論文

# 유압과 함께 압축 부하가 가해지는 상태에 탄소섬유 복합재료의 강도 예측

지용주* · Stephen R. Swanson**

# Strength Prediction of Carbon/Epoxy Composites under Compressive Loading with Hydrostatic Pressure

Yong Ju Jee* and Stephen R. Swanson**


## 초 록

여러가지 두꺼운 복합재료 구조물은 다축 방향의 부하 상태에 노출되는 경우가 발생한다. 예를들면, 원통형 구조물의 안과 밖에 동일한 유압이 가해진 상태에 축방향의 압축 부하가 가해지는 경우를 만난다. 이런 경우에 있어서의 복합재료 압축 강도는 압축 평균 응력을 이용하면 예측이 가능할지도 모른다. 이번 연구에서는 압축 평균 응력을 이용하여 탄소 섬유 강화 복합재료들의 압축 강도를 예측하는 모델을 개발하고자 한다.

본 모델은 압축강도에 영향을 주는 요소, 초기 misalignment와 초기 섬유 waviness를 고려하였고, 탄소섬유와 수지사이에 접합강도가 임계값을 초과할 때 복합재료의 파괴가 일어난다고 가정한다. 또 여러가지 문헌들을 통하여 유압이 접합강도에 미치는 점들을 고려한다. 본 모델을 이용한 예측값들은 가해지는 유압에 따라 증가되며, 여러가지 문헌에서 얻어진 실험값들도 유압의 증가에 민감하게 변한다.

## ABSTRACT

Compression loadings in thick composites can in some cases lead to three-dimensional states of stress with a compressive mean stress. Models are examined in the present work that attempt to predict the effects of this compressive mean stress on the compression strength of carbon/epoxy fiber composites. The models assume that the fibers have an initial misalignment, and that composite failure occurs when the fiber-matrix bond strength is exceeded. Literature values for the effect of pressure on bond strength are included. Comparisons with experimental data from the literature support the predicted increase in compression strength with pressure.


**Key Words:** Compressive Strength, Carbon/Epoxy, Composites, Pressure Effect, Compressive Failure, Bond Strength, Fiber Waviness

* 미시시피 주립대학, 항공우주공학과
** 유타대학교, 기계공학과

## Introduction

Composite materials are being used in applications where the compressive strength is important. The apparent compressive strength of fiber composites seems to be a quite complex subject, with a number of variables affecting the results. One of these factors appears to be a mean compressive stress effect. For example, data exists in the literature that shows that the compressive strength of fiber composites with polymeric materices increases with hydrostatic pressure. It is possible that three-dimensional mean compressive stress may play a similar role as pressure, and thus this effect may be important in thick laminates loaded in compression, where three-dimensional stress fields will be significant.

Composites are being considered for applications involving thick laminates loaded in compression, such as in a submersible structures. Thick laminates will habve special features relative to more conventional thin laminates. In addition to possible manufacturing problems, thick composites laminates will tend to have three-dimensional state of stress. These is some experimental evidence that three-dimensional compressive stress states can actually improve the apparent compressive strength of the laminates. This apparent strength increase is likely associated with a compressive mean stress that acts as a superposed pressure. There is evidence in the literature, as will be discussed later, that superposed hydrostatic pressure acts to increase the apparent compressive strength of fiber composites. A further question is thus to explain the mechanisms behind this beneficial pressure effect. The present paper will attempt to show that this strength increase can be explained in terms of known effects of pressure on the polymer matrix, and the interaction of the matrix with compressive strength of fiber composites.

Although many researchers have studied compression failure mechanisms of composite structures, there is not at present a well established theoretical and/or experimental basis for the prediction of compressive strength. A number of models for compressive strength of unidirectional composites have been suggested. The problem is complex, not only because of the mechanics of analysis, but also because of the variable failure mode of different composite materials. Nevertheless, the various micromechanical models available in the literature are valuable in gaining an understanding of the controlling damage mechanisms and in directing future efforts at increasing compressive strength. The failure of carbon fiber composite materials has been studied by a number of investigators, including Rosen[1], Chaplin[2], Evans and Adler[3], Budiansky[4], DeTeresa et al.[5], Hahn and Willams[6], Swanson[7], Argon[8], Wronski and Howard[9], Piggott[10], DeFerran and Harris[11], Greszczuk[12], and Hayashi[13], and many others. Guynn et al.[14] give a number of additional references.

In the following, theoretical models of compressive failure of fiber composites will be reviewed. Modifications of the models to incorporate pressure effects on polymeric matrices will be shown. The model predictions will then be compared with literature results of compression tests carried out on carbon/epoxy laminates under hydrostatic pressure.

## Theoretical models

There have been a large number of theoretical models put forth to attempt to explain the mechanisms in compressive failure of fiber composites. A number of these models consider compressive failure to be governed by bifurcations bucking of perfectly straight fibers that are stabilized by the matrix. The matrix is typically represented by the modulus only, although a tangent modulus can be incorporated, as by Rosen[1], Wang[5], Hahn and Willams[6]. The fibers are typically assumed to act cooperatively, as in the classical shearing and extension models of Rosen [1]. A second approach considers that the models are initially inperfect, by assuming that the fibers have an initial periodic waviness. Examples are given in the work of Herrman et al.[16], Lanir and Fung[17], and Hahn and Williams[6]. This category of models does not exhibit bifurcation bucking, but rather fails by excessive deformation of the fibers, leading to either excessive fiber or matrix stresses or strains.

The authors, and many others, believe that models involving initially wavy fibers are more realistic for carbon/epoxy composites. As noted above, models with initially straight fibers predict a compressive strength that depends on the matrix stiffness, while the initially wavy fiber models include not only the stiffness but either the fiber or the matrix strength. In previous results reported by out laboratory, tests were carried out on fiber composites in which the fiber-matrix bond strength had been artificially reduced with a release agent, but leaving the matrix stiffness unchanged. The apparent laminate compressive strength was reduced by up to a factor of four, indicating the importance of the matrix bond strength and thus supporting the use of imperfect fiber models(Swanson and Colvin[18]). Systematic changes in compressive strength with fiber -matrix adhesion strength were also reported by Madhukar and Drzal[19].

The following work will attempt to show that the effect of pressure or mean compressive stress can be readily incorporated into existing models for fiber composite compressive strength based on the above. Two models will be examined in the following. The first is a very simple model used previously by the authors that permit examination of the basic ideas, while the second follows recent work of Zhang and Latour[20] in giving an improved treatment of the matrix stresses.

Model 1–A model that expersses the features described above, i.e. of initially wavy fibers and a limiting fiber-matrix bond, has been used previously by Swanson[7] and Swanson and Colvin [18] for compression failure of laminates. The model assumes that both fiber and matrix will have a sinusoidal displacement field, based on the work presented by Hahn and Williams[6]. This, of course, is an approximation, but it has permitted calculations to be made involving lamination effects in compression failure. The basic ideas of the model will be illustrated in the following. The critical axial plies are assumed to have an initial fiber waviness given by

$$v_o = f_0 \sin\lambda x \qquad \cdots\cdots\cdots\cdots\cdots (1)$$

where $f_0$ : amplitude of initial fiber waviness
$\lambda$ : wavelength of fiber

The subsequent lateral deformation is taken as

$$v - v_o = (f - f_0) \sin\lambda x \qquad \cdots\cdots\cdots\cdots\cdots (2)$$

where $v$ : lateral displacement
$f$ : amplitude of fiber waviness

The deformation under load can then be solved for fiber lateral displacement by using the minimum potential energy therorem, with the parameter f governing the amplitude of the bending deformation of the fibers. The task is to formulate the strain energy of the axial fibers and matrix, and then to minimize the potential energy under applied axial compression displacement.

The strain energy terms are given as follows:
(1) In-plane shear in axial plies:

$$\Upsilon_{xy} = \frac{\partial(v - v_0)}{\partial x} = (f - f_0)\,\lambda\,(\cos\lambda x) \qquad \cdots\cdots\cdots (3)$$

$$U_1 = \int_0^1 \int_0^1 \int_0^t \frac{1}{2} G_m \gamma_{xy}^2 \, dzdydx = G_m t \lambda^2 \ (f-f_0)^2 \ / \ 4$$

(2) Axial compression of axial plies

$$U_1 = \int_0^1 \int_0^1 \int_0^t \frac{1}{2} E_{11} \, \varepsilon_A^2 \, dzdydx \qquad \cdots\cdots\cdots\cdots (5)$$

$$\varepsilon_A = \varepsilon_{11} - \varepsilon_b \qquad \cdots\cdots\cdots\cdots (6)$$

$$\varepsilon_b = \int_0^1 \frac{v'^2}{2} dx - \int_0^1 \frac{v_0'^2}{2} dx = \lambda^2 \ (f^2 - f_0^2) \ / \ 4 \qquad \cdots\cdots\cdots\cdots (7)$$

where $\varepsilon_{11}$ is the applied displacement per unit length in the axial direction, $\varepsilon_A$ is the axial strain in the fibers, and $\varepsilon_B$ is the axial displacement per unit length due to the bending undulation of the fibers. The bending energy in the fibers could also be included, but as discussed previously (Hahn and Willams[6] and Swanson[7]) this term has little effect. Substituting these expressions for strain energy into the potential energy, and minimizing with respect to f, the fiber bending displacement parameter, under an applied axial displacement per unit length of $\varepsilon_{11}$, gives

$$G_m(f-f_0) + E_{11}\lambda^2(f^2-f_0^2)f - E_{11}f\varepsilon_{11} = 0 \quad \cdots\cdots (8)$$

The limiting condition is assumed to be established by the shear stress in the matrix or the fiber matrix bond. This is calculated by multiplying the sheat strain in the matrix, given by Eqn 3 above, by the matrix shear modulus, to get

$$\tau = G_m(f-f_0)\lambda \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (9)$$

It can also be observed from Eqn 1 that $\lambda_f$ is the maximum value of the fiber misalignment angle, so that Eqn 9 can be written as

$$\phi = \frac{\tau}{G_m} + \phi_0 \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (10)$$

where $\phi$ and $\phi_0$ are the current and initial values of fiber of misalignment angle. The maximum value of the fiber misalignment angle is thus determined by the ultimate allowable matrix shear stress $\tau_u$ giving

$$\phi_u = \frac{\tau_u}{G_m} + \phi_0 \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (11)$$

Substituting this value for $\phi_u$ into Eqn 8 gives an expression for the axial compressive stress as

$$\sigma_{11} = -\{E_{11}(\phi_u^2 - \phi_0^2) + G_m(\phi_u - \phi_0) / \phi_u\} \cdots (12)$$

Thus the model predicts a compressive strength related to the initial and ultimate fiber misalignment angle, and the ultimate fiber misalignment angle is determined by the allowable matrix shear stress.

It is known that the stiffness and strendth of polymeric materials increase with pressure (Pae and Bhateja[21], Silano et al.[22]). Thus the pressure effect can be directly incorporated into the above model of compressive strength. The effect of pressure on the fiber-matrix bond strength was taken from data of Shin and Pae[23] given in the nondimensional from of

$$\tau / \tau_0 = 1 + \alpha_1 (p / \tau_0) \qquad \cdots\cdots\cdots\cdots\cdots (13)$$

with $\alpha_1$=0.159, and where $\tau$ and $\tau_0$ are the matrix bond strength with and without pressure. The effect of pressure on the modulus is much lower than the effect on matrix bond strength, and did not change the calculation significantly. This expression for the increase of matrix bond strength with pressure is quite similar to that given by Groves et al.[24] at lower pressures. This form of the pressure effect has been presented in previous work by Jee and Swanson[25].

Model 2 – Zhang and Latour[20] have recently presented a model for compression failure in composites, that significantly improves the treatment of the matrix stresses. It will be shown in the following that the pressure effect can be readily incorporated into this model, using ideas similar to those shown above.

Zhang and Latour[20] follow the general ideas of earlier model for compression failure in fiber composites, in that they use a 2−D formulation in which the fibers and matrix are both idealized as slabs in a plane stress analysis. In addition, they use a beam on elastic foundation analysis for the fiber. However Zhang and Latour have made a significant improvement on previous models in the treatment of the stress distribution within the matrix. They were able to obtain an elasticity solution for the matrix stresses that is exact for the idealization addressed. One of their significant results is that they show that the shear mode of fiber deformation is favored for all fiber volume fractions, is disagreement with early work that suggested that the preferred deformation pattern would change with volume fraction. The equation developed by Zhang and Latour needed for the subsequent work will be briefly reviewed here, and then used to display the pressure effect on compression strength.

Zhang and Latour start with a 2-dimensional representation of the fiber and matrix, in which the slab representing the fibers has thickness of 2r, and the spacing between fibers is 2a. the coordinate system is in the x-y plane, with x in the direction of the fibers. They then related the stresses in the matrix to the deformation of the fibers by use of the stress function given as

$$\phi(x,y) = \sin \alpha x[c_1\cosh \alpha y + c_2\sinh \alpha y + c_3 y\cosh \alpha y + c_4 y\sinh \alpha y] \quad \cdots (14)$$

The stresses are obtained from the stress function using the usual relations. The strains are then obtained from the stresses using Hooke's law, and integrated to obtain the displacements. The constants are then determined by matching the displacements at the fiber-matrix interface. The centerline displacement of the fiber is assumed to have a sinusoidal displacement goven by

$$v(x) = A \sin \alpha x \quad \cdots\cdots\cdots\cdots\cdots (15)$$

The displacements u and v at the fiber-matrix inteface are then obtained from the above using the usual assumption of plane sections remaining plane for the fiber. Thus the stresses and strains within the matrix can be fully determined by the assumed fiber deformation. The expression for the matrix shear stress at the interface with the fiber will be interest in the present development. Zhang and Latour give an expression for the shear stress as (for the shearing model of fiber deformation)

$$B=\frac{a\alpha(1+v_m)+(1-v_m)\sinh a\alpha\cosh a\alpha+2\alpha r\cosh^2 a\alpha}{2a\alpha(1+v_m)+(3-v_m)\sinh 2a\alpha} \quad \cdots\cdots\cdots (16)$$

$$\tau_{xy} = 4\ G_m A\alpha\cos\alpha x B \quad \cdots\cdots\cdots\cdots\cdots (17)$$

where the matrial properties are that of the matrix, and 2a is the space between the fibers. Zhang and Latour then use the matrix normal and shear stresses in the usual beam on elastic foundation representation of the fiber. The equation for fiber microbuckling is given by

$$EI_f\frac{d^4v}{dx^4} + P\frac{d^2v}{dx^2} - 2r\frac{d\tau_{xy}}{dx} + 2\sigma_y = 0 \quad \cdots\cdots\cdots (18)$$

where r is the radius of the fiber (the half thickness of the slab). Substituting for the matrix interface stresses permits the solution for the critical axial force in the fibers, and thus the composite compressive stress, to be obtained as follows. Defining

$$C=\frac{2\xi(1+v_m)+(1-v_m)\sinh 2\xi+\dfrac{2\sinh^2\xi}{\alpha r}+2\alpha r\cosh^2\xi}{(1+v_m)[2\xi(1+v_m)+(3-v_m)\sinh 2\xi]} \quad \cdots\cdots\cdots\cdots\cdots (19)$$

The composite failure stress for perfectly aligned fibers is given by Zhang and Latour as

$$\sigma_f = v_f[EI_f\frac{\alpha^2}{2r} + 2E_m C] \quad \cdots\cdots\cdots\cdots\cdots (20)$$

The above expression must be modified to account for initially imperfect fibers. However it has pointed out by Yeh and Teply[26] and used by Zhang and Latour, that the failure stress for fibers with initial waviness can be related to that above by

$$\sigma_{f,wavy} = [\frac{\phi_m}{\phi_m+\phi_0}]\ \sigma_{f,aligned} \quad \cdots\cdots\cdots\cdots\cdots (21)$$

where $\phi_0$ is the initial fiber misalignment angle, and $\phi_m$ is the additional fiber misalignment angle required to produce failure. This equation can then be used to predict the compressive strength of the composite, including the effects of hydrostatic pressure. The procedure is to determine the maximum fiber misalignment angle from Eqn 17, using the fiber-matrix interface shear stress as being critical. Note that the critical additional angle for fiber-matrix interface failure is given by $\phi_m = \alpha Am$, where A is the amplitude of the additional deformation and Am is the critical value of this additional deformation. As before, the critical interface shear stress is taken to be a function of the pressure, as given in Eqn 13. The critical amplitude is then substituted into Eqn 21 to get the predicted composite compressive stress for fibers initial waviness, including the effect of superposed pressure.

## Results

Table 1. Material properties used in the models.

| | | |
|---|---|---|
| Model 1 | | |
| Composite axial modulus E11 | 127 GPa | (18.4 Msi) |
| Composite shear modulus G12 | 6.55 GPa | (0.95 Msi) |
| Matrix shear strength $\tau m$ | 95.9 MPa | (13.9 ksi) |
| Coefficient of pressure effect $\alpha$ | 0.159 | |
| Initial fiber misalignment angle | 3.8° or variable | |
| Model 2 | | |
| Fiber Modulus Ef | 212 GPa | (30.7 Msi) |
| Fiber volume fraction vf | 0.6 | |
| Fiber diameter | 7 $10^{-6}$ m | |
| Matrix tensile modulus Em | 8.52 GPa | (1.235Msi) |
| Matrix shear modulus Gm | 3.28 GPa | (0.475Msi) |
| Matrix shear strength $\tau m$ | 95.9 MPa | (13.9 ksi) |
| Coefficient of pressure effect $\alpha$ | 0.159 | |
| Initial fiber misalignment angle | 3.2° or variable | |

The properties used in the two models are listed in Table 1. In general the properties used are consistent between the two models, with the exception of the matrix shear modulus. Model 1 uses a smeared composite shear modulus, while model 2 distinguishes between matrix and composite properties.

One issue of the models that must be addressed is the question of whether the results are depondent on the wavelength of the assumed initial fiber waviness. The equations of model 1 are simple enough so that it can be seen by inspection that only the initial misalignment angle is involved. This is not the case with model 2, where the complexity of the equations conceals the form of the dependence. However, the numerical results show that indeed for all ranges of practical importance, only the initial misalignment angle is numerically important, independent of the value of sinusoidal wavelength. These results are important, as it is very difficult to accurately characterize the initial fiber imperfections.

The primary feature of the models that is the focus of the present work is the predicted dependence of compressive strength on superposed hydrostatic pressure. The predictions of the two

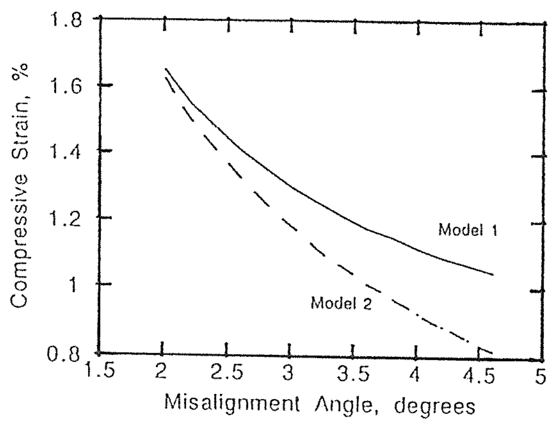


Fig. 1. Effect of initial misalignment angle of wavy fibers on the predicted compressive failure strain for carbon/epoxy composites.

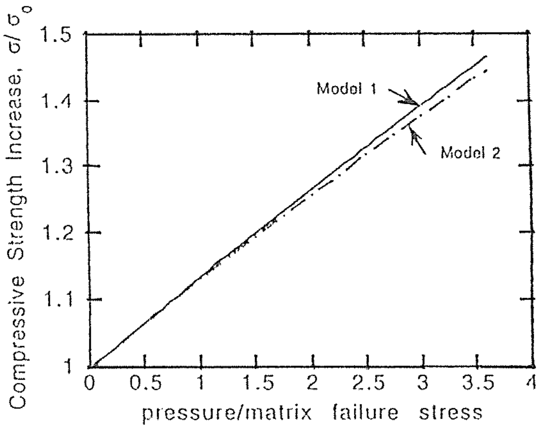


Fig. 2. Effect of pressure on the compressive strength of carbon/epoxy composites as predicted by the present models.

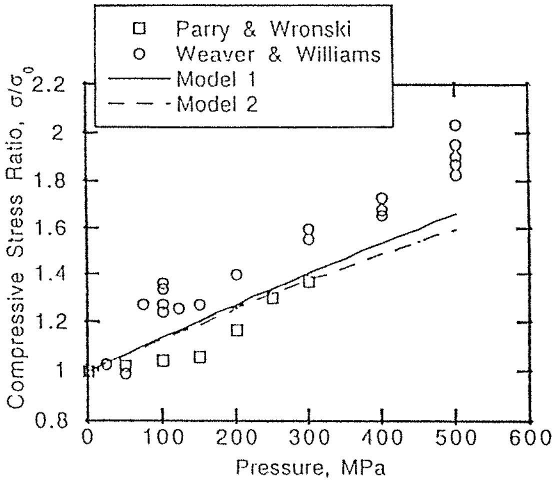


Fig. 3. Comparison of model prediction for pressure effect with data of Parry & Wronski[29] 60% $V_f$ Type III carbon/epoxy) and Weaver & Williams[28], (36% $V_f$ Modmur Type II /Epikote 828 epoxy).

models are very similar, even though the two models differ significantly in their treatment of the state of stress in the matrix. Again it should be emphasized that to avoid undue fitting in these comparison, similar properties were used in the two models, with the exception of the matrix shear modulus and the initial fiber misalignment angle. As mentioned above, the matrix is identified in model 2, but enter as a composite property in model 1, and the matrix properties are adjusted accordingly. The other property that was varied was the initial fiber misalignment angle. The measured values of 3.8° nd 3.2° were used in model 1 and model 2, respectively, to provide a realistic representation of composite failure properties without pressure effects. These values give model results consistent with the measured compressive strength without pressure. The initial misalignment angles are also consistent with a value of 3° reported by Jelf and Fleck [27]. A value of fiber-matrix allowable strength equal to the measured interlaminar shear strength of 95.9 MPa for AS4/3501-6 was used in the calculation for both models.

Experimental data for the increase of compressive strength with superposed hydrostatic pressure have been published by Weaver and Willams [28] and Parry and Wronski[29], for carbon/epoxy materials. The model predictions are shown compared with these data in Fig. 3, for hydrostatic pressures up to 500 MPa. Since the experimental data are for systems with different fiber volume fractions properties, the data have been normalized to the case of zero pressure to permit comparisons. The properties used in the models are the same as described above, i.e. no changes in input data were made to attempt fit the literature data.

It can be seen that both models give about the same prediction, and are both reasonably consistent with the trends of the experimental data. Teh experimental data differ in detail between the two references, although both show significantly increases in compressive strength with pressure. It may be noted that the data shown for Weaver and Willams[28] are from Fig. 3 of that reference. Because only one data point was reported at the zero presure condition used to normalize the data, it is possible that the normalized experimental curve could be shifted up of down. However, the slope would not be affected.

## Discussion

It is interesting to note the close agreement of the two models, particularly in the prediction of the effects of pressure. Clearly the prediction is strongly influenced by the assumption for the effect of pressure on the matrix or fiber-matrix bond strength given in Eqn 13, taken from the work of Shin and Pae[23] and used in the both models. It is surprising that the other features of the models agree as well as they do, in view of the differences in model formulation. The agreement between the two models does not imply that either is correct, but it does help to identify the essential features in each.

The major point of the present work is to establish a plausible mechanism for the effect of hydrostatic pressure on compression failure in carbon/epoxy laminates. As mentioned in the Introduction, it is believed that this effect should be applicable to thick limanates, in which 3-d stress-state can be important. The first premise of the models examined here is that fiber-matrix bond strength is important in establishing compressive strength of carbon/epoxy composites. For this to be the case, the models must have initial imperfections. The assumption of initially wavey fibers with uniform wavelength and amplitude is or cause a gross idealization, but is simple enough to be readily incorporated into the models. There is quite a bit of evidence that initial imperfections are important. For example, initially perfect fibers lead to the usual models of bifurcation buckling of fibers, with the predicted composite compressive strength depending on the matrix stiffness, and not the matrix strength. However it has been shown by many investigators that incorporating initial imperfect fibers into the failure model provides a straightforward way to establish a matrix bond strength dependence. The experiments reported by Swanson and Colvin[18] in which an artificially lowered fiber-matrix bond reduced the laminate compressive strength by up to a factor of four also lends experimental support to this idea, as well as the results of Madhukar and Drzal[19].

The second basic premise of the models is that hydrostatic pressure tends to increase the matrix and fiber-matrix bond strength. As discussed in the Introduction, it is well established in the literature that pressure can enhance the strength of polymers. The data of Shin and Pae[23] provide a quantitative assessment of the increase of epoxy bond strength with pressure, and was used here in the present models. Additionally, in a qualitative sense the effect of compressive normal stress on epoxy bond shear allowables is readily apparent and was used both by Groves et al.[24] and in our laboratory(Smith and Swanson[30]) to design end grips for tubular test specimens. It thus seems that the basic ingredients of the model are quite plausible. It should be immediately apparent, however, that the specific implementation of these ideas into a model involves a high degree of idealization.

The comparisons of the models with the experimental data shown in Fig. 3 would seem to be quite supportive of the major features of the models. The slope of the increase in composite compressive strength with superposed hydrostatic pressure is captured very well, indicating that the basic mechanisms have been represented in the models. However a more detailed quantitaive agreement would require more experimental data, as well as detail in the models.

A generalization from compression under superposed hydrostatic pressure to general three dimensional states is required to directly use the present work in analysis of thick composites. Clearly, superposed hydrostatic pressure is just one very simple state of three-dimensional compressive stress. However, in view of the directional properties of the material and the presemed failure mechanism of failure of the fiber-matrix bond, the stress component normal to the fibers may be more appropriate. In particular, it is suggested here that in general the pressure term be replaced by the least compressive value of either the in-plane normal stress $\sigma_2$ or the through-the-thickness normal stress $\sigma_3$. However, this point must necessarily be established by experiments under general states of stress. Clearly more work is reuqired to generalize the present work to 3-d compressive stress states.

## Summary and Conclusions

Two models are presented that demonstrate a dependence of compressive strength of carbon/epoxy composites on superposed hydrostatic pressure. The essential features of both models include the assumption of initially wavy fibers, and that failure is predicted when the strength of the matrix or fiber-matrix bond is exceeded. Literature values for the effect of pressure on the bond strength are employed. The models predict an increase of composite compressive strength with hydrostatic pressure. Comparisons with experimental data support the idea of an increase in compression strength with pressure. The results are believed to be applicable to state of stress in thick composites that can include three-dimensional compression, but further work is required to generalize the pressure dependence to a mean stress dependence of strength.

## References

1. Rosen, B.W., 1965, "Mechanics of Composite Strengthening," Fiber Composite Materials, ASM, Metals Park, OH, pp.37-75.

2. Chaplin, C.R., 1977, "Compressive Fracture in Unidirectional Glass-Reinforced Plastics," J. of Materials Science, Vol.12, pp.347-357.

3. Evans, A.G. and Alder, W.F., 1978, "Kinking as a Mode of Structure Degradation in Carbon Fiber Composites," Acta Metallurgica, Vol.26, pp.725-738.

4. Budiansky, B., 1983, "Micromechanics," Computers and Structures, Vol.16, pp.3-12.

5. DeTeresa, S.J., Poter, R.S., and Farris, R.J., 1986, "A Model for the Compressive Buckling of Extended Chain Polymers," J. of Materials Science, Vol.20, pp.1645-1659.

6. Hahn, H.T.and Williams, J.G., 1986, "Compression Failure Mechanisms in Unidirectional Composites," Composite Materials: Testing and Design(7th Conference), ASTM STP 893, pp.115-139.

7. Swanson, S.R., 1992, "A Model for Compression Failure in Fiber Composite Laminates," ASME J. of Engineering Materials and Technology, Vol.114, pp.8-12.

8. Argon, A.S., 1972, "Treatise on Materials Science and Technology," ed. Herman, H., Vol. 1, Academic Press, pp.79-114.

9. Wronski, A.S. and Howard, R.J., 1980, "Failure Criteria in Brittle Solids under Complex Loading," High Pressure Science and Technology Edited by Vodar, B., and Matenau, P., Pergamon Press, pp.270-296.

10. Piggott, M.R., 1981, "A Theoretical Framework for the Compressive Properties of Aligned Fibre Composites," J. of Materials Science, Vol. 16, 2837-2845.

11. DeFerran, E.M., and Harris, B., 1970, "Compression Strength of Polyester Resin Reinforced with Steel Wires," J. of Materials Science, Vol.4, pp.62-72.

12. Greszczuk, L.B., 1982, "On Failure Mo-

des of Unidirectional Composites under Compressive Loading," Fracture of Composite Materials, ed. Shi, G.C., and Tamuns, V.P., Martiinus Nijhoff, pp.231-244.

13. Hayashi, T., 1970, "Compressive Strength of Unidirectionally Fibre Reinforced Composite Materials," Seventh Intl.

14. Guynn, E.G., Ochoa, O.O., and Bradley, W.L., 1982, "A Parameter Study of Analyses," J. Composite Mtls, Vol.26, pp.1594-1643.

15. Wang, A.S.D., 1978, "A Non-Linear Microbuckling Model Predicting the Compressive Strength of Unidirectional Composites," ASME Paper 78-WA/Aero-1.

16. Herrman, L.R., Mason, W.E., and Chan, T.K., 1967, "Response of Reinforcing Wires to Compressive State of Stress," J. Composite Mtls, Vol.1, pp.212-226.

17. Lanir, Y., and Fung, Y.C.B., 1972, "Fiber Composite Columns under Compression," J. Composite Mtls, Vol.6, pp.387-401.

18. Swanson, S.R., and Colvin, G.E., 1993, "Compression Failure in Reduced Adhesion Fiber Laminates," ASME J. of Engineering Materials and Technology, Vol.115, pp.187-192.

19. Madhukar, M.S., and Drzal, L.T., 1992, "Fiber-Matrix Adhesion and Its Effect on Composite Mechanical Properties III., Longitudinal (0°) Compressive Properties of Graphite/Epoxy Composites," J. Composite Mtls, Vol.26, pp. 310-333.

20. Zhang, G., and Latour, R.A., 1993, "FRP Composite Compressive Strength and Its Dependence upon Interfacial Bond Strength, Fiber Misalignment, and Matrix Nonlineality," Proc. American Soc. for Composites 8th Tech. Conf. Technomuc Pub, Co., pp.519-528.

21. Pae, K.D., and Bhateja, S.K., 1975, "Influence of Pressure on Yield and Fracture in Polymers," J. of Macromolecular Science-Reviews in Macromolecular Chemistry," Vol.c13(1), pp. 1-75.

22. Silano, A.A., Pae, K.D., and Sauer, J. A., "Effects of Hydrostatic Press on Shear Behavior of Graphite/Epoxy Composites," J. Composite Mtls, Vol.26, pp.462-485.

23. Shin, E.S., and Pae, K.D., 1992, "Effects of Hydrostatic Pressure on the Torisional Shear Behavior of Graphite/Epoxy Composites," J. Composite Mtls, Vol.26, pp.462-485.

24. Groves, S., Sanchez, R., Ryon, R., and Magness, F., 1992, "Evaluation of Cylindrical Shear Joints for Composite Materials," J. Composite Mtls, Vol.26, pp.1134-1150.

25. Jee, Y.J., and Swanson, S.R., 1993, "Effect of Hydrostatic Pressure on Compression Failure in Carbon/Epoxy Laminates," AMD-Vol. 162, Mechanics of Thick Composites, Y.D.S. Rajapakse, ed., Proc. Joint SES/ASME/ASCE Mtg. Charlottesville, Virginia, pp.127-136.

26. Yeh, J.R., and Teply, J.L., 1988, "Compressive Response of Kevlar/Epoxy Composite," J. Composite Mtls, 3, pp.245-257.

27. Jelf, P.M., and Fleck, N.A., 1992, "Compression Failure Mechanisms in Unidirectional Composites," J. Composite Mtls, Vol.26, pp. 2206-2726.

28. Weaver, C.W., and Williams, J.W., 1975, "Deformation of a Carbon/Epoxy Composite under Hydrostatic Pressure," J. of Materials Science, Vol.10, pp.1323-1333.

29. Parry, T.V., and Wronski, A.S., 1982, "Kinking and Compressive Failure in Uniaxially Aligned Carbon Fiber Composites Tested under Superposed Hydrostatic Pressure," J. Materials Science, Vol.17, pp.893-900.

30. Smith, L.V., and Swanson, S.R., 1994, "Design of Cylindrical Specimen for Biaxial Testing of Composite Materials," submitted to Experimental Mechanics.