Recent advances in UD failure simulation and its application to laminate strength

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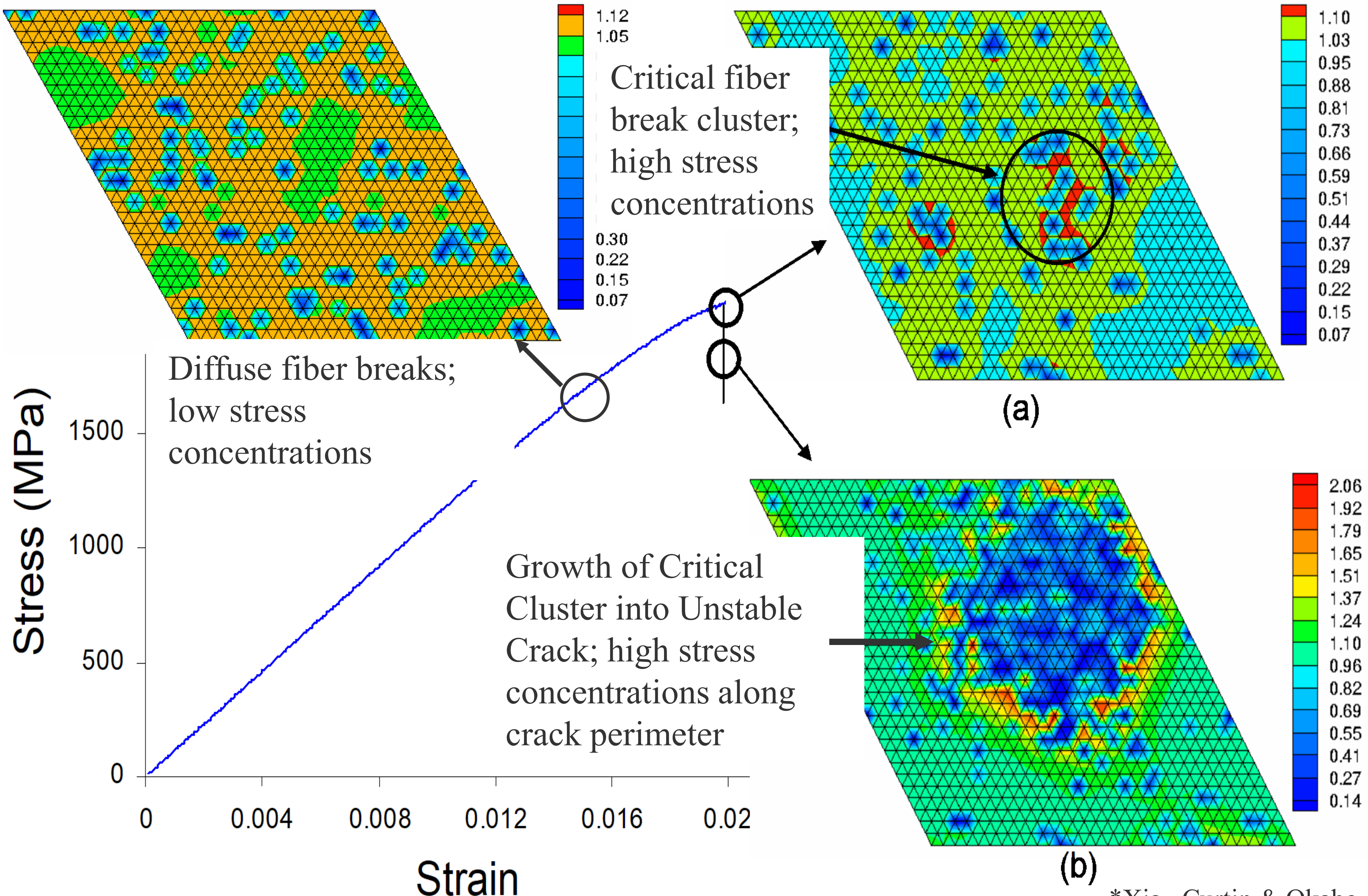
Damage Progression: Accumulation of fiber breaks up to critical point

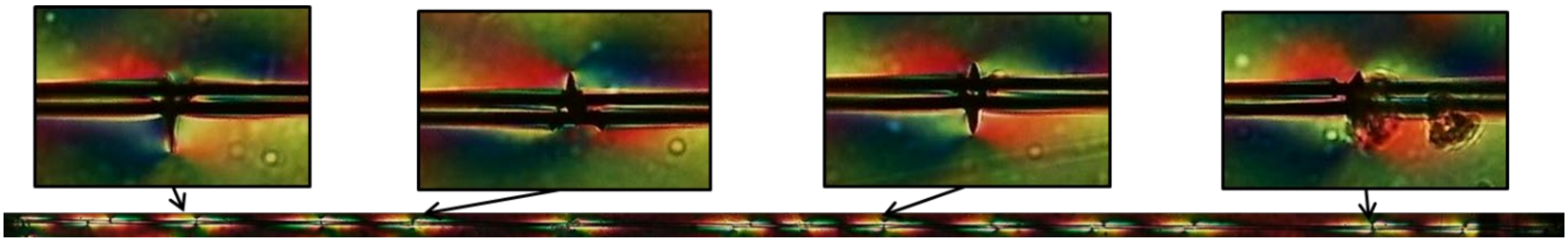


*Xia , Curtin & Okabe

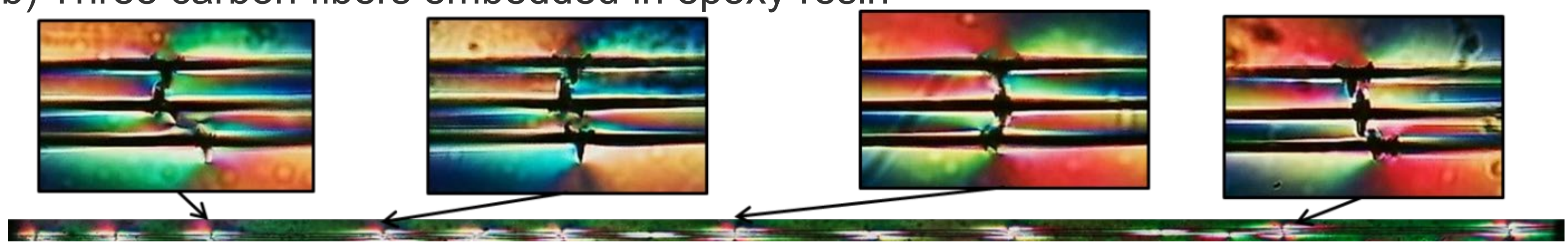
Fragmentation behavior of multiple fiber composites

The typical observation of adjacent fracture sections in T1100G/Epoxy in multiple fiber composite

(a) Two carbon fibers embedded in epoxy resin



(b) Three carbon fibers embedded in epoxy resin



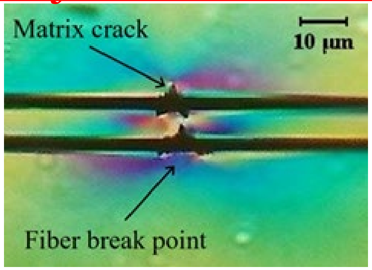
(c) Four carbon fibers embedded in epoxy resin

Fragmentation tests for estimating the stress concentration factors

Double Fiber Fragmentation Test(DFFT)

We observed fiber breaking behavior and measured the adjacent break probability using test specimens embedded with two fibers.

Adjacent fiber break



Matreials

Matrix resin: Bisphenol A-type epoxy resin (curing condition: 180°C, 2 hours)

Carbon fiber: PAN-based carbon fibers (T1100G, T800S, T800H, T700S, T300)

$$P(\sigma) = 1 - \exp\left[-\frac{L}{L_0}\left(\frac{\sigma}{\sigma_{01}}\right)^{m_1} - \frac{L}{L_0}\left(\frac{\sigma}{\sigma_{02}}\right)^{m_2}\right] \quad (2)$$

Fiber	Tensile strength (MPa)	Young's modulus (GPa)	Weibull parameter				Remarks
			σ_{01} (GPa)	m_1	σ_{02} (GPa)	m_2	
T1100G	7000	324	7.7	4.5	9.1	13.0	14)
T800S	5880	294	6.9	4.1	8.3	13.0	15), 16)
T800H	5490	294	5.9	7.5	6.3	13.0	This study
T700S	4900	230	5.2	4.8	6.1	12.0	15), 16)
T300	2350	230	4.1	4.0	4.2	15.0	This study

Numerical simulation for failure simulation of UD composites

SEM（Spring Element Model）

- Fiber: Longitudinal truss element
- Matrix: Transverse shear element

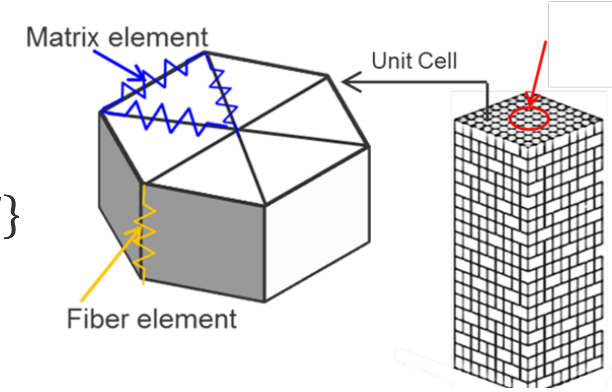
T. Okabe, H. Sekine, K. Ishii, M. Nishikawa, N. Takeda, "Numerical method for failure simulation of unidirectional fiber-reinforced composites with spring element model", Composites Science and Technology, 65 (2005), 921-933.

In the slipping region or at a breaking point, those elements are removed and stresses obtained from the analytical solution are given as internal forces in the equilibrium equations.

【Equilibrium equation of spring system (one-dimentional FEM)】

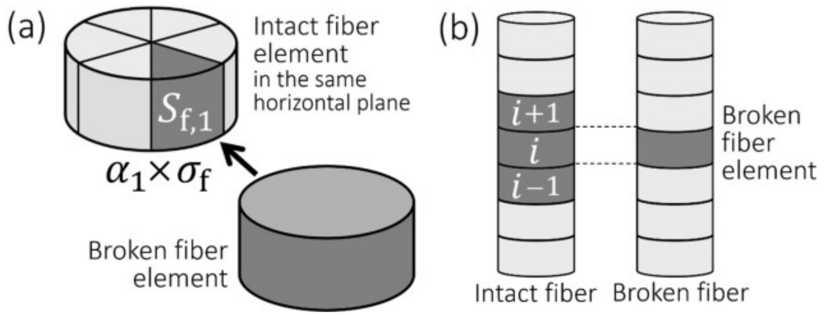
$$\left[\sum_{e=1}^{N_f-N_b-N_p}[K_L^e]+\sum_{e=1}^{N_T}[K_T^e]\right]\{u\}+\sum_{e=1}^{N_p}\pi R^2\int_0^l [B_L^e]^T\sigma_s dz=\{f\}$$

Intact region　　Slipping region



【Stress concentration factor around a fiber break】

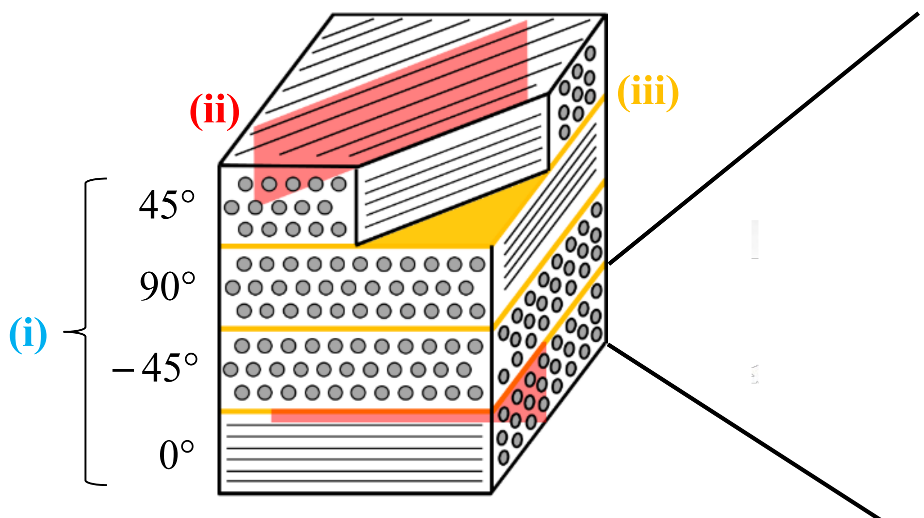
$$\alpha_i\times\sigma_f=\left\{1+\gamma_i\left(1-\frac{D_S}{l_s}\right)\right\}\times\sigma_f$$



Modeling strategy & Simulation procedure

Modelling strategy Five kinds of numerical model were introduced to model progressive damage

Characteristics	Numerical models	
Nonlinear stress-strain response		
Transverse crack & Delamination ➢ Interaction ➢ Pressure-dependent strength	Transverse crack	Delamination
Longitudinal tensile failure		
Longitudinal compressive failure		



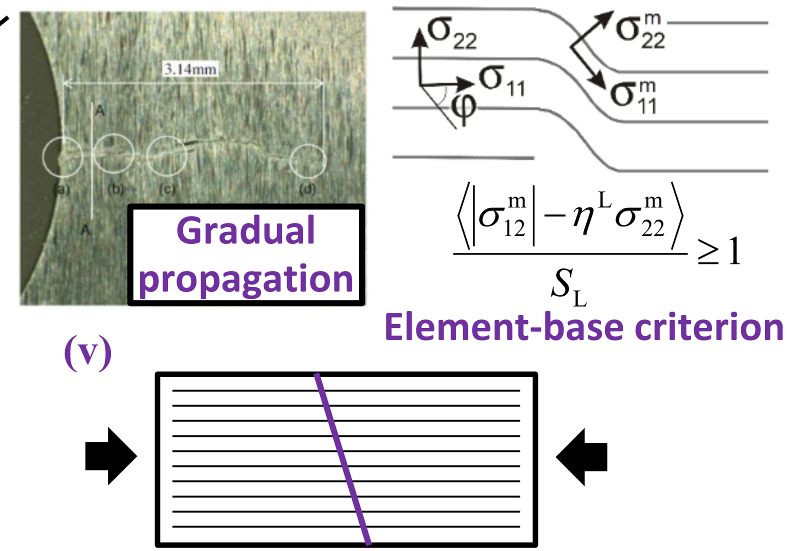


Fig.3 Schematics of modelling strategy.

[2] T. Yokozeki et al., Compos. Sci. Technol., 2007. [3] X. Li et al. Composites Part A, 2008.
[4] S.R. Hallett et al., Composites Part A, 2009. [5] C.G. Davila et al., NASA / TM-2003- 212663.

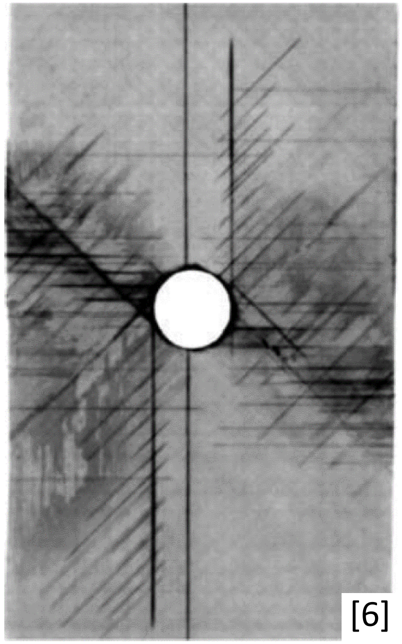
Results for Open-hole tensile (OHT) test

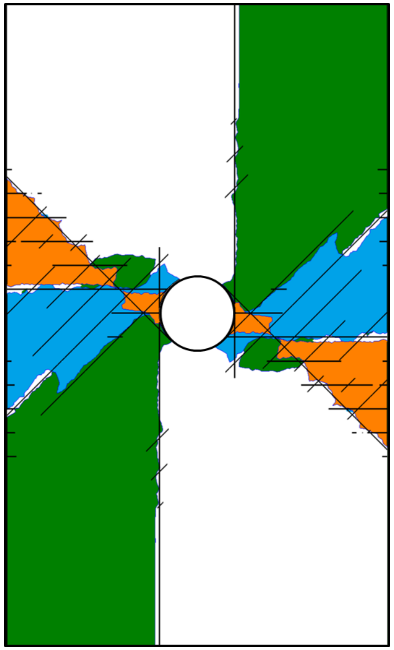
Open-hole tensile (OHT) test

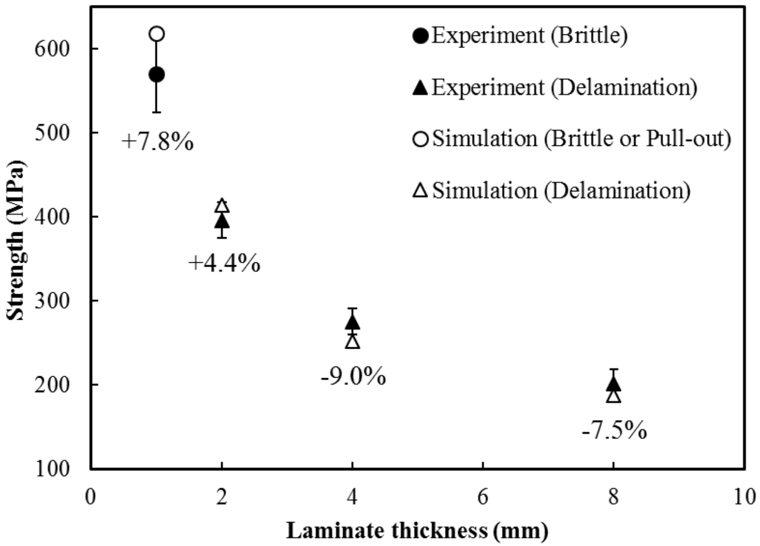
R. Higuchi, T. Okabe, T. Nagashima, Composites Part A, 95, (2017), 197-207

Simulation results – damage distribution

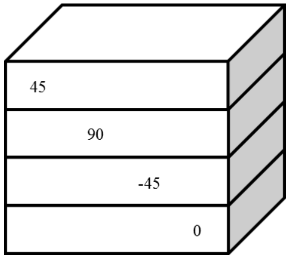
Ply-level scaling : $[45_4/90_4/-45_4/0_4]_s$







(a) Ply level scaling $[45_n/90_n/-45_n/0_n]_s$



The proposed simulation tool was able to reproduce the similar damage patterns as experiment.

$$M(\sigma) = \sum_{i=1}^{nelem} \frac{V_i}{V_0}\left(\frac{\sigma_i}{\sigma_0}\right)^m \geqslant 1.$$

$m = 40.1$, $V_0 = 1.0\ \mathrm{mm}^3$, and $\sigma_0 = 3131$ MPa.