PROGRESSIVE DAMAGE STRUCTURAL ANALYSIS OF CARBON/EPOXY COMPOSITE LAMINATES

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Abstract

For the development of composite material underwater vehicle propeller superior to the radiation noise, it is necessary to carry out the researches on the diverse fiber directions and arrays and also to develop numerical simulation techniques for its optimum structural analysis with the experiments. In this study, characteristics and weight drop tests of composite laminar specimens were performed and their mechanical properties and damage states were examined according to their tests. In addition, using composite material model MAT_162 (Composite_DMG_MSC) linked with LS-DYNA code, progressive damage structural analysis technique was developed by the investigation of the damage mechanism and by the calibration of the parameters according to the damage criteria. Through this study, it might be thought that the optimum structural design of composite laminates and propeller could be derived with high accuracy for the maximization of its performance at the reversed design stage by the estimation of their strengths, energy absorption capacities and damage states according to the diverse fiber arrays.

Keywords: *composite laminates, underwater vehicle propeller, radiation noise, progressive damage structural analysis, optimum structural design, MAT_162, LS-DYNA code*

1. Introduction

Underwater vehicle propellers of submarine and torpedo, etc. are well known as the primary noise sources, and polymer composite material with high damping has actively been attempted and investigated for the reduction of radiation noise, as shown in Fig. 1.

Fig. 1 AIR CONTUR composite propeller for German Navy U 206

Two composite material propellers were produced, as shown in Fig. 2, cutting prepregs, piling them on the molds according to their fiber weaving and array, and adopting compressible molding process. Self performances and radiation noise characteristics were also measured. The possibility could be found that the systematic research would be applied to the changes of performance and noise characteristics of composite material propeller according to the diverse fiber weaving and array systems, and it could be also confirmed that this result would be used partially for the verification information. However, reverse engineering procedure was not carried out according to the blade flexibility [1].

Fig. 2 Composite propellers Flex 02 & 03 and performance test [1]

For the optimum structural design of composite material propeller according to the fiber direction and array of its blade, it is necessary to develop the numerical simulation technique with consideration of damage, in addition to the mechanical characteristics test and impact one of composite laminar specimens.
With the advent and ongoing advances in numerical simulation capabilities and its sophisticated tools, such as highly accurate dynamic nonlinear simulation code LS-DYNA [2], structural analysis could be carried out efficiently and accurately. MAT_162 (Composite_DMG_MSC) uses damage mechanics principle for progressive damage and material degradation with failure surface, as shown in Fig. 3, based on a continuum damage mechanics (CDM). Linking MAT_162 to LS-DYNA code, the progressive damage and delamination phenomenon between layers in the composite laminate could be predicted with high accuracy through the numerical simulation compared to the experimental results, as shown in Fig. 4 [3].

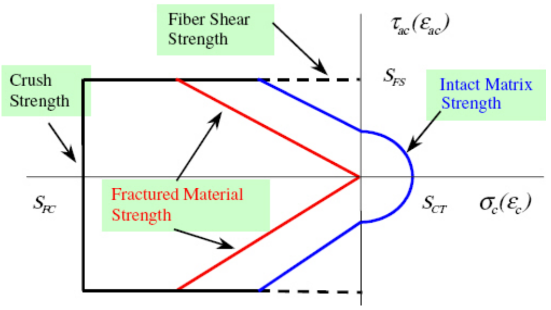


Fig. 3 Failure surface of MAT_162 damage mechanics model [3]

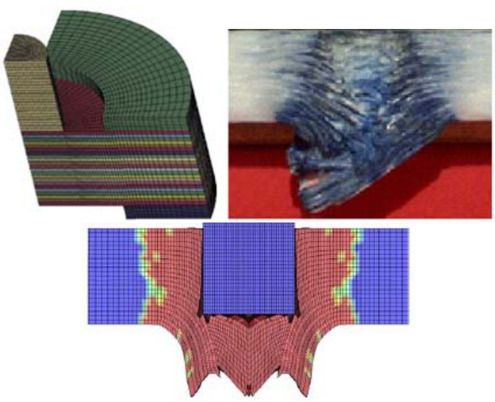


Fig. 4 Fiber tensile/shear failure simulation using MAT_162 of LS-DYNA [3]

In this study, numerical simulation technique using composite material model MAT_162 was developed for the optimum structural design by calibrating the material parameters and damage criteria according to characteristics test and weight drop one of composite laminar specimens. Mechanical characteristics test was carried out for the unidirection (UD) and plain weave (PW) of carbon fiber/epoxy resin laminar specimens, such as tension, compression, shear in plane (V-notch) and shear between layers (SBS; short beam strength), and also weight drop tests, for the PW laminar specimens. Their material properties, damage state and mechanism were also figured out.

2. Composite Material Damage Model MAT_162

Damage model MAT_162 linked with LS-DYNA code is used for the progressive damage analysis of UD or PW composite laminates, and the behaviors of fiber failure, matrix damage and delamination can effectively be simulated under diverse loading conditions. In addition to the criteria for these damages, softening behavior after damage can be also realized. All the failure criteria are expressed in terms of stress components based on ply level strains and the associated elastic moduli. For the unidirectional model, a, b and c denote the fiber, in-plane transverse and out-of-plane directions, respectively, while for the fabric model, the in-plane fill, in-plane warp and out-of-plane directions, respectively.
Failure criteria of UD and PW laminate model are consisted of three fiber failure ones, such as tensile/shear fiber mode, compression fiber mode and crush mode under pressure, and two matrix failure ones without fiber failure, such as perpendicular matrix mode and parallel matrix mode (delamination). They are chosen in terms of quadratic strain forms as follows [2, 3].

2.1 Unidirectional laminar damage functions

• Tensile/shear fiber mode

$$f_1 = \left(\frac{\langle \sigma_a \rangle}{S_{aT}}\right)^2 + \left(\frac{\tau_{ab}{}^2 + \tau_{ca}{}^2}{S_{FS}{}^2}\right) - 1 = 0$$

• Compressive fiber mode

$$f_2 = \left(\frac{\langle \sigma'_a \rangle}{S_{aC}}\right)^2 - 1 = 0, \quad \sigma'_a = -\sigma_a + \left\langle -\frac{\sigma_b + \sigma_c}{2} \right\rangle$$

- Crush mode

$$f_3 = \left(\frac{\langle p \rangle}{S_{FC}}\right)^2 - 1 = 0, \quad p = -\frac{\sigma_a + \sigma_b + \sigma_c}{3}$$

- Perpendicular matrix mode

$$f_4 = \left(\frac{\langle \sigma_b \rangle}{S_{bT}}\right)^2 + \left(\frac{\tau_{bc}}{S'_{bc}}\right)^2 + \left(\frac{\tau_{ab}}{S_{ab}}\right)^2 - 1 = 0$$

- Parallel matrix mode (Delamination)

$$f_5 = S^2 \left\{ \left(\frac{\langle \sigma_c \rangle}{S_{cT}}\right)^2 + \left(\frac{\tau_{bc}}{S''_{bc}}\right)^2 + \left(\frac{\tau_{ca}}{S_{ca}}\right)^2 \right\} - 1 = 0$$

where < > are Macaulay brackets, S_{aT} and S_{aC} are the tensile and compressive strengths in the fiber direction, and S_{FS} and S_{FC} are the layer strengths associated with the fiber shear and crush failure, respectively. S_{bT} and S_{cT} are the transverse tensile strengths. The shear strengths for the transverse shear failure and the two axial shear failure modes are assumed to be the following forms, based on the Coulomb-Mohr theory:

$$S_{ab} = S_{ab}^{(0)} + \tan(\varphi)\langle -\sigma_b \rangle, \quad S'_{bc} = S_{ab}^{(0)} + \tan(\varphi)\langle -\sigma_b \rangle$$
$$S_{ca} = S_{ca}^{(0)} + \tan(\varphi)\langle -\sigma_c \rangle, \quad S''_{bc} = S_{bc}^{(0)} + \tan(\varphi)\langle -\sigma_c \rangle$$

where φ is a material constant, and $S_{ab}^{(0)}$, $S_{ca}^{(0)}$ and $S_{bc}^{(0)}$ are the shear strength values of the corresponding tensile modes.

2.2 Fabric lamina damage functions

- Fill/Warp fiber tensile/shear failure modes

$$f_6 = \left(\frac{\langle \sigma_a \rangle}{S_{aT}}\right)^2 + \frac{\left(\tau_{ab}^2 + \tau_{ca}^2\right)}{S_{aFS}^2} - 1 = 0, \quad S_{aFS} = S_{FS}$$

$$f_7 = \left(\frac{\langle \sigma_b \rangle}{S_{bT}}\right)^2 + \frac{\left(\tau_{ab}^2 + \tau_{bc}^2\right)}{S_{bFS}^2} - 1 = 0, \quad S_{aFS} = S_{FS} * \frac{S_{bT}}{S_{aT}}$$

- Fill/Warp fiber compressive failure modes

$$f_8 = \left[\frac{\langle \sigma'_a \rangle}{S_{aC}}\right]^2 - 1 = 0, \quad \sigma'_a = -\sigma_a + \langle -\sigma_c \rangle$$

$$f_9 = \left[\frac{\langle \sigma'_b \rangle}{S_{bC}}\right]^2 - 1 = 0, \quad \sigma'_b = -\sigma_b + \langle -\sigma_c \rangle$$

- Fiber crush failure mode under compressive pressure

$$f_{10} = \left(\frac{\langle p \rangle}{S_{FC}}\right)^2 - 1 = 0, \quad p = -\frac{\sigma_a + \sigma_b + \sigma_c}{3}$$

- In-plane matrix shear failure mode

$$f_{11} = \left(\frac{\tau_{ab}}{S_{ab}}\right)^2 - 1 = 0$$

- Through-thickness matrix failure mode (delamination)

$$f_{12} = S^2 \left\{ \left(\frac{\langle \sigma_c \rangle}{S_{cT}}\right)^2 + \left(\frac{\tau_{bc}}{S_{bc}}\right)^2 + \left(\frac{\tau_{ca}}{S_{ca}}\right)^2 \right\} - 1 = 0$$

where S_{aT} and S_{bT} are the axial tensile strengths in the fill and warp directions, respectively, and S_{aFS} and S_{bFS} are the layer shear strengths due to fiber shear failure in the fill and warp directions. S_{aC} and S_{bC} are the axial compressive strengths in the fill and warp directions, respectively. S_{FC} is the fiber crush strength, and S_{ab}, the layer shear strength due to matrix shear failure. S_{cT} is the through-thickness tensile strength, and S_{bc} and S_{ca} are the shear strengths assumed to depend on the compressive normal stress, σ_c, as follows:

$$S_{ca} = S_{ca}^{(0)} + \tan(\varphi)\langle -\sigma_c \rangle, \quad S_{bc} = S_{bc}^{(0)} + \tan(\varphi)\langle -\sigma_c \rangle$$

2.3 Progressive Damage Modeling

The most important another aspect of MAT_162 is the capability of modeling post-damage softening behavior of composites, that is, progressive damage. Elastic moduli reduction, $E' = (1-\omega)E$, is expressed in terms of an exponential damage functions, $\omega = 1 - \exp\left(\left(1 - (\varepsilon / \varepsilon_y)^m\right)/ m\right)$, with the strain softening parameter m for four different damage modes, such as m_1 and m_2 for fiber damages in material directions 1 and 2, respectively, m_3 for fiber crush and punch shear, and m_4 for matrix crack and delamination. E' and E are the reduced and initial elastic moduli, respectively, and ω and ε_y, the modulus reduction parameter and the yield strain, respectively [2, 4, 5].

3. Specimen Tests of Carbon/Epoxy Composite Laminates

Mechanical characteristics and weight drop tests were performed for UD and PW of carbon fiber/epoxy resin laminar specimens, such as tension, compression, shear in plane (V-notch) and shear between layers (SBS; short beam strength), and also weight drop tests, for the PW laminate specimens. Their tested specimens are shown in Figs. 5-9, their stress-strain curves of characteristics tests are shown in Fig. 10, and collision force and absorbed energy responses of weight drop test, in Fig. 11.

(a) UD 0° (b) UD 90° (c) PW fill (d) PW warp

Fig. 5 Carbon/Epoxy tensile test specimens

(a) UD 0° (b) UD 90° (c) PW fill (d) PW warp

Fig. 6 Carbon/Epoxy compressive test specimens

(a) UD

(b) PW

Fig. 7 Carbon/Epoxy V-notch test specimens

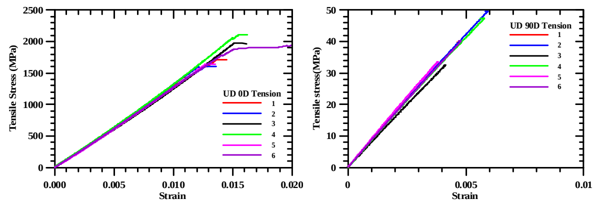
(a) UD

(b) PW

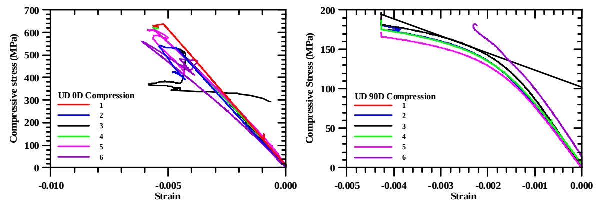
Fig. 8 Carbon/Epoxy SBS test specimens

(a) face (b) back (c) C scan

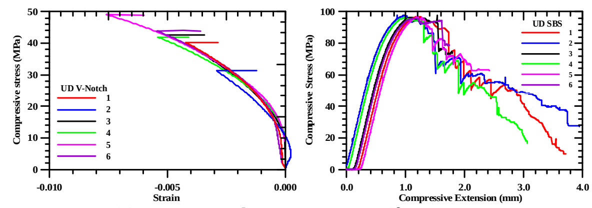
Fig. 9 Carbon/Epoxy weight drop test specimen



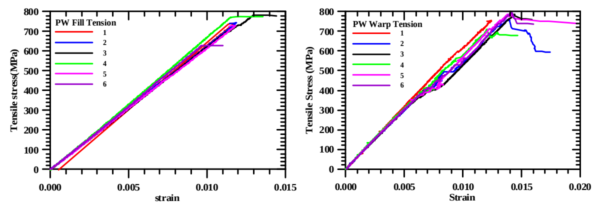
(a) UD 0D Tension (b) UD 90D Tension



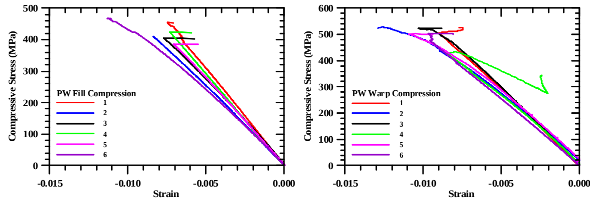
(c) UD 0D Compression (d) UD 90D Compression



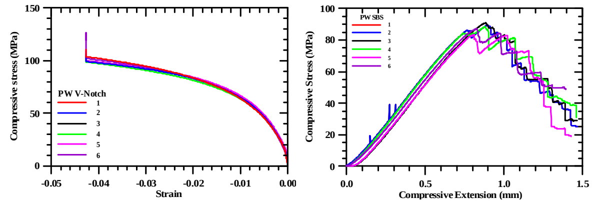
(e) UD V-Notch (f) UD SBS



(g) PW Fill Tension (h) PW Warp Tension

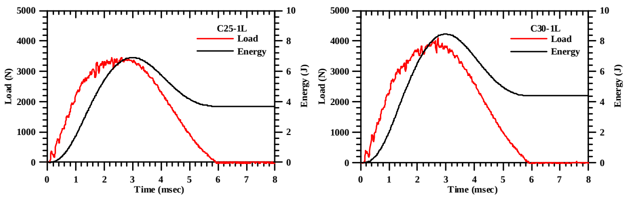


(i) PW Fill Compression (j) PW Warp Compression



(k) PW V-Notch (l) PW SBS

Fig. 10 Stress-strain curves of Carbon/Epoxy UD & PW characteristics test



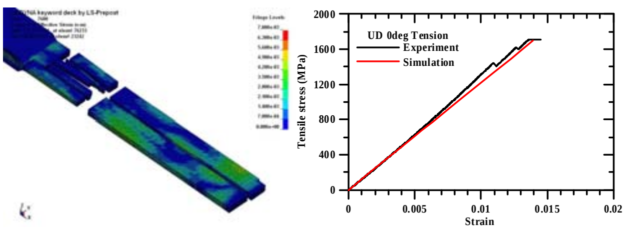
(a) C25 (b) C30

Fig. 11 Collision force and absorbed energy responses of weight drop tests

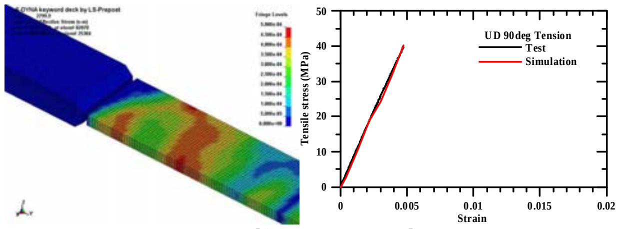
4. Structural Analysis Simulations of Carbon/ Epoxy Composite Laminates

Progressive damage simulations were carried out for the mechanical characteristics tests of UD and PW laminar specimens and weight drop tests of PW ones, as shown in Chapter 3, using MAT_162 of LS-DYNA code.

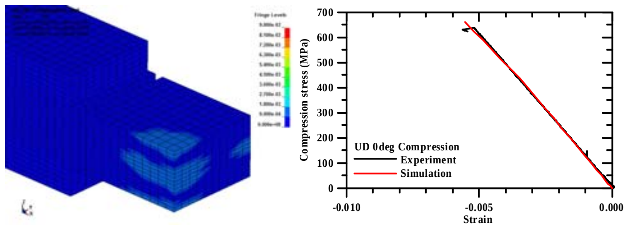
Figures 12 and 13 illustrate the progressive damage configurations and stress-strain curves for the UD and PW laminate characteristics test simulations, and Fig. 14, for the PW laminate weight drop test one. Material properties and calibrated parameters for the UD and PW carbon fiber/epoxy resin in this simulation are summarized in Table 1.



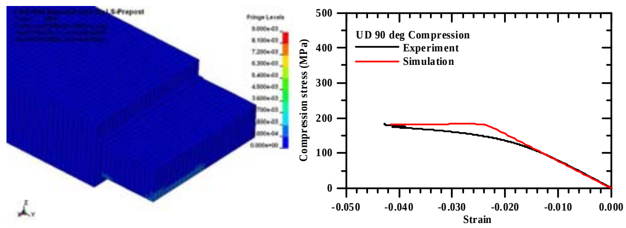
(a) UD 0° tensile



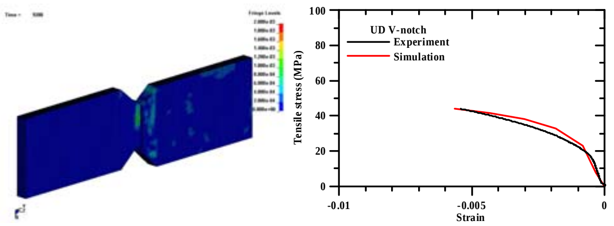
(b) UD 90° tensile



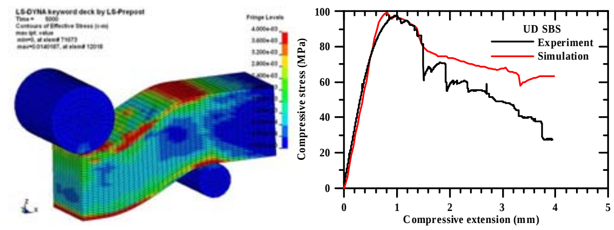
(c) UD 0° compressive



(d) UD 90° compressive

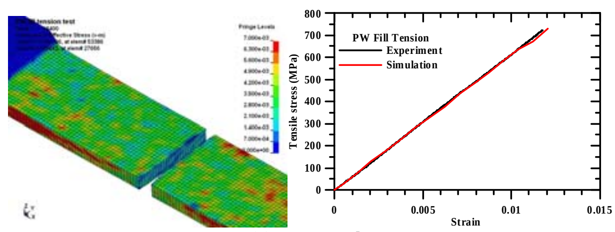


(e) UD V-notch

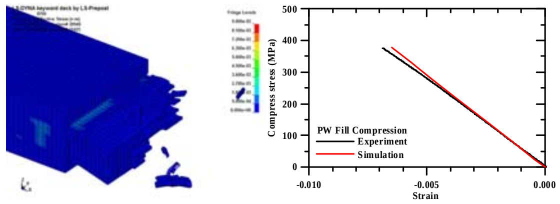


(f) UD SBS

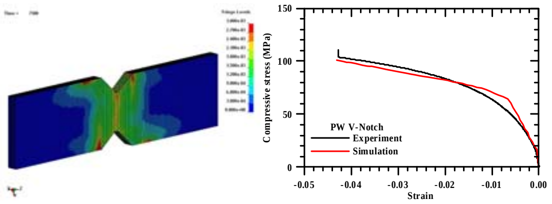
Fig. 12 Damage configurations and stress-strain curves of UD laminate test simulation



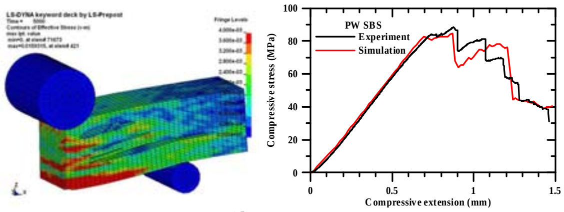
(a) PW tensile



(b) PW compressive



(c) PW V-notch



(d) PW SBS

Fig. 13 Damage configuration and stress-strain curve of PW laminate test simulation

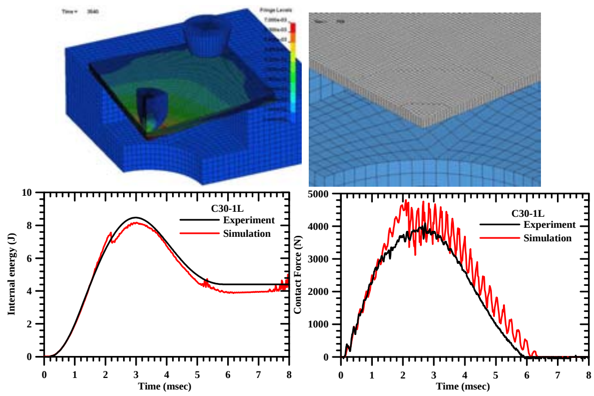


Fig. 14 Damage configuration (delamination) and collision response of weight drop test simulation

Table 1 Material properties and calibrated parameters for Carbon/Epoxy UD and PW laminates

(a) UD laminate

RO (kg/m^3)	EA(GPa)	EB(GPa)	EC(GPa)	PRBA	PRCA	PRCB
1,497.5	122.51	8.4	8.4	0.10	0.20	0.20
GAB(GPa)	GBC(GPa)	GCA(GPa)	SAT(MPa)	SAC(MPa)	SBT(MPa)	SBC(MPa)
4.76	1.5	1.5	1,835.4	700.0	40.5	184.2
SCT(MPa)	SFC(MPa)	SFS(MPa)	SAB(MPa)	SBC(MPa)	SCA(MPa)	SFFC
80.0	2,500.0	405.0	41.5	55.0	55.0	0.35
AMODEL	PHIC	E_LIMT	S_DELM	OMGMX	ECRASH	EEXPN
1	10	0.005	1.2	0.999	0.8	1.10
AM1	AM2	AM3	AM4			
1.0	0.001	0.5	0.3			

(b) PW laminate

RO (kg/m^3)	EA(GPa)	EB(GPa)	EC(GPa)	PRBA	PRCA	PRCB
1,497.5	62.5	62.5	20.0	0.06	0.08	0.08
GAB(GPa)	GBC(GPa)	GCA(GPa)	SAT(MPa)	SAC(MPa)	SBT(MPa)	SBC(MPa)
4.76	1.3	1.3	1,300.0	800.0	1,300.0	800.0
SCT(MPa)	SFC(MPa)	SFS(MPa)	SAB(MPa)	SBC(MPa)	SCA(MPa)	SFFC
48.0	1,000.0	600.0	70.0	60.0	60.0	0.35
AMODEL	PHIC	E_LIMT	S_DELM	OMGMX	ECRASH	EEXPN
2	10	0.005	1.2	0.999	0.8	1.10
AM1	AM2	AM3	AM4			
1.0	1.0	0.5	0.8			

5. Conclusions

Characteristics and weight drop tests of Carbon/Epoxy composite laminar specimens were performed, and their mechanical properties, damage states and mechanisms were examined according to test. Progressive damage analysis techniques were developed using material model MAT_162 linked with LS-DYNA code with the investigation of their damage mechanism and calibration of their parameters. Through this study, it might be thought that the optimum structural design of composite laminates and propeller could be derived with high accuracy for the maximization of its performance at the reversed design stage by the estimation of their strengths, energy absorption capacities and damage states according to the diverse fiber arrays.

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