EVALUATION OF POTENTIAL COMPOSITE APPLICATION IN SHIP SHAFTLINES* 2. THEORETICAL STUDY OF THE CRACK-
NUCLEATION THRESHOLD AND LOAD-CARRYING CAPACITY
OF \([0^\circ/\pm \varphi]\) LAMINATED COMPOSITES LOADED IN SHEAR
AND UNIAXIAL TENSION OR COMPRESSION IN THE
REINFORCEMENT PLANE

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1. As follows from the results of the analysis in [1], layers of filament-wound composites for ship shaftlines are loaded
in their plane mainly by shear stresses from torsion and axial normal stresses from axial thrust and bending. Hoop stresses
formed in a layer due to the anisotropy of the material (in the case \(a_{13} \neq a_{23}\)) can be ignored. The interlaminar stresses
(\(\tau_{xz}, \tau_{yz}\)) depend to a considerable extent on the scheme of reinforcement of the layers and must be evaluated for each specific case
from the viewpoint of the danger they pose in regard to the formation of interlaminar cracks. However, the resistance of the
composite to interlaminar rupture and shear are determined mainly by the type of polymer binder and depend little on the
reinforcement scheme when \(\varphi \neq 0\) and \(\varphi = \pi/2\). Thus, the reinforcement angle should be chosen so as to obtain the best
resistance to shear (\(\tau_{yz}\)) and axial (\(\sigma_z\)) stresses.

The stresses \(\sigma_z\) include compressive stresses (from axial thrust) and cyclic tensile and compressive stresses from
bending. The relations between the stress components \(\sigma_z\) and the ratio \(\sigma_z/\tau_{yz}\) can vary within broad ranges. These relations
depend on the regime of operation of the engine and the motion of the ship, as well as the designation of the shaft section in
the ship propulsion system (propeller, intermediate, or thrust shaft). It is important that the material of the shaft be able to
withstand a combination of shear stresses and both tensile and compressive stresses. As shown by an analysis of the service
conditions of steel shafts [2-4], the shear stresses are considerably greater than the normal stresses.

The difficulties encountered in coming up with a sufficiently general and but accurate formulation of the conditions
of loading of the shaft material make it expedient to analyze the load-carrying capacity of composites with different structures
within a broad range of ratios of normal and shear stresses. One characteristic feature of such problems is that the composite
must have good resistance to shear in combination with good tensile and compressive strength. It is necessary to find a certain
compromise structure suited to both types of stress state for each specific case. As a result, we theoretically examined the load-
carrying capacity (crack-nucleation threshold and limit load) of composite laminates within a broad range of reinforcement
structures and loading parameters \(\beta = \sigma_z/\tau_{yz}\). The relations that were found can serve as initial data for choosing (in a first
approximation) the best reinforcement scheme for a composite shaft in each specific case. Let us now discuss the results that
were obtained.

2. We studied the load-carrying capacity of the filament-wound structures of unidirectional glass- and carbon-fiber-
reinforced plastics (the properties of the monolayers were reported in [1]). Besides the \([\pm \varphi]\) structures (where \(\varphi\) is the
angle between the direction of the fibers and the generatrix of the shaft), we also examined \([0^\circ/\pm \varphi]\) structures and the more


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practicable scheme \([\pm 10^9 / \pm \varphi]\). The value of \(\varphi\) ranged from 0° to 90° in increments of 1°. The range of loads, characterized by the parameter \(\mid \beta \mid\), was from 0 to 1.

The crack-nucleation threshold and limit load were calculated using a program for layer-by-layer analysis of the composite. The principles laid out in [5] were used to write the program. The analysis is based on a model of the behavior of a monolayer and employs the criterion of the maximum stresses:

\[
F_{12}^{(0)} \leq \sigma_{12}^{(0)} \leq F_{12}^{(0)}, \quad |\sigma_{12}^{(0)}| \leq F_{12}^{(0)},
\]

where \(F_{12}^{(0)}\) and \(F_{21}^{(0)}\) are the strengths of the i-th layer along (1) and across (2) the fibers, respectively; the (+) and (−) signs denote tension and compression; \(F_{12}^{(0)}\) is the strength of the i-th layer in shear. In many cases, this criterion is enough to satisfactorily describe the behavior of unidirectional composites. The crack-nucleation threshold is defined as the first fracture of the monolayer due to tensile stresses across the fibers or shear.

The load-carrying capacity of the sandwich is determined either by the attainment of limiting values of tension or compression along or across the fibers or by loss of stability of the material during loading, i.e., by an unlimited increase in the strains of the material with cracks in the layers.

The results are represented in the form of polar diagrams, where the angular coordinate corresponds to the reinforcement angle ±\(\varphi\), while the position vector corresponds to the calculated value of either the crack-nucleation threshold \(\tau_{cr}\) or the limit load \(\tau_{lim}\) for a given stress ratio \(\beta\). Figure 1 illustrates the principle of construction of the diagrams and the notation used for different types of fracture.

If we consider that loading in bending is of a fatigue nature, then a high crack-nucleation threshold may prove decisive in choosing the structure of the material. This is because endurance decreases sharply when the cyclic stresses exceed the level corresponding to the appearance of cracks [6-11]. In light of the stringent reliability requirements established for shaftlines, the appearance of cracks in the constituent material obviously cannot be tolerated. Also, the substantial difference between the crack-nucleation threshold and the limit load ensures a high level of safety in shaftline operation, since it increases the