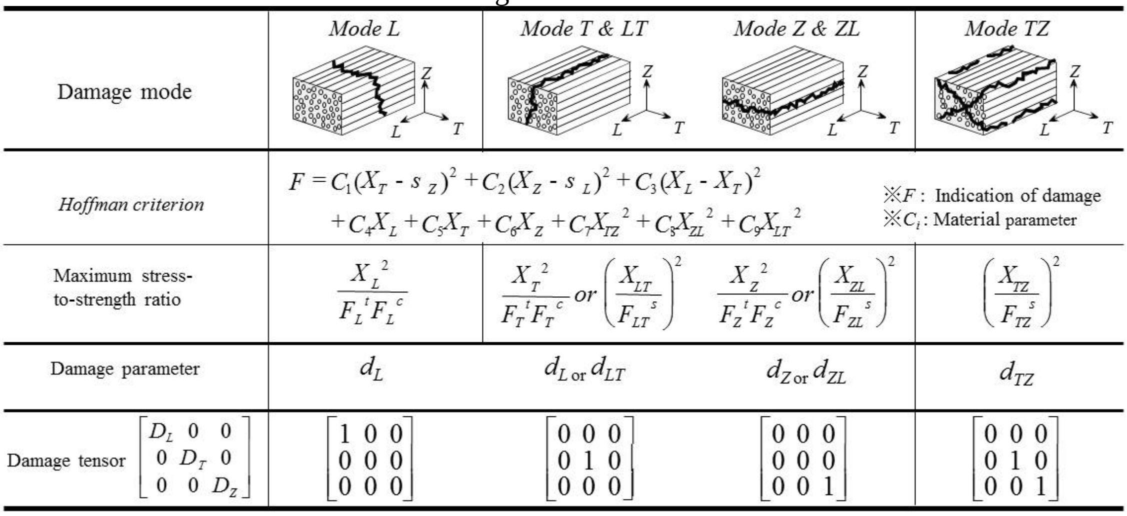


Fig.5 The comparison of experimental result with the simulation ones under tensile condition based on strain damage criterion

2.3 Damage model

A marco damage evaluation method is employed to simulate the mechanical behavior under tensile loading condition [6]. Hoffman failure criterion [7] has been applied and the damage sheme and the damage mode are represented in table2. When the indication of damage (F) for the element is over 1, a damage mode shown in table 2 will occur. The stiffness metrix is represented by equation 2 using a second order tensor suggested by Murakami and Ohno. Q_{ij} representes the component of the original stiffness matrix [8]. The damage parameters of d_L,d_T and d_Z are determined by Eq.3. In order to varify the proposal procedure, a numerical simulation for the mechanical behavior under tensile loading condition is carried out. The numerical model consists of three layers which has the same dimension as measured from the specimen. Figures 4 and 5 show the comparison of stress-strain relation between the experimental results and the simulation ones. It is recognized that the numerical results using both criterion agree well with the experimental results. The tool of numerical simulation is "Composite Dream", which is one of the commercial FEM program code.

Table 2 Damage scheme and modes



Damage mode	*Mode L*	*Mode T & LT*	*Mode Z & ZL*	*Mode TZ*
Hoffman criterion	$F = C_1(X_T - s_Z)^2 + C_2(X_Z - s_L)^2 + C_3(X_L - X_T)^2 + C_4 X_L + C_5 X_T + C_6 X_Z + C_7 X_{TZ}{}^2 + C_8 X_{ZL}{}^2 + C_9 X_{LT}{}^2$ ※F : Indication of damage ※C_i : Material parameter			
Maximum stress-to-strength ratio	$\dfrac{X_L{}^2}{F_L{}^t F_L{}^c}$	$\dfrac{X_T{}^2}{F_T{}^t F_T{}^c}$ *or* $\left(\dfrac{X_{LT}}{F_{LT}{}^s}\right)^2$	$\dfrac{X_Z{}^2}{F_Z{}^t F_Z{}^c}$ *or* $\left(\dfrac{X_{ZL}}{F_{ZL}{}^s}\right)^2$	$\left(\dfrac{X_{TZ}}{F_{TZ}{}^s}\right)^2$
Damage parameter	d_L	d_L or d_{LT}	d_Z or d_{ZL}	d_{TZ}
Damage tensor $\begin{bmatrix} D_L & 0 & 0 \\ 0 & D_T & 0 \\ 0 & 0 & D_Z \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

(X_i, X_{ij} : stress or strain, F^t: Tensile strength or failure strain, F^c:Compressive strength or failure strain, F^s : Shear strength or failure strain)

$$Q_{LTZ}{}^* = \begin{bmatrix} d_L^2 Q_{11} & d_L d_T Q_{12} & d_Z d_T Q_{13} & 0 & 0 & 0 \\ d_L d_T Q_{12} & d_T^2 Q_{22} & d_T d_Z Q_{23} & 0 & 0 & 0 \\ d_Z d_T Q_{13} & d_T d_Z Q_{23} & d_Z^2 Q_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & d_{TZ} Q_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{ZL} Q_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{LT} Q_{66} \end{bmatrix} \tag{2}$$

$$\begin{aligned} d_L &= (1 - D_1) & d_{TZ} &= \left(\frac{2(1 - D_2)(1 - D_3)}{(1 - D_2) + (1 - D_3)}\right)^2 \\ d_T &= (1 - D_2) & d_{ZL} &= \left(\frac{2(1 - D_3)(1 - D_1)}{(1 - D_3) + (1 - D_1)}\right)^2 \\ d_Z &= (1 - D_3) & d_{LT} &= \left(\frac{2(1 - D_1)(1 - D_2)}{(1 - D_1) + (1 - D_2)}\right)^2 \end{aligned} \tag{3}$$

3 DAMAGE BEHAVIOR OF CHANEL STRUCTURE OF SPECIMEN UNDER 3-POINT BENDING TEST

3.1 Experiment

Two kinds of channel-shaped structure, which are the same component as tensile specimen has been prepared. One is the structure which has been produced by injection molding with centre gate and the other is injecting molding with edge gate. In order to evaluate the effect of the gate position on the strength, 3-point bending test has been carried out. Figure 7 shows the dimension of specimen and the loading condition of bending test. Figure 8 shows the damaged channel-shaped structure after the test. The transverse crack propagates to the width direction for the structure produced by center gate. On the other hand, the crack propagates to the longitude direction for the structure produced by edge gate. The change of gate position may be triggered the different failure mode. The fiber orientation of both channel-shaped structures has been measured using X-ray CT. The observation results are shown in Fig. 9. The fiber arranges almost in the longitude direction at locations a,b and c. For the location i, the fiber is arranged to the longitude direction in case of edge gate, but the fiber is arranged to the with direction in case of center gate. The difference of damage mode is caused by the fiber orientation difference.

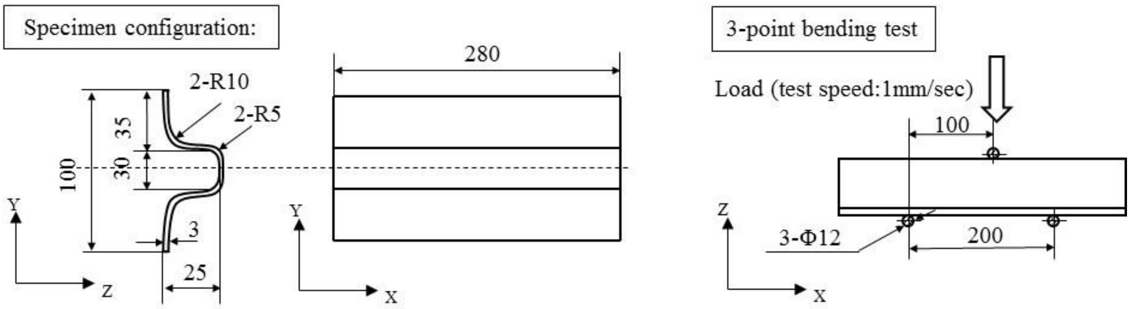


Fig. 7 Specimen configuration and outline of 3-point bending test

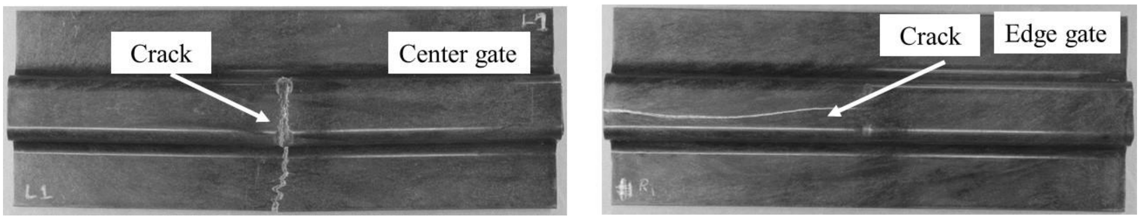


Fig.8 Damage modes of channel-shaped specimen with different gate position

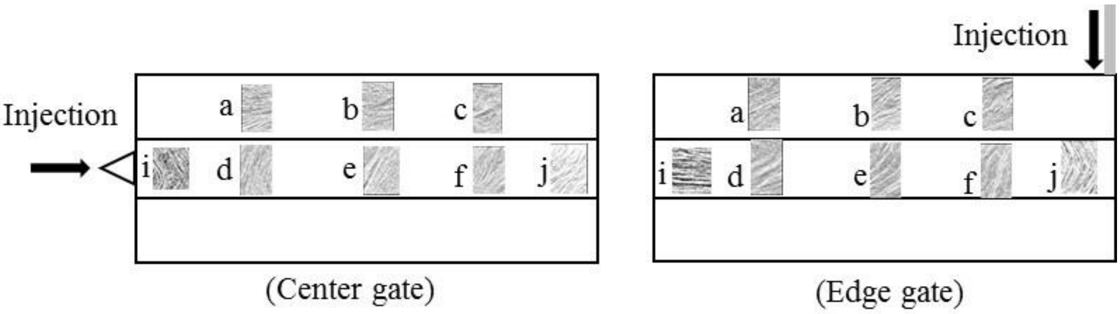


Fig. 9 μCT images of channel-shaped specimen

3.2 Simulation

In order to make clear the effect of the gate position on the strength and the failure mode, FEM has carried out. Finite element model consists of 5 layers, which the total number of solid elements is 25200 and the total number of nodal points is 34404, respectively. The fiber orientation for each element is decided according to the observation of X-ray CT shown in Fig. 9. The mechanical properties shown in table 2 are applied to simulation. Figures 10 and 11 show the numerical and experimental results of the relation between the applied load and the displacement of loading point under 3-point bending test. Figure 10 shows the results of load-displacement curve in case of the damage criterion with stress. Figure 11 shows the result in case of the damage criterion with strain. From these results, it is clear that the numerical results have a good agreement with the experimental ones. However, some differences of the state of damage propagation for each layer have been recognized. The states of damage propagation are shown in Figs 12 and 13. Figure 12 shows the damaged elements in surface and middle layers in case of stress criterion. Figure 13 shows the result in case of strain criterion. The total number of damage elements in case of stress criterion is larger than that of strain criterion in the surface layers, but damage element does not appear to the middle core layer for the reason that the surface layer can sustain the applied load. It is the most important thing whether the damaged elements appear at the edge part of channel-shaped structure or not. In case of the edge gate, the fiber near edge (location i) has been arranged to the longitudinal direction. The fiber orientation near to the edge will be the result of generation of different failure mode.

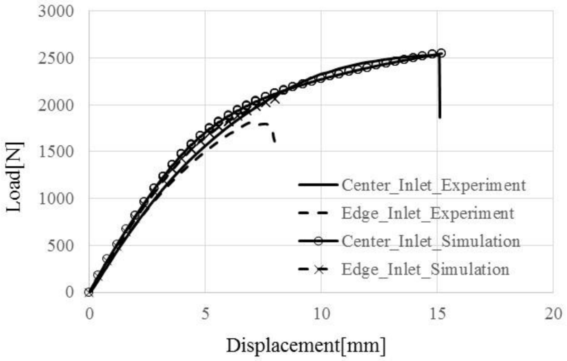


Fig.10 The comparison of experimental result with the simulation ones under 3-point bending condition based on stress damage criterion

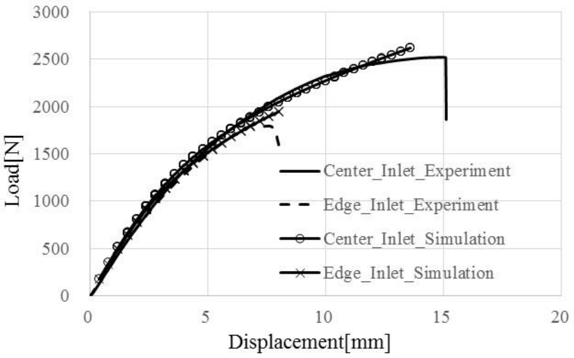


Fig.11 The comparison of experimental result with the simulation ones under 3-point bending condition based on strain damage criterion

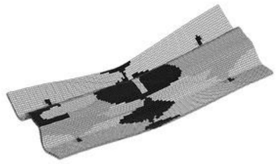
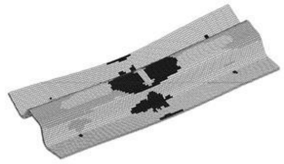
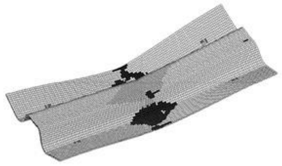
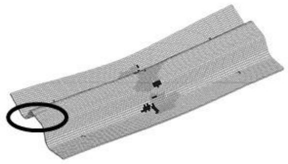
■ Fiber damage ▢ Resin damage	Center inlet	Edge inlet
Surface layer		
Middle layer		
Failure displacement	15mm	8mm

Fig.12 Damage propagation in case of stress damage criterion

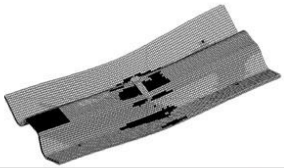
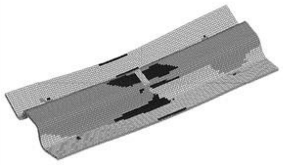
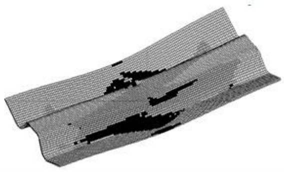
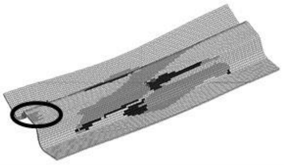
■ Fiber damage ▢ Resin damage	Center Inlet	Edge Inlet
Surface layer		
Center layer		
Failure displacement	15㎜	8.8㎜

Fig.13 Damage propagation in case of strain damage criterion

4 CONCLUSIONS

An effective method of estimation for the mechanical properties and the damage propagation of short glass fiber reinforced composites structure made by injection molding has been proposed. It has been revealed that the fiber orientation in a structure effects on the strength and damage propagation. As the fiber orientation in the surface layer differs from it in the center layer to thickness, the structure is considered as sandwich plate. The information of fiber orientation in the structure is important to simulate the mechanical behavior. This event must be taken into consideration when the mesh generates. Since we can estimate not only the rigidity but the strength, the failure mode and the damage propagation for a structure produced by injection molding, the proposed method in this paper will be very effective to determine the gate position and to design the structure.

REFERENCES

[1] Jay H. Phelps, Charles L. Tucker III, An anisotropic rotary diffusion model for fiber orientation in short- and long-fiber thermoplastics, *Journal of Non-Newtonian Fluid Mech.,* **156** 2009, pp. 165-176 (doi: 10.1016/j.jnnfm.2008.08.002).

[2] S. Kammoun, I. Doghri, L. Brassart and L. Delannay, Micromechanical modeling of the progressive failure in short glass-fiber reinforced thermoplastics -First Pseudo-Grain Damage model, *Composites: Part 73 2005* , pp. 166-175 (doi: 10.1016/j.compositesa.2015.02.017).

[3] Digimat, The nonlinear multiscale material and structure platform, Users’ manuel **,V5.0**, 2014.

[4] D. Notta-Cuvier , F. Lauro and B. Bennani, Modelling of progressive fiber/matrix debonding in short-fiber reinforced composites up to failure, International journal of solids and structures, 66(1) 2015, pp.140-150. (doi: 10.1016/j.ijsolstr.2015.03.034)

[5] M.Zako, Computational mechanics of Composite Materials, Yokendo,1989.

[6] Y.Uetsuji, M.Zako, Damage Analysis of Woven Fabric Composite Materials, *The Society of Materials Science.,* ***48(9) 199***9, pp. 1029-1034.

[7] O.Hoffman, The brittle strength of orthotropic materials, *Journal of Composite materials,* **1(2)** 1967, pp. 200-206 (doi: 10.1177/002199836700100210).

[8] S.Murakami, Mechanical Modeling of Material Damage, *Journal of Applied Mechanics,* **55(2)** 1988, pp. 280-286 (doi: 10.1115/1.3173673).