RELIABLE OPTIMAL USE OF MATERIALS FOR WIND TURBINE ROTOR BLADES

OPTIMAT BLADES

(ENK6-CT-2001-00552)

# Residual strength characterization of orthotropic ply material (OB_TG2_003_UP)

TASK GROUP 2: Investigation of blade material behavior under complex stress states

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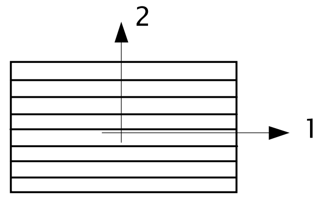
# STATIC STRENGTH REDUCTION OF LAMINATED COMPOSITES DUE TO CYCLIC LOADS PRODUCING PLANE STATES OF STRESS

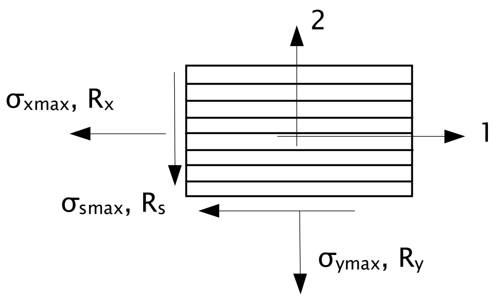
In-plane static strength of an orthotropic lamina is usually characterized by five strength values in the principal material system:




X: Tensile strength in material direction 1
X': Compressive strength in material direction 1
Y: Tensile strength in material direction 2
Y': Compressive strength in material direction 2
S: Shear strength in plane 1-2 (assumed independent on the sign of the applied shear stress)

Degradation of static strength due to uniaxial or complex cyclic loading:

$\sigma_{imax}$: i-component of maximum cyclic stress
$R_i = \sigma_{imin}/\sigma_{imax}$




results after a certain number of cycles in a modified set or residual static strengths: $X_R$, $X_R'$, $Y_R$, $Y_R'$, $S_R$. Irrespective of damage accumulation, it is assumed that the material retains its initial elastic and strength symmetry properties. This could be particularly true for UD plies where most of damage is accumulated in the form of fiber splitting, i.e. matrix cracks running parallel to the fibers. In general, each residual static strength value is a function of the state of stress, number of cycles, stress ratio, loading frequency and environmental conditions. Assuming that both the loading frequency and the environment are kept constant and representative of the actual application, the following set of equations is valid:

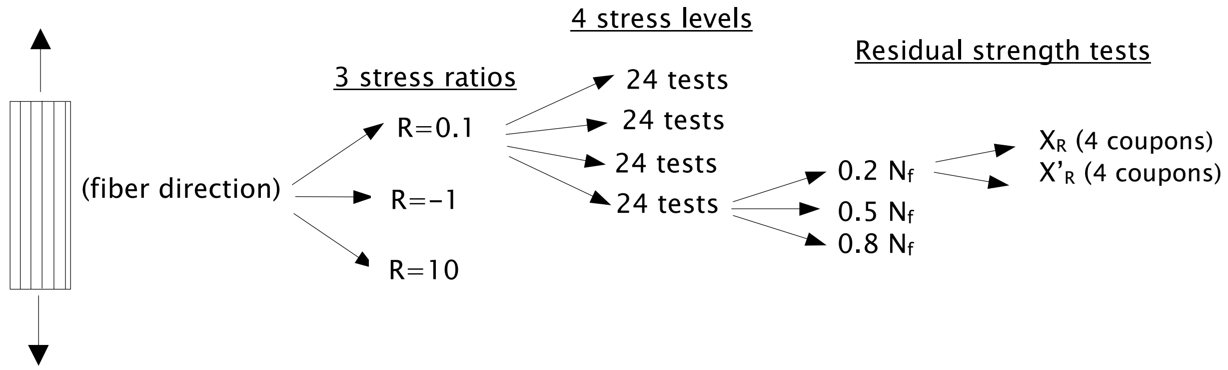
$$
\begin{aligned}
X_R &= f_{X_R}\left(\sigma_{x\max},\sigma_{y\max},\sigma_{s\max},R_x,R_y,R_s,N\right)\\
Y_R &= f_{Y_R}\left(\sigma_{x\max},\sigma_{y\max},\sigma_{s\max},R_x,R_y,R_s,N\right)\\
X'_R &= f_{X'_R}\left(\sigma_{x\max},\sigma_{y\max},\sigma_{s\max},R_x,R_y,R_s,N\right)\\
Y'_R &= f_{Y'_R}\left(\sigma_{x\max},\sigma_{y\max},\sigma_{s\max},R_x,R_y,R_s,N\right)\\
S_R &= f_{S_R}\left(\sigma_{x\max},\sigma_{y\max},\sigma_{s\max},R_x,R_y,R_s,N\right)
\end{aligned}
\qquad (1)
$$

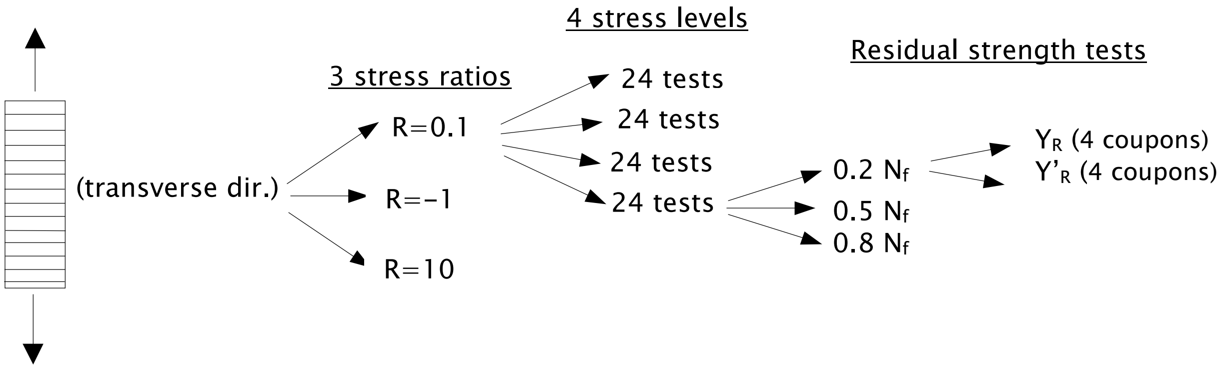
Experimental evaluation of such a model would require a huge experimental effort just for basic characterization tests in order to understand the phenomenon and develop a theoretical model for data reduction.

A more viable approach is to consider reduction of each strength component as a function only of load cycling at the same direction, see eq.(2). Although the underlying hypothesis is arbitrary, not based on experimental observation, this approach is the current state-of-the-art residual strength model under plane stress states[1].

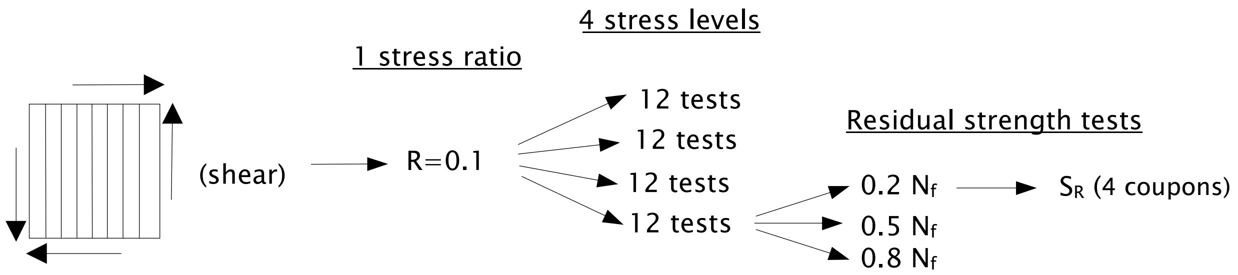
$$\begin{aligned} X_R &= f_{X_R}(\sigma_{x\max}, R_x, N) \\ Y_R &= f_{Y_R}(\sigma_{y\max}, R_y, N) \\ X'_R &= f_{X'_R}(\sigma_{x\max}, R_x, N) \\ Y'_R &= f_{Y'_R}(\sigma_{y\max}, R_y, N) \\ S_R &= f_{S_R}(\sigma_{s\max}, R_s, N) \end{aligned} \qquad (2)$$

To define the functional dependence of residual static strength components, i.e. functions $f_i$ shown in eq.(2), appropriate theoretical models can be implemented[2] by fitting experimental data. The following sets of experiments would be necessary, assuming that a well populated static test program for the orthotropic ply material has preceded:




[1] X. Diao, L. B. Lessard, M. M. Shokrieh, "Statistical model for multiaxial fatigue behaviour of unidirectional plies", Comp. Sci. Tech. 59 (1999) 2025-2035.
[2] J. N. Yang, "Fatigue and residual strength degradation for graphite/epoxy composites under tension-compression cyclic loadings, J. Comp. Mat. 12 (1978) 19-39.




Residual strength components can be combined in a quadratic failure criterion to predict residual static strength under plane stress due to complex stress cycling or can be used to predict fatigue life.

## Time schedule for residual strength tests

The time required per S-N curve (4 stress levels of 5 coupons each) was estimated to 1 month.

Denoting by t the characteristic time for a specimen to fail at a certain stress level, the time required for residual strength tests at the same stress level is:

8 x 0.2t + 8 x 0.5t + 8 x 0.8t = 12t
4 x 0.2t + 4 x 0.5t + 4 x 0.8t = 6t

where 8 or 4 stand for the number of coupons and 0.2, 0.5 and 0.8 are life fractions.

At the same stress level, the fatigue tests to failure would require time of 5t and therefore, for the residual strength tests per stress ratio, R, and loading direction, test time is equal to:

12t/5t x 1month = 2.4 months/R and load direction
6t/5t x 1month = 1.2 months/R for shear loading

Total Time: 3R x 2 dir. x 2.4 months + 1R x 1 dir. x 1.2 months = 15.6 months or taking also into account the residual static strength tests approximately ≈ 18 months.

Therefore, the total "machine-time" effort required for complete basic residual strength characterization for an orthotropic ply is estimated to 18 months (624 coupons).