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Continuum damage modeling and progressive failure analysis of a Type III composite vessel by considering the effect of autofrettage

Key words:

Composite vessel; Damage evolution behaviors; Hashin failure criteria; Finite element analysis (FEA)

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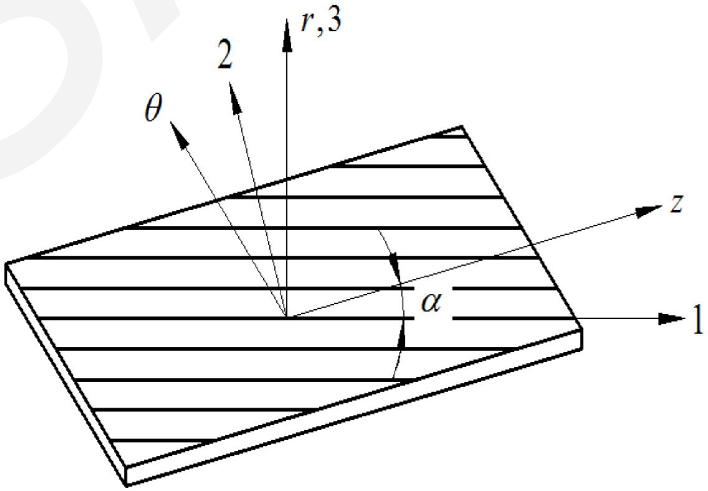
1. Theoretical models

(1) Constitutive relationships of composites

A multi-layered composite vessel can be considered by three-dimensional (3D) stress analysis as a cylindrical part with closed-end conditions.

$$\begin{Bmatrix} \sigma_z \\ \sigma_\theta \\ \sigma_r \\ \tau_{\theta r} \\ \tau_{zr} \\ \tau_{z\theta} \end{Bmatrix}^{(k)} = \begin{bmatrix} \bar{C}_{11} & \bar{C}_{12} & \bar{C}_{13} & 0 & 0 & \bar{C}_{16} \\ \bar{C}_{12} & \bar{C}_{22} & \bar{C}_{23} & 0 & 0 & \bar{C}_{26} \\ \bar{C}_{13} & \bar{C}_{23} & \bar{C}_{33} & 0 & 0 & \bar{C}_{36} \\ 0 & 0 & 0 & \bar{C}_{44} & \bar{C}_{45} & 0 \\ 0 & 0 & 0 & \bar{C}_{45} & \bar{C}_{55} & 0 \\ \bar{C}_{16} & \bar{C}_{26} & \bar{C}_{36} & 0 & 0 & \bar{C}_{66} \end{bmatrix}^{(k)} \begin{Bmatrix} \varepsilon_z \\ \varepsilon_\theta \\ \varepsilon_r \\ \gamma_{\theta r} \\ \gamma_{zr} \\ \gamma_{z\theta} \end{Bmatrix}^{(k)}.$$

The off-axis stress-strain relationships of the *k*th (*k*=1,2,…,ns) layer under the cylindrical coordinate system



The on-axis coordinate (1, 2, 3) and the off-axis coordinate (r, θ, z) for a composite layer

1. Theoretical models

(2) Failure criteria and damage evolution laws of composites

In this research, energy-based CDM models are implemented in the FE model to predict the damage of the composite layers. Strain-based Hashin criteria for four failure modes are used.

Damage evolution laws

(a) Fiber damage

$$\begin{cases} \left(F_{11}^{\mathrm{T}}\right)^2 = \left(\dfrac{E_{11}}{E_{0,1}^{\mathrm{T}}}\right)^2 + \left(\dfrac{E_{12}}{E_{0,12}}\right)^2 + \left(\dfrac{E_{13}}{E_{0,13}}\right)^2 \geq 1, \\ \left(F_{11}^{\mathrm{C}}\right)^2 = \left(\dfrac{E_{11}}{E_{0,1}^{\mathrm{C}}}\right)^2 \geq 1. \end{cases}$$

➡

$$d_{11}^{\mathrm{T(C)}} = 1 - \frac{1}{F_{11}^{\mathrm{T(C)}}} \exp\left((1 - F_{11}^{\mathrm{T(C)}}) \frac{\left(X^{\mathrm{T(C)}}\right)^2 l}{E_1 \mathit{\Gamma}_{11}^{\mathrm{T(C)}}} \right).$$

(b) Matrix tension damage

$$(F_{22}^{\mathrm{T}})^2 = \frac{(E_{22} + E_{33})^2}{E_{0,2}^{\mathrm{T}} E_{0,2}^{\mathrm{T}}} - \frac{E_{22} E_{33}}{\left(E_{0,23}\right)^2} + \left(\frac{E_{12}}{E_{0,12}}\right)^2 + \left(\frac{E_{13}}{E_{0,13}}\right)^2 + \left(\frac{E_{23}}{E_{0,23}}\right)^2 \geq 1$$

➡

$$d_{22}^{\mathrm{T}} = 1 - \frac{1}{F_{22}^{\mathrm{T}}} \exp\left((1 - F_{22}^{\mathrm{T}}) \frac{\left(Y^{\mathrm{T}}\right)^2 l}{E_2 \mathit{\Gamma}_{22}^{\mathrm{T}}} \right).$$

(c) Matrix compression damage

$$\left(F_{22}^{\mathrm{C}}\right)^2 = \frac{(E_{22} + E_{33})^2}{E_{0,2}^{\mathrm{C}} E_{0,2}^{\mathrm{C}}} + \frac{E_{22} + E_{33}}{E_{0,2}^{\mathrm{C}}} \left(\frac{E_{0,2}^{\mathrm{C}}}{2 E_{0,12}} - 1 \right) - \frac{E_{22} E_{33}}{\left(E_{0,23}\right)^2} + \left(\frac{E_{12}}{E_{0,12}}\right)^2 + \left(\frac{E_{13}}{E_{0,13}}\right)^2 + \left(\frac{E_{23}}{E_{0,23}}\right)^2 \geq 1.$$

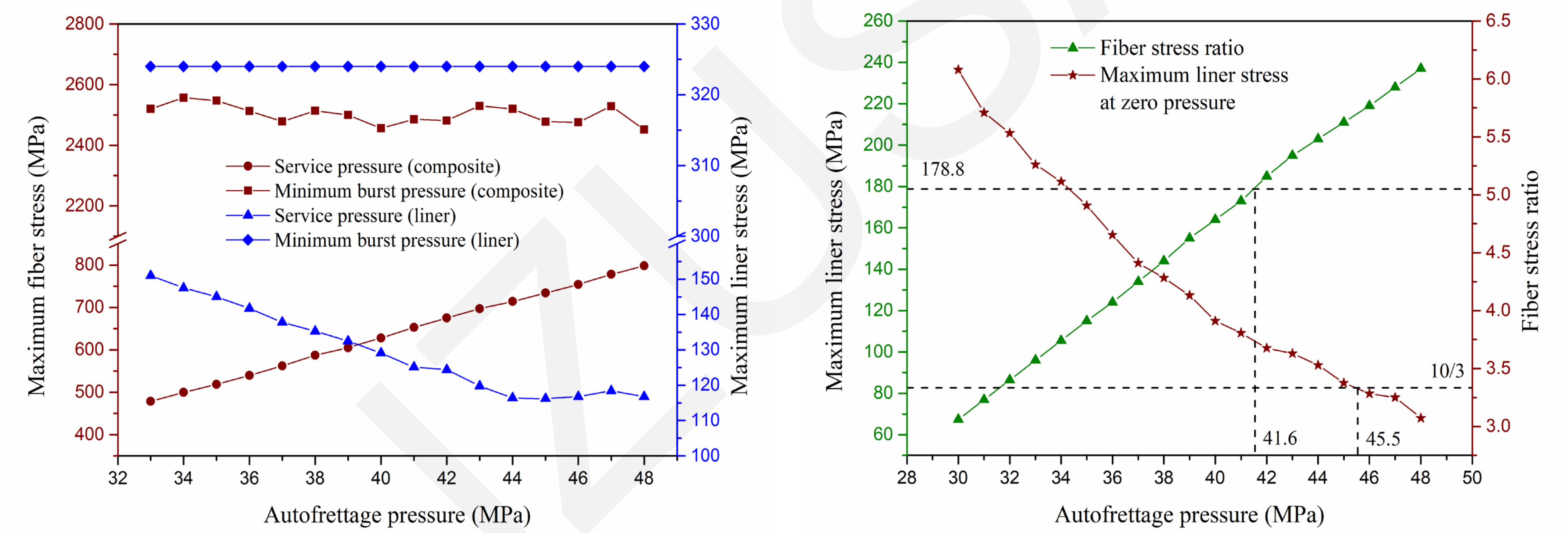
➡

$$d_{22}^{\mathrm{C}} = 1 - \frac{1}{F_{22}^{\mathrm{C}}} \exp\left((1 - F_{22}^{\mathrm{C}}) \frac{\left(Y^{\mathrm{C}}\right)^2 l}{E_2 \mathit{\Gamma}_{22}^{\mathrm{C}}} \right).$$

2. Finite element analysis for vessel

(1) Determination of the appropriate autofrettage pressure

Results: Appropriate autofrettage pressure is determined as 45 MPa in order to minimize the liner stress and make full use of carbon fibers at service pressure.



(a)

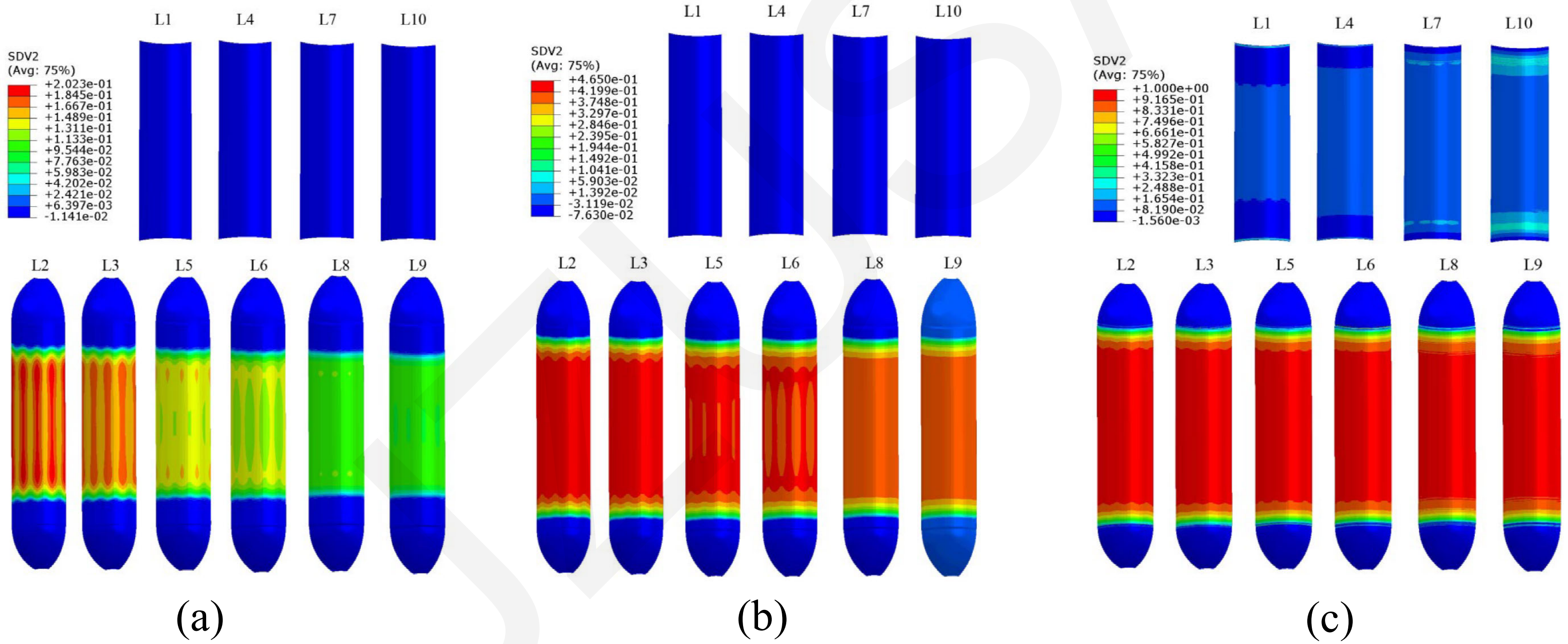
(b)

Stress analysis for determining the appropriate autofrettage pressure: (a) Maximum fiber stress and maximum liner stress at service pressure and minimum burst pressure conditions and (b) Maximum liner stress at zero pressure and the fiber stress ratio

2. Finite element analysis for vessel

(2) Progressive failure analysis with autofrettage

Results: Matrix and fiber damage at different pressure.



Matrix damage at (a) 40 MPa in Step 1, (b) autofrettage pressure in Step1 and (c) 60 MPa in Step 4

3. Concluding remarks

- Matrix damage appears initially at the helical layers but fiber damage appears initially at the hoop layers. Besides, most of the matrix damage appears at the helical layers while fiber damage at the hoop layers is more severe than at the helical layers. Both matrix damage of helical layers and fiber damage of hoop layers evolve from the middle part to the ends of the cylinder.
- By comparison, the damage evolution behaviors of the composite vessel with autofrettage are almost consistent with the vessel without autofrettage except the unloading process and the repressurization process with the pressure rising from zero pressure to the pressure that the value is equal to the autofrettage pressure. At this stage, matrix damage remains unchanged and the same as that at the autofrettage pressure. It is obvious that matrix damage exists after autofrettage but does not exist without autofrettage at the service pressure.
- Autofrettage process only affects the stress distribution when the internal pressure is lower than the value that is equal to the autofrettage pressure. By comparison, although the matrix damage remains unchanged during this stage, the aluminium liner stress reduces except the low pressure at the beginning and fiber stress increases remarkably. In addition, the maximum hoop and axial liner stress with autofrettage reduce significantly and appear at both ends of cylinder at service pressure.