A numerical reliability design method of winding vessels based on damage mechanics

Yoshitaka Sakata*, Masaru Zako*, Tetsusei Kurashiki *,
Hiroaki Nakai*, Shirou Nishibu*, Masataka Sugahara**
***Graduate School of Engineering, Osaka University, Osaka, Japan**
****Maruhachi Corporation, Fukui, Japan**
[Yoshitaka Sakata*]:y-sakata@mit.eng.osaka-u.ac.jp

Keywords*: Damage mechanics, Failure modes, Filament winding, Finite element method*

Abstract

Recently, high-pressure vessels made of CFRP are used for the hydrogen vessels of the fuel-cell vehicles. Previously, these pressure vessels have been designed by a design method which is combination method of netting theory and membrane theory. But the method was not satisfied applying to high-pressure vessels, because it was not considered thickness and damage propagation of FRP.

In this paper, we've proposed a new design method for high-pressure composite vessels. High-pressure vessels are designed by finite element method based on damage mechanics. A prototype vessel has been made of CFRP. In order to verify, a pressure test has been curried out and the strains at each point on surface of vessel have been compared with the numerical results. It is recognized that the proposed method is a reasonable design one, since the numerical result agree well with the experimental ones.

1 Introduction

Filament winding vessels have some advantages like lightweight and high-strength. These vessels are great demand for the fuel cell vehicles with hydrogen gas. Especially, 70MPa hydrogen gas vessels have been interested in allowable service pressure, because the total mileage can be increased than the current hydrogen gas vessel with 35MPa.

Filament winding vessels has been already applied to natural gas fueled car and medical hydrogen cylinder. These filament winding vessels may be modeled by netting theory and membrane theory [1]. The concept of netting theory is to sustain the applied load only by the fiber reinforcement. Membrane theory is constructed by the shell as the thickness tends to zero. Therefore, the initial failure like matrix cracking, the bending stress etc. are not considered. FRP has the weakness of bending stress and shows the initial failure mode like a transverse crack in matrix region and the complex failure modes such as the debonding or the delamination. The final failure mode of FRP is the fiber break. In order to design the FRP vessel, it is necessary to consider these progressive failure modes.

In this paper, we've proposed a design method based on damage mechanics. A pressure vessel of 70MPa has been designed by the proposed method and produced by CFRP pre-preg tape. The mechanical behavior of the vessel under the inner pressure has been simulated by FEM based on damage mechanics. The internal pressurized test has been carried out, and. the strains on the outer surface of vessel have been measured by strain gauges. In order to verify the proposed method, the numerical result has been compared with the experimental one.

2 Design procedure of Filament Winding Vessels

Fig.1 shows the cross-sectional drawing of the filament winding vessels. Liner is made of plastic. The plastic liner is subjected because it is expected to lighter in weight. Plastic liner needs boss in order to put a valve, but metal liner does not need boss because metal liner was machined threading tap. Filament winding vessels are designed stiffness enhancement by combining helical winding and hoop winding.

In Japan, hydrogen vessel of fuel cell vehicles is designed under Japan Automobile Research Institute (JARI) standard: JARI S 001(2004) [2]. In this standard, the safety factor must be bigger than 2.25(157.5MPa). We have proposed a design flow chat that meets the requirements of JARI standard using the finite element analysis based on damage mechanics.

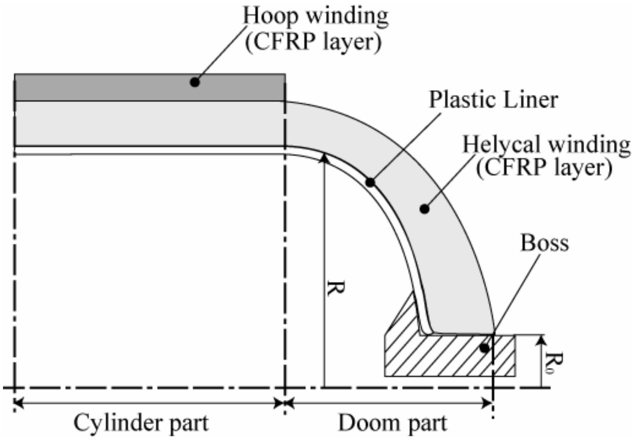


Fig.1 Cross-sectional drawing of filament wound vessel

Fig.2 shows a flow chart for design procedure of high pressure vessels. An initial geometry is determined by conventional design method; a shape of doom part, a shape of boss and thickness of CFRP layer. We call this process a rough design.

After that, the design parameters of filament winding vessels are set to meet the requirement that the matrix does not break at filling pressure and the safety factor must be bigger than 2.25. This process of filling in the gap of the rough design is defined as detail design.

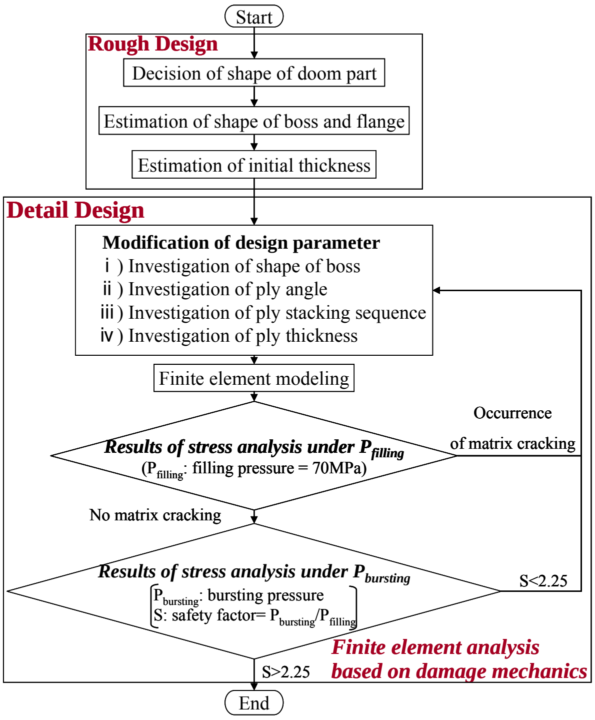


Fig.2 Flow chart for design procedure of a high pressure vessel

3 Finite Element Method Based on Damage Mechanics

The modulus of elasticity of unidirectional composites is changed stiffness by the occurrence is of matrix crack. Fig.3 shows the typical damage modes of laminates under loading. In this section, we introduce finite element method based on damage mechanics [3].

The failure of unidirectional composites is classified some damage modes, such as fiber breaking, transverse cracking and delamination. These modes affect strongly the mechanical behavior after the occurrence of damage. The damage modes of unidirectional composites can be classified into four types as shown in Fig.4. The axes L, T, and Z mean the principal coordinates of orthotropic material, and they correspond to fiber and transverse directions, respectively.

The occurrence of damage is determined by Hoffman's failure criterion [4]. After calculating the corresponding stress-to-strength ratios for the different modes, the modulus of elasticity of the element is reduced if an element is judged as the damage. The correlation between the stress-to-strength ratios and damage modes is summarized in Table 1. The parameters F^t, F^c and F^s indicate the tensile, compressive and shear strengths, respectively. Finite element analysis based on damage mechanics has been carried out up to the final failure.

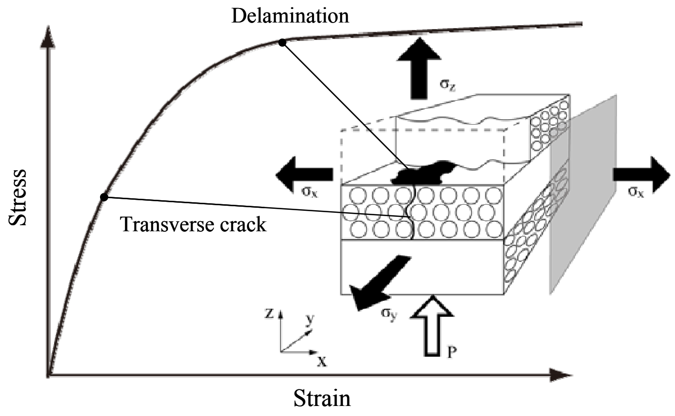
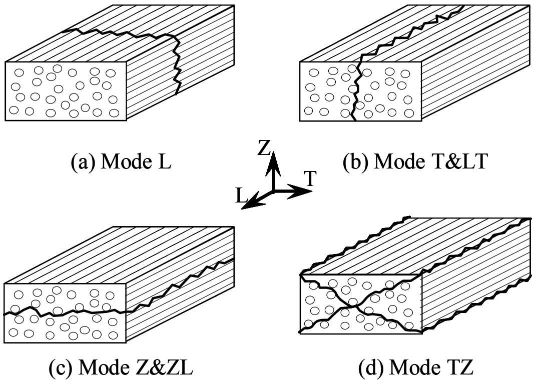


Fig.3 Typical damage modes of laminates under multiaxial loading



(a) Mode L (b) Mode T&LT (c) Mode Z&ZL (d) Mode TZ

Fig.4 Anisotropic damage models for unidirectional FRP

Table 1 Determination of damage mode

Stress-to-strength ratio	Damage mode
$\frac{\sigma_L^2}{F_L^t F_L^c}$	Mode L
$\frac{\sigma_T^2}{F_T^t F_T^c}$ or $\left(\frac{\tau_{LT}}{F_{LT}^s}\right)^2$	Mode T&LT
$\frac{\sigma_Z^2}{F_Z^t F_Z^c}$ or $\left(\frac{\tau_{ZL}}{F_{ZL}^s}\right)^2$	Mode Z&ZL
$\left(\frac{\tau_{TZ}}{F_{TZ}^s}\right)^2$	Mode TZ

4. Finite element method based on damage mechanics

4.1 Analysis

The length and the diameter are of vessels are 650mm and 382mm, respectively. Fig.5 shows a FEM model of the vessel. Although the filament or the strand for helical winding are crossed over each other, the FEM model is not so simple.

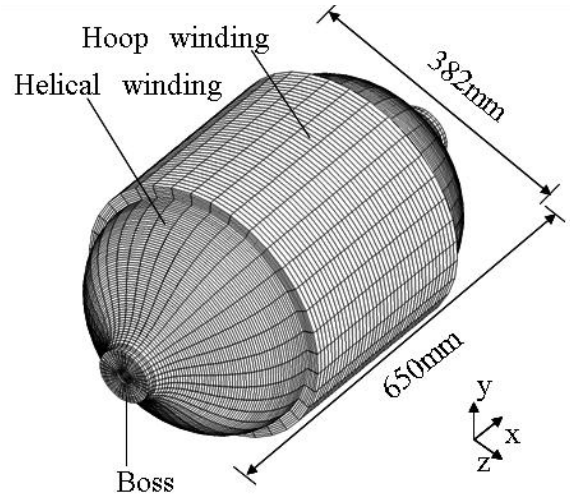


Fig.5 A FEM model of the winding vessel

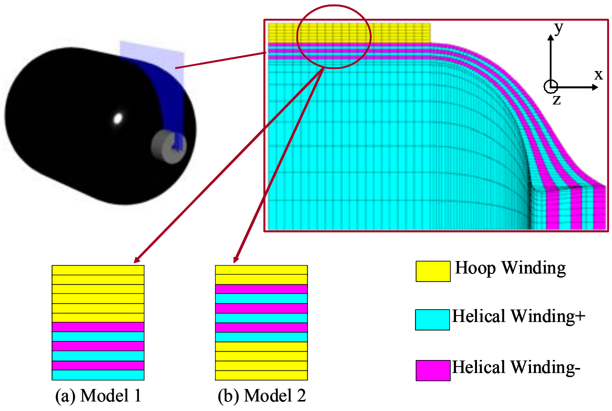
Main axis L is defined as each is element, and the orientation of fiber is defined as the meridian direction. Under this condition, the material properties are calculated a fiber winding status. Helical winding angle β which is obtained by Eq.(1), is rolled according to the geodetic line.

$$\beta = \sin^{-1}\frac{R_0}{R} + \delta \qquad (1)$$

R_0 is radius of boss and R is the radius of the cylinder as shown in Fig.1. δ is the gap in the geodetic line. δ is a design parameter that affects the stiffness of doom part. Helical winding layer is regarded as a $[\pm\beta]_n$ laminate.

4.2 Examination Case-Ply Stacking-

Fig.6 shows Ply stacking model. Model 1 and Model 2 differ from each other in stacking sequence as shown in Fig.6.

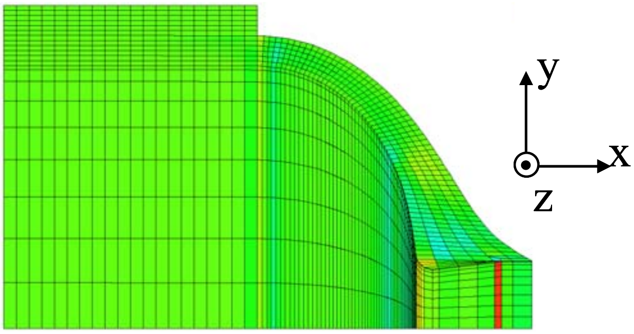


(a) Model 1 (b) Model 2

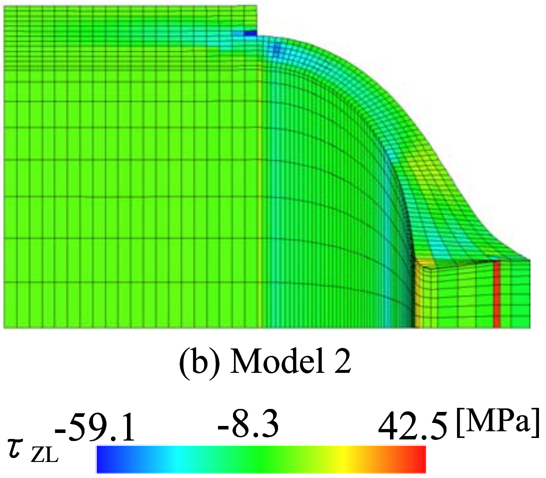
Fig.6 Ply stacking models of Model 1 and Model 2

The shear stresses when the pressure reaches 70MPa are shown in Fig.7 (a) and (b). And it is cleared that the shear stress appears the big difference. The ratios of damaged elements for each model are shown in Fig.8. From Fig.8, it can be recognized that the number of damages in Model 2 is larger than the ones of Model 1. The damage states of two models, at 85MPa are shown in Fig.9 (a) and (b). The biggest difference appears in the hoop winding layer.

The damage development in Model 2 at 85MPa is shown in Fig.10. The early damage is found in the hoop layer. Fig.10 shows the state of damage development in Model 2 at 85MPa, too. The initial damage is generated at the concentrate area of shear stress in ZL-plane. It can be considered that the ModeL is influenced bending stress at the boundary of cylinder part and doom part. Structure design for high pressure vessels with analysis presents a possibility of design.



(a) Model 1



(b) Model 2

Fig.7 Distribution of shear stress TZ in-plane at 70MPa

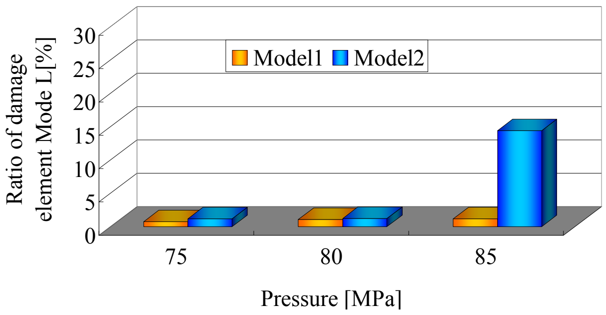
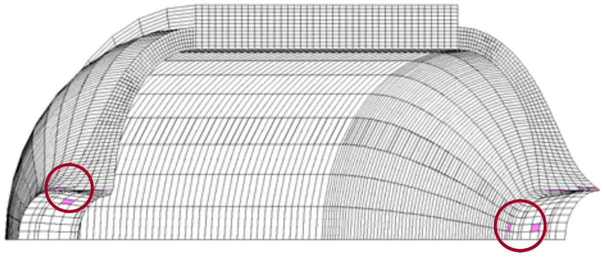
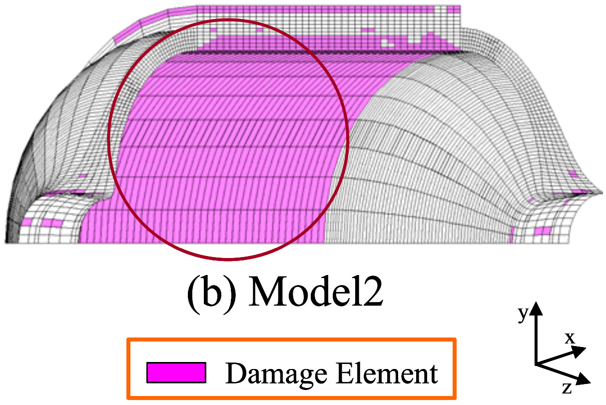


Fig.8 Ratio of damage elements for Model 1 and Model 2



(a) Model1



(b) Model2

Fig.9 Damage element states for Model 1 and Model 2 at 85MPa

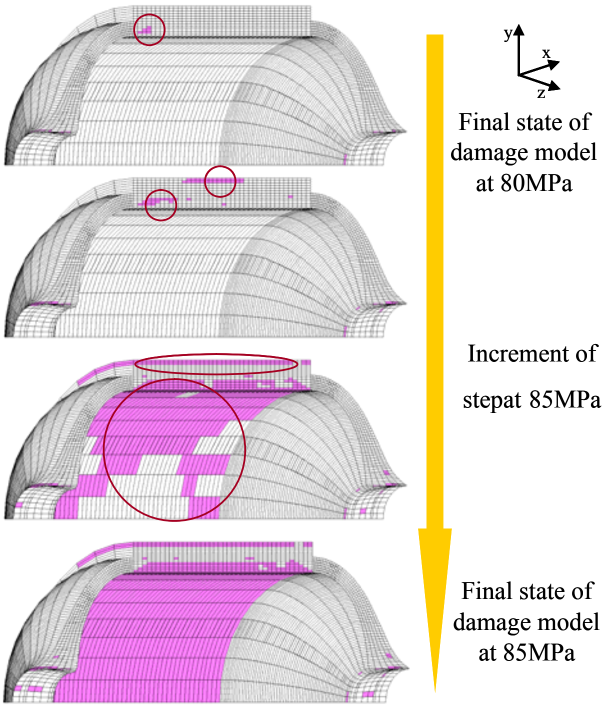


Fig.10 Damage development states in Model 2

5. Testing for prototype vessel

The prototype vessel which is designed by the proposed method has been manufactured. Fig.11 shows the produced vessels.

Fig.11 A prototype vessel

Fig.12 shows a burst testing system. The strain gage is attached on the surface of vessel. The strain is measured under increased pressure of water.

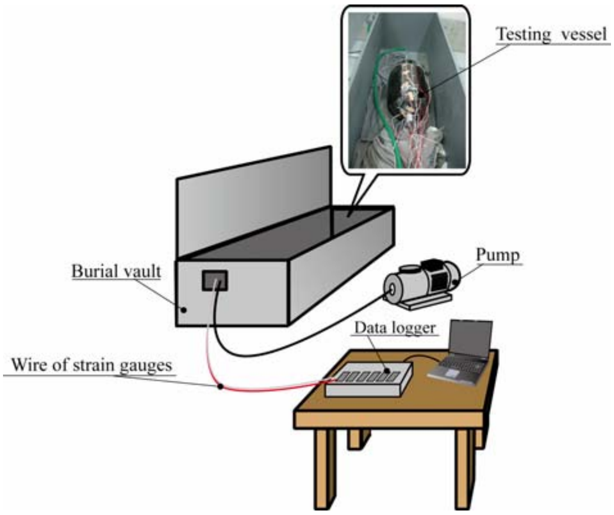
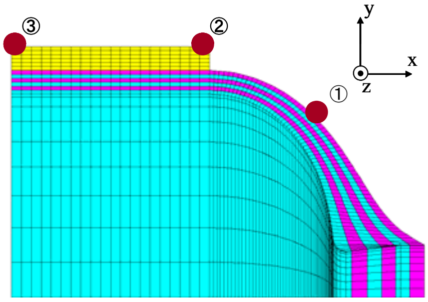
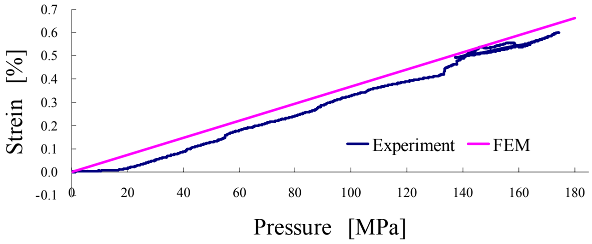


Fig.12 Burst test system

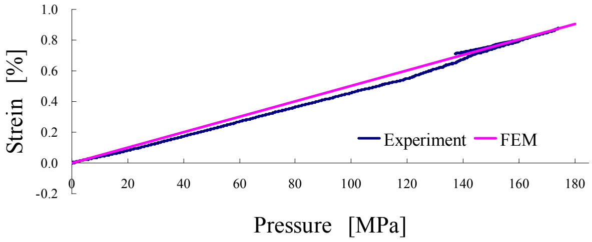
Fig.13 (a) shows the point of strain gages. The experimental results and the numerical results are shown in Fig.13 (b) and (c) and (d). The stiffness of numerical results has a good agreement with the experiments.



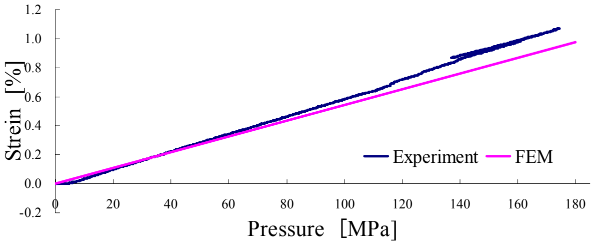
(a) point of strain gages



(b) At ① point (T-direction)



(c) At ② point (L-direction)

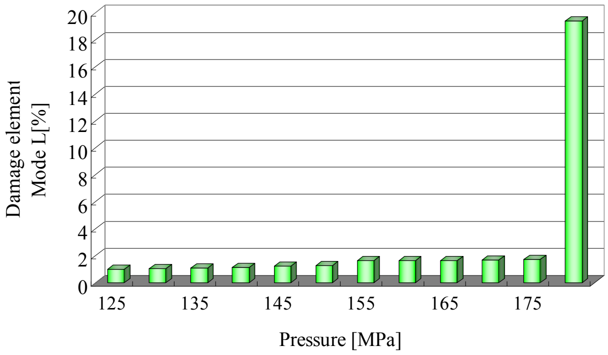


(d) At ③ point (L-direction)

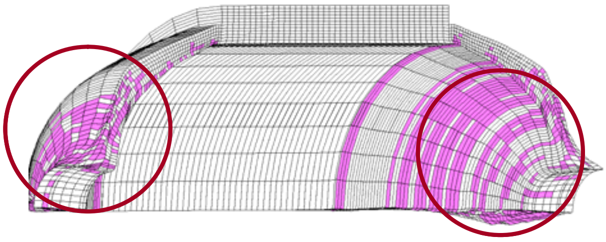
Fig.13 Comparison between experiments and calculation results

Fig.14 shows the vessel after burst. The prototype vessel designed by the proposed method exceed JARI standard in pressure. Fig.15 (a) indicates the ratio of damaged elements of ModeL, and the deformation under 180MPa is shown in Fig.15 (b). It is recognized from the damage development analysis that the ratio of damaged elements is increased and severe damage is found around the dome at 180MPa. In addition, the trend obtains from analysis and the correction is confirmed by the burst test.

Fig.14 Busted condition of filament winding vessels



(a) Ratio of damage element model



(b) Damaged condition of filament winding vessels damage element state at 180MPa

Fig.15 Damage development in prototype of filament winding vessels

6. Conclusion

The proposed design method for filament winding vessel aims at covering weakness of traditional design method. The stacking-sequence is a critical design parameter. It is recognized that the effect of the stacking sequence damage propagation can be analyzed by the proposed method based on damage mechanics. The prototype vessel has been designed by the proposed method and been produced. The vessel exceeds the JARI standard in burst pressure.

Acknowledgement

The work was supported by The Kansai Bureau of Economy, Trade and Industry (consortium for developing local industry" Research and development of pressure vessel for fuel cell vehicle").

References

[1] Fukunaga H., Uemura M., "Optimum Design of Filament-wound Pressure Vessels(Part 1) Structural Analyses of Pressure Vessels and Optimal Dome Shape Based on Failure Criterion" *The Japan Sciety for Aeronautical and Space Sciences,* pp432-439,(1981).

[2] "Compressed Hydrogen Vessels Design Standard for Fuel Cell Vehicles". JARI S 001(2004).

[3] Zako M., Tujikami T., Tumura T., "Development of Finite Element Method Considered an Anisotropic Damaged State for Composite Materials". *Proceedings of the Thirty-Seventh Japan Congress on Materials Research*, pp.174-179, (1994).

[4] Hoffman.O, "The Brittle Strength of Orthotropic Materials", *Journal of composite materials*, 1(1967), 200.