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Review

A Review of Delamination Damage of Composite Materials

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Abstract: The theoretical and practical achievements in the field of the theory of strength and reliability of composite materials are discussed in a review conducted on the scientific research conducted on the effect of delamination on the reliability and quality of composites. The methodological aspects of the stability of the mechanical characteristics of composite materials under the combined action of cyclic and impact loads are examined, as are the manufacturing and processing technologies. The reasons for delamination, such as technological, manufacturing and application, free edge, joints and loads, are revealed. The influence of delamination on the bearing capacity of structural elements made of composite materials is analyzed. The mechanism of delamination growth is outlined, and the criteria and processes are defined, such as the growth of delamination cracks in a multidirectional laminated plate from a straight edge, edge delamination during plate bending, delamination in plates in the field of residual stresses, etc. The importance of taking into account the visco-plastic effect at the top of the edge crack of delamination of composite materials is emphasized. The concept of critical delamination behavior is characterized, and the issues of delamination stability are described.

Keywords: composite material; delamination; crack; damage

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1. Introduction

In recent years, a discernible shift has been observed from traditional metal materials, such as aluminum, titanium, nickel alloys, and corrosion-resistant steels, toward polymer composite materials. These composites are primarily grounded in epoxy matrices with carbon and glass fibers, including organoplastics [1]. Due to their unique application characteristics, the stability of the mechanical properties of composite materials under combined cyclic and impact loads, alongside their manufacturing and processing technologies, has gained heightened significance [2,3].

Composite materials are mostly used in structural elements that are subjected to uniaxial tensile loads. However, their advantages over traditional structural materials (high specific strength and stiffness in the direction of fibers, manufacturability, insulating, damping properties, radio transparency, resistance to aggressive environments, etc.) have led to the desire to use them in core elements, in both compression and bending plates, in shells and even in massive bodies [3–5]. Multidirectional layered structures with variable properties have had to be created to meet these different external loads.

Layered composites on polymer matrices (glass, carbon, boron plastics, etc.) are characterized by a strong anisotropy of the physical and mechanical properties of the individual unidirectional layers. Moreover, the degree of strength anisotropy is significantly higher than the degree of stiffness anisotropy [5,6]. In addition, due to the compression of deformations in the layer as part of a multidirectional package in the transverse fiber direction, the brittle layer nearly collapses under tension and shear. This also applies to a greater extent to interlayer fractures' delamination.

These properties of layered composite materials determine the processes of their destruction. In the fracture mechanics of layered composite materials, it is customary to distinguish between the following mechanisms [7,8]: fracture of fibers of a single layer;

intralayer fracture along the matrix or along the fiber–matrix boundaries, usually over the entire thickness of the layer; delamination; and micro- and macroscopic loss of stability. Real fracture processes of composite materials usually involve the development and interaction of various mechanisms, with the dominance of some of them at different stages of the process [9,10].

Delamination is the main fracture mechanism [11,12], given the fact that the appearance of delamination usually reduces the stiffness, stability and strength of a structure, i.e., determines its survivability and, ultimately, its reliability. The theoretical and experimental study of the statics and dynamics of delamination cracks is aimed at improving the properties of composite materials; improving the technology of manufacturing materials and structures (often these are simultaneous processes); designing and formulating requirements for operating conditions; damage control aimed at preventing sudden and brittle failures; and evaluating durability parameters.

The mechanics governing delamination cracks in composite materials deviate markedly from traditional crack mechanics. The reason is that composites are significantly heterogeneous and anisotropic systems at all levels (package, layer, fiber), with less stable characteristics than traditional structural materials.

A large amount of the literature is devoted to the study of delamination principles in composites, which needs to be generalized and summarized as necessary. This paper focuses more on the causes of delamination and the load-bearing capacity of structural elements with delamination, presenting the results of the last 10–15 years of research. These include recent additions to the causes of delamination, further refinement of the delamination damage extension criterion and applications to finite element analysis simulations. The effect of material delamination on the structural load-bearing capacity is analyzed. This study can also be considered as a supplement to earlier studies [13–17].

2. Causes of Delamination

2.1. Technological

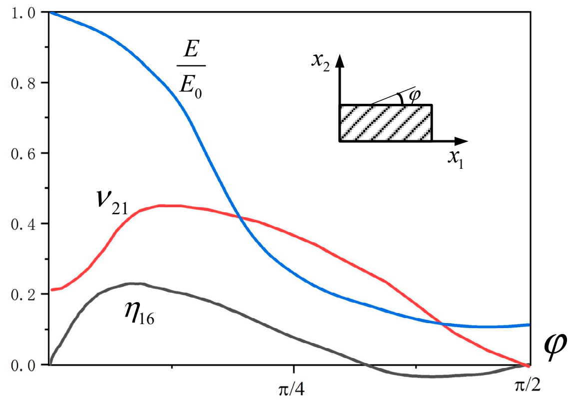
The technological problems include implementing the technology: selecting components, forming the interface, the temperature and time of curing, the humidity, pressing pressure and the belt tension when winding the products. This determines the values of the residual (initial) stresses, which, together with working stresses and sometimes without them, can cause delamination, especially in thick-walled products [18,19]. These include mechanical processing (trimming, drilling), as well as deviations from the technology: layer defects, resin-depleted areas, tape folds, air bubbles, residual lubricant, etc. [20–22].

2.2. Free Edge

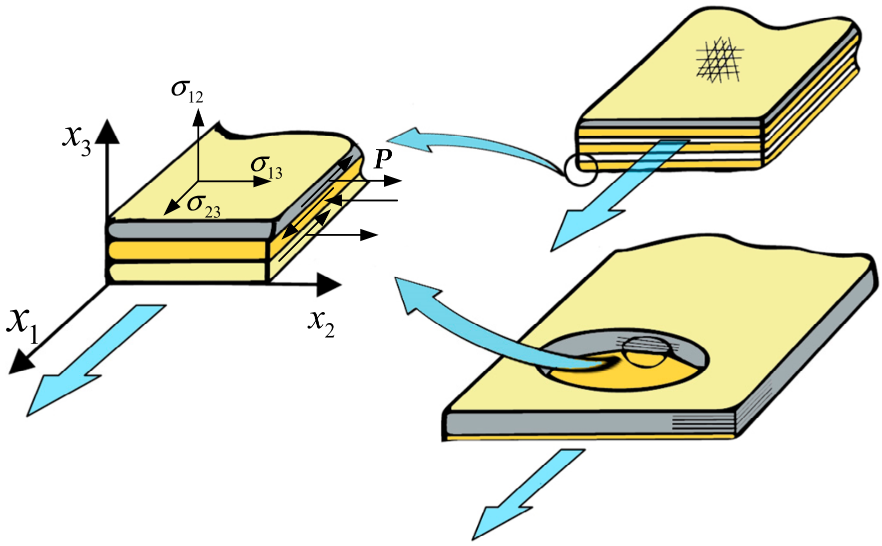
The mechanism of occurrence [23,24] of interlayer normal and tangential stresses in interlayered thin-walled composite structures made of layers of different fiber orientations φ near the edge (edge effect) is shown in Figure 1. Generalized curves of the dependences of the elastic modulus E_1, Poisson's ratio v_{21} and the coefficient of mutual influence η_{16} from the direction of reinforcement φ (Figure 1a) are characteristic of all fiber polymer composites [5,25]. The uniaxial macroscopic stress state at the edge ($p > h$, where p is the radius of curvature of the edge) causes different intralayer stresses. From the equilibrium of the part shown in Figure 1b, it is evident that interlayer stresses σ_{13}, σ_{23} and σ_{33} occur at the edge. Their magnitude and direction depend on the orientation and thickness of the layers in the package, and the edge effect zone $\lambda \lesssim h$.

The above analysis of the edge effect mechanism is based on the assumption of homogeneity of the anisotropic composite layer within the framework of applied theories.

Changes in temperature (including at the manufacturing stage) and humidity can also cause the edge effect strain σ_{j3} [26,27]. When a structure is bent, edge strains can also occur between identical layers [28]. Carbon–oxide composites are the most susceptible to edge delamination, compared to glass and organoplastics [29]. From the reviews on the edge effect as a cause of delamination, we note [30–32].



(**a**) General Relationship Curve for Reinforcement Direction



(**b**) Edge Equilibrium

Figure 1. Tangential stresses in interlayered thin-walled composite structures.

2.3. Connections

Virtually all types of macro-stress concentrators [33,34] and compounds (Figure 2) of composite elements or composites with metal are sources of possible delamination: bolted (a), various types of adhesives (b–d), and the most natural for composites have smooth changes in product thickness ("ladder of layers") (e).

2.4. Percussion Loads

High-speed impacts on composite structures (projectiles, meteorites) lead to localized damage (piercing, penetration, crater formation), depending on the energy of the impactor, the geometry and the target fixation (Figure 3b) [35–37]. The consequences of impacts with low velocities (stones from the airfield pavement, hail, birds, falling tools, etc.) or pressure pulses are more diverse [38–40] (Figure 3c,d). All of these cases are accompanied by delaminations.

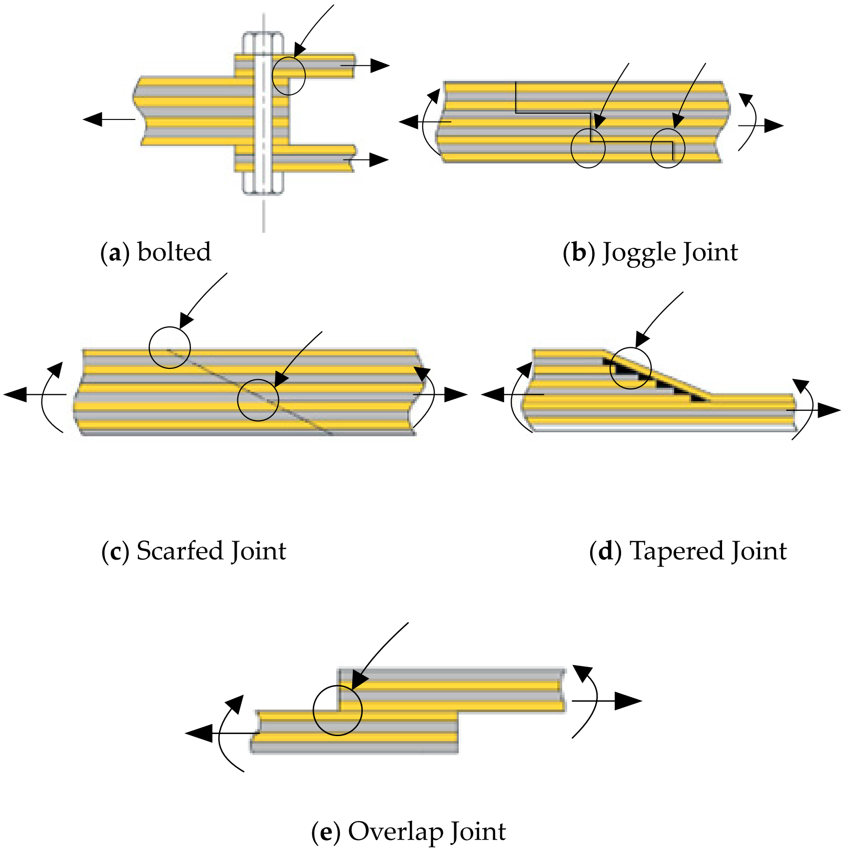


Figure 2. Types of macro-stress concentrators.

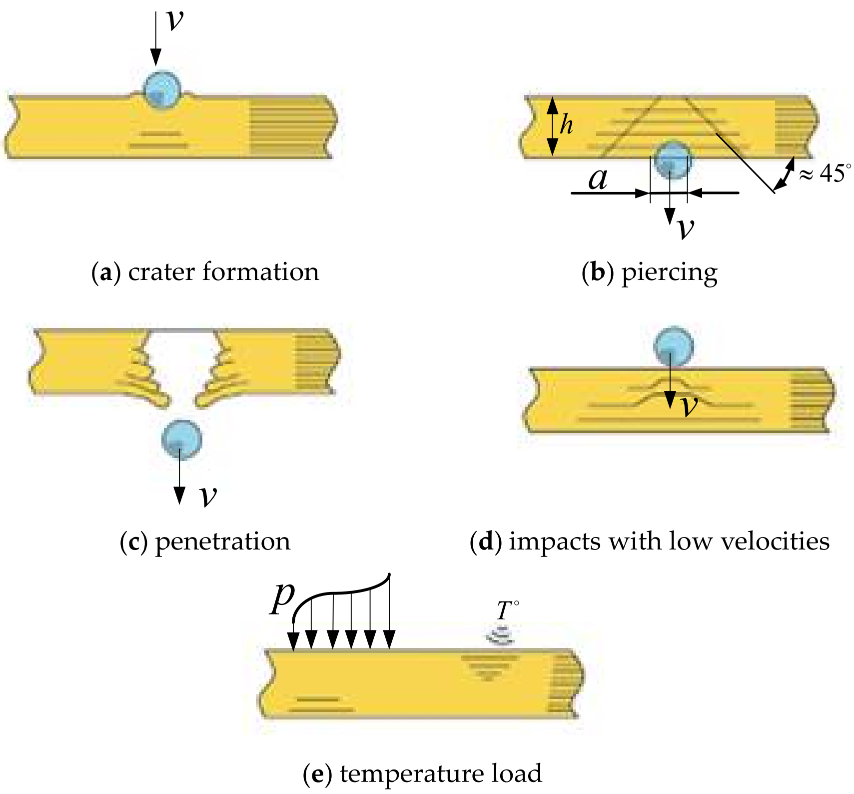


Figure 3. Types of pressure.

2.5. Cyclic Loading

The mechanisms of delamination formation during cyclic loading are largely similar to those described in Sections 2.2 and 2.3. However, it is significant that synergistic effects are manifested during alternating cycles; for example, delaminations that appear at the edge of the plate under macroscopic tension can grow under compression due to microbuckling [41,42].

2.6. Delamination from Other Defects

The application conditions and environment of fiber-reinforced composites warrant meticulous attention. Elements like pronounced temperature changes [43,44], high radiation levels [45,46], hygroscopic effects [47] and various environmental factors [48] might prompt resin movement, deteriorate both fibers and resin or trigger material stress shifts, culminating in composite delamination. The sources of delamination can be ruptures of the fiber layer [49]; intralayer cracks along the entire thickness of the layer along the fibers [50], especially the intersection of such cracks in adjacent layers [51]; and mutual rotations of adjacent layers with different reinforcement directions [52]. The diagnosis for delamination is presented in detail in the literature [53–55].

3. Load-Bearing Capacity of Structural Elements with Delamination

A large number of studies are related to theoretical and experimental research on the stress–strain state, the fracture mechanisms of structural elements made of composites with delamination, the assessment of permissible values of delamination parameters and the development of fracture criteria. Attention is mainly paid to thin-walled structural elements, since they are usually made of composites.

3.1. Development of Delamination (Quasi-Statics)

3.1.1. Mechanisms of Delamination Growth

At the crack tip on the boundary of two half-spaces, the solution of the elasticity problem yields the stress tensor $\sigma_{jk} \backsim r^{-1/2 \mp i\gamma}$ (review of early results) [16,17,34].

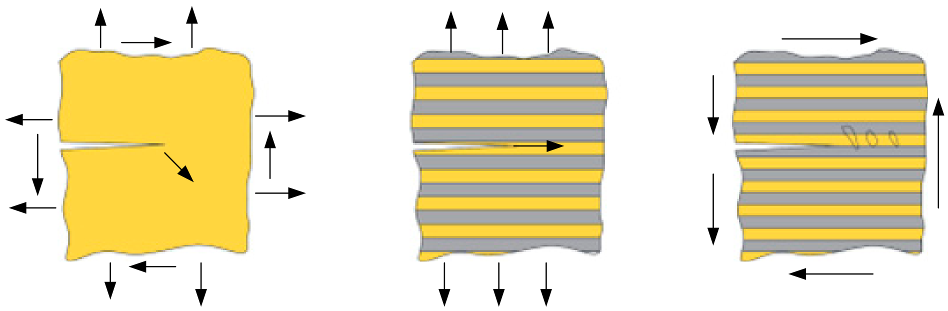
The stresses in the vicinity of the crack oscillate, except in some special cases [14], and the crack modes (normal tear—Mode I, transverse—Mode II and longitudinal—Mode III, shear) are not separated as in a homogeneous medium. However, these results are practically not used in the fracture mechanics of layered multidirectional composites. The reason is that the composite has small (as opposed to long) cracks, characteristic structural dimensions (fiber diameter, matrix thickness between fibers and between layers), significant synergistic effects of fracture surfaces, etc. [5].

The main difference between the conditions of crack growth in a homogeneous isotropic medium and a delamination crack in a composite is illustrated in Figure 4. If, in an isotropic medium (a) in quasi-static conditions, the crack reacts to the stress field as a rule by rotation, and growth is predominantly in Mode I; then, in a layered composite (b), it more often propagates along weak interfaces as a mixed-type crack—a combination of modes [56].

The fractographic analysis of the crack tip vicinity and delamination surfaces in a unidirectional composite shows the following. In cases of Mode I dominance, the fractures are predominantly adhesive in coal/epoxy and mixed adhesive–cohesive in coal/PEEK composites (PEEK is a polyether ketone thermoplastic matrix), with the involvement of layers in the fiber fracture process [57]. In cases of Mode II (transverse shear) dominance, the crack surfaces of delamination in relatively brittle matrices (epoxy) are comb-like, which indicates multiple turns of the crack front in the interlayer [58]. In this case, a refracture zone is formed (Figure 4c). In thermoplastic matrices, viscous effects play a major role [59,60].

Most laminated composites are characterized by the presence of mechanical bonds of the edges in the final zone of the delamination crack and bundles of reinforcing fibers pulled from the layers [61,62].

In multidirectional composites, delamination cracks may branch and jump to neighboring interlayer boundaries [63,64].



(a) Model I (b) Model II (c) Model III

Figure 4. Conditions of crack growth in a homogeneous iso-tropic medium and a delamination crack in a composite.

3.1.2. Criteria for Increasing Delamination

The criteria for crack initiation are either stress- or energy-based. The former, usually quadratic, includes normal and tangential interlayer stresses and corresponding strengths [65–67]:

$$\frac{(\sigma_{33}+\alpha)^2}{\beta^2}+\frac{\sigma_{13}^2+\sigma_{23}^2}{\gamma^2}=1 \tag{1}$$

The axis directions are shown in Figure 1; the coefficients are determined by the interlayer strengths in transverse tension, compression and interlayer shear.

The energy criteria of crack mechanics in their most general form are formulated in terms of the energy release rate (generalizations of the crack advancement force) G or the invariant J—integral along a closed loop around the crack tip [5,67]:

$$G = G_c \tag{2}$$

$$J = J_c \tag{3}$$

where G_c and J_c are critical values of parameters related to the macro energy of the formation of a new unit of the interlayer surface (work of crack advancement resistance forces [16] or fractures toughness).

Formula (1) is usually used if the stresses are determined analytically or by finite element analysis with regard to applied elasticity theories, since the stresses at the crack front (within the framework of elasticity theory) are special.

Different forms of criteria (2) and (3) are most often used. They are used in both geometrically and physically nonlinear problems. In addition, G_c and J_c are more stable characteristics of layered composites than the parameters α, β and γ in (1). In [68], a fairly good coincidence of results was reported for FRPs of [0/+30] and [+45/0/90] structures according to criteria (1) and (2). However, the conditions for determining α, β and γ (1) are far from the mechanisms of delamination failure in the composite, especially when shear Modes II and III dominate (Figure 4c) [69].

The left part of (2) is calculated from integral considerations—the energy balance of the entire system during crack growth:

$$G = -\frac{\partial \Pi}{\partial l_c},\ G = \mp\frac{\partial U}{\partial l_c} \tag{4}$$

where Π and U are the total energy and strain energy of the system, respectively, and l_c is the characteristic crack size [4,16,23] or local, considering the situation in the vicinity of the delamination crack front point [24,34]. The first way is preferable if the solution is built "on average"—taking into account approximate methods, especially in nonlinear systems [70,71]. In applied theories, U is usually understood as the sum of the energies of membrane and bending deformations, which is asymptotically accurate [72].

To apply (4), the potentiality of forces is required, and for the second formula, the linearity of the system is also required [73]. In its most general form, the integral approach has been developed in multivariate fracture mechanics [74]. The basis of the approach is the generalization of the principle of virtual displacements to the case of a body with cracks, the dimensions of which are unilaterally varying parameters of the theory (Griffiths variations). In applications, the multiparametric mechanics are usually reduced to (2), where the left-hand side is calculated via (4) for all parameters of I_c available in the system.

Later, the multivariate fracture mechanics for delamination cracks were developed in the case of bilateral variations in crack sizes, i.e., for "healing" cracks [75]. Some specific variants of the multivariate delamination mechanics were proposed in [76].

The general form of energy criterion (2) for planning a delamination crack is rarely used, which is explained by the significant difference in fracture toughness G for Modes I, II and III of delamination cracks. The most commonly used criteria are [69,74]:

$$\left(\frac{G_I}{G_{I_c}}\right)^l + \left(\frac{G_{II}}{G_{II_c}}\right)^m + \left(\frac{G_{III}}{G_{III_c}}\right)^n = 1 \tag{5}$$

where $G_I + G_{II} + G_{III} = G$, and G_{I_c}, G_{II_c} and G_{III_c} represent the fracture toughness for the crack of the corresponding modes.

Condition (5) is purely phenomenological, reflecting experimental results in the space G_I, G_{II} and G_{III}. It is analogous to boundary surfaces in stress spaces and is also used in nonlinear systems. The parameters l, m and n in the range from one/two to three are purely approximations. In criterion (5), it is assumed that the delamination grows in its plane, normal to the front; the ratio between G_I, G_{II} and G_{III} does not change [69].

In [17], a variant of the boundary surface from a set of planes quantitatively close to (5) is proposed. In [70], some refinements of criterion (5) are proposed, but the scatter of experimental results makes various "refined" variants hardly justified.

3.1.3. Mode Separation

The use of criterion (5) involves the calculation of G components by individual modes. First, the stress–strain states (SSS) of composite structures with delaminations are determined.

Studies [77–79] consider the problems of planning thin extruded delaminations based on an integral approach using applied theories (for a beam, plate and shell as a whole) in linear and geometrically nonlinear formulations. Here, the components of the strain energy release rate are calculated by the following formulas:

$$G_I = -\frac{\partial U_b}{\partial I_c},\ G_{II} = \mp\frac{\partial U_c}{\partial I_c} \tag{6}$$

where U_c and U_b are the energy of membrane and bending deformations, respectively, and I_c is the characteristic active size of the delamination. In this case, it is explicitly or implicitly implied that $G_{II_c} = G_{III_c}$, and in (5), the second and third terms are combined. Indeed, in the integral approach, the Griffiths variation of the characteristic length of the delamination crack means, for example, in elliptical delamination [80], variation in the delamination area, where all generally modes are present (Figure 5).

In the local form of criterion (5), using analytical methods for determining the SSS (i.e., applied theories), the components of G are calculated through internal generalized forces and generalized displacements at the delamination crack front (beam approach). In [81], for a classical beam with delamination, G_{II} is separated from G through the components of the SSS after symmetrization. Mode I corresponds to equal moments and transverse forces. Taking into account the displacements, the separation of Modes I and P for the rods was studied in [82], taking into account the geometric nonlinearity in [78].

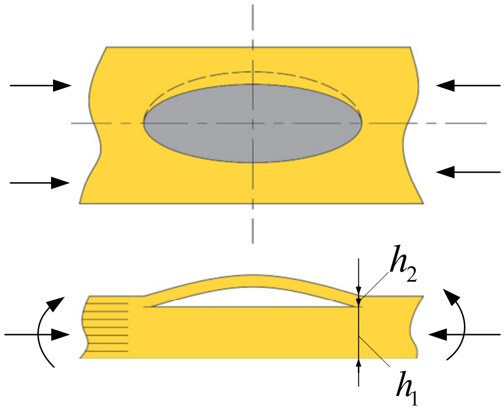


Figure 5. Elliptical delamination.

In [83], the calculation of G in bending a plate with delamination for various approximations of the theory was considered, and the impossibility of such a separation within the Kirchhoff approximation was noted. The use of the Reissner-type approximation [84] to determine the SSS shows that in some cases [85], G_{III} can significantly exceed G_{II}.

In [86], the influence on the values of G_I and G_{II} in the beam of possible geometric and elastic mismatches of the structures in the delaminated parts was examined.

Model problems on cracks—delamination at the boundary of two isotropic bodies—are considered in [9,34,35]. The axisymmetric problem of pressure tearing of an annular layer in delamination with displacement constraints was solved with the method of boundary integral equations [9]; the plane problem was reduced to systems of singular integral equations [34]; and the three-dimensional problem was solved by asymptotic expansions [35]. The correlation between G_I and G_{II} was obtained and parametrically studied, in particular the mechanical connections at the crack mouth, and conclusions were drawn about the error of the "bookmark" model for thin-walled delamination at the crack tip.

In [87,88], an analytical elastic analysis of G_I and G_{II} in plane orthotropic beam-shaped bodies with delamination was performed. Many estimates were obtained by scaling the results for isotropic bodies using two parameters, $\lambda = \frac{E_2}{E_1}$ and $\rho = \frac{1}{2}(E_1E_2)^{\frac{1}{2}}G^{-1} - (v_{12}v_{21})^{\frac{1}{2}}$. In [89], the limitations of the beam approach for mode separation are discussed, based on an analysis within the framework of elasticity theory. Some results of determining the stress intensity coefficients K_I, K_{II} and K_{III} in model problems of delamination in anisotropic piecewise homogeneous layered bodies are presented in [74,90]. The results are used to analyze the effect of the $[\pm\theta]$ and $[0/\pm\theta^\circ/90^\circ]$ layered composite structure on the ratio of fracture modes.

The finite element method (FEM) is most often used to calculate G_I, G_{II} and G_{III} when substantiating integral "beam" formulas for processing the experiment [91–93], in order to determine the interlayer fracture toughness. The essence of the method is similar to the Irwin method in a continuum medium (Figure 6) ("crack closure method"):

$$G_I = \frac{F_2^i \Delta u_2^{i-1}}{2a_1a_3},\ G_{II} = \frac{F_1^i \Delta u_1^{i-1}}{2a_1a_3} \tag{7}$$

where a_j are the dimensions of the finite elements by x_j; F_j^i are the forces at node i; and Δu_1^{i-1} are displacement gaps in the node $i-1$. The accuracy significantly depends on a_j [93].

The finite element plane analysis allows us to estimate the error and limits of beam approaches [92], to assess the contribution of "extraneous" modes in the experimental determination of G_{I_c} and G_{II_c}. Sometimes, a special finite singular element is used at the top of the delamination crack [94] to avoid unnecessary fragmentation of the region, or to eliminate oscillation of the solution.

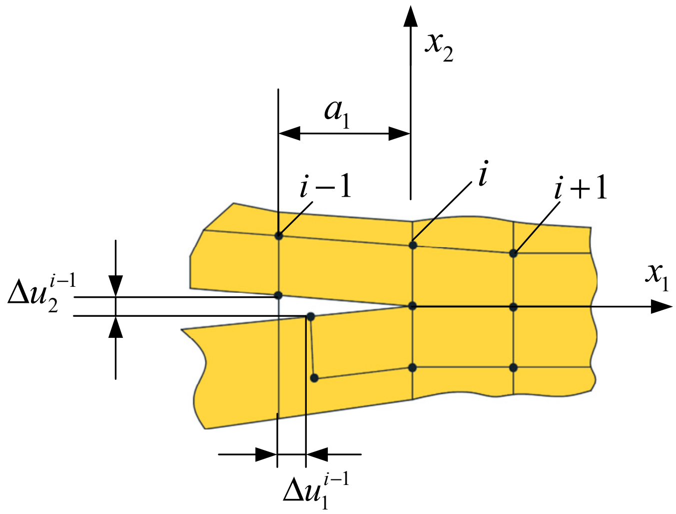


Figure 6. The Irwin method in a continuum medium.

In addition to the aforementioned model, the Interlaminar Element Model is another frequently utilized approach in addressing fatigue delamination of fiber-reinforced composite laminates [95]. This model is rooted in the Dugdale–Barenblatt (D–B) model [96,97]. With respect to the cohesive law, Needleman [98] introduced the exponential law, while Tvergaard and Hutchinson [99] presented the trapezoidal law, and Mi et al. [100] put forth the bilinear law. The interlaminar element model possesses a lucid physical interpretation and seamlessly integrates with finite element method (FEM) software. Subsequent studies [101,102] have integrated the cohesive interface constitutive law's interface model into the LS-DYNA explicit finite element code. Notably, the domain of fatigue delamination simulation has witnessed significant advancements, with viscous elements emerging as an invaluable instrument for elucidating and prognosticating interlayer interface behaviors under fatigue loading conditions [103–105].

3.1.4. Some Peculiarities of Applying the Criteria for Increasing Delamination

The denominators of (5) are the fracture toughnesses at "pure" modes. However, the mechanisms of delamination growth are significantly different: Mode I is mainly adhesion, and II and III are cohesion (Figure 4). Quantitatively, these mechanisms in composites depend on the properties of the components, the layering and the degree of reinforcement [16,65]. Hence, the differences in the parameters l, m and n (5) are selected from the approximation of experimental data on mixed modes. In such modes, the interaction of delamination mechanisms that are characteristic of different modes is significant, and a synergistic effect is manifested [74,78]. In [106], it was proposed to introduce "joint" fracture toughnesses into the criteria.

Furthermore, the partial fracture toughness in composites of unidirectional layers significantly depends on the difference in the directions of stacking of adjacent layers [107,108] and on the thickness of the layer [109,110], i.e., they are constants of the composite.

The peculiarities of using (5) include the uncertainty of the concept of crack size l_c (Figure 7). Many laminated composites are characterized by the presence of delamination banks—fiber bundles—in the final regions of the plastic zone, microcracks (Figure 4) and normal and tangential mechanical bonds [16,34,54]. The formation mechanisms, the role and the contribution of these bonds to the development of delamination are different in Modes I, II and III. Taking $l^3{}_c$ as the crack parameter, the influence of bonds can be attributed to the calculation of G_I, G_{II} and G_{III}, considering the fracture toughness as the constants of this composite [34,54], or to the increases in G_{I_c}, G_{II_c} and G_{III_c} [77,111]. In [15,20], it was proposed to distinguish between the characteristic crack sizes $l_{cI} \neq l_{cII}$ when calculating G_I and G_{II}.

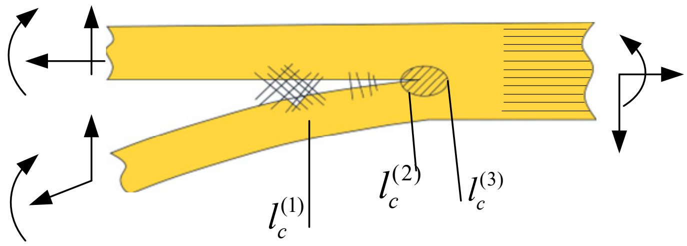


Figure 7. Crack size.

Another approach to this problem is to take l_c as $l^{(1)}{}_c$ (Figure 7), and consider the entire situation at the apex as the accumulation of damage before the crack [16,19,20,27], taking into account the decrease in fracture toughness.

This raises the problem of accounting for the displacement jump on the banks of the delamination crack at the apex [54] and formulating conditions when applying applied theories to determine the SSS. In particular, the application of the general straight normal hypothesis here [32,68,69] can lead to an overestimation of the forces in the layers and G_I and G_{II} [35,77,85]. It should be noted that the non-continuity of the final delamination crack zone in composites (Figures 4 and 7) may call into question the application of conditions (3). The calculation of J—integrals along a closed contour around the crack tip—implies the continuity of the body inside the contour.

Additional difficulties in the separation of modes and in the assessment of the behavior of a delamination crack are associated with the possible anisotropy of the delaminated parts of the structure (even with quasi-isotropy without delamination) [8,27], and the exit of the delamination crack from its plane.

Finally, we note once again that (2) and (5) define only the conditions for planning a delamination crack. Only its steady growth can be studied with quasi-static methods (growth requires an increase in loads). In the case of unstable growth, the dynamic effects, in particular the wave energy, cannot be neglected [89]. In its most general form, the stability of delamination crack growth is described in [13,14,23]. It is impossible to apply energy criteria for bodies without a crack [89] or in the "integral form" by comparing states at the final crack growth, as carried out in [81,82], also due to the failure to take into account dynamic effects.

3.1.5. Processes of Delamination Growth

Papers [33,72,84] provide reviews of early results of delamination crack growth in a multidirectional laminated plate from a straight edge. In the [±θ] structure packages, tensile failure Mode III (longitudinal displacement) predominates. Analytical estimates based on solving the two-dimensional equations of the anisotropic elasticity theory [5] and the FEM [91] give [±θ] structure packages; tensile failure Mode III (longitudinal displacement) predominates. Analytical estimates based on solving the two-dimensional equations of the anisotropic elasticity theory [5] and the FEM [91] give $\frac{G_I}{G_{II}} \sim 10^{-2}$. It has been established that crack growth in Mode III for small crack lengths $l_c < (h \div 2h)$ is unstable (h is the plate thickness); then, the crack grows from $G_{III} = \text{const}$ to almost complete plate delamination. The nature of the dependence of G_{III} on θ approximately repeats the dependence of $\eta_{16}(\theta)$ (Figure 1a).

In cases where Mode I predominates in the delamination crack near the plate edge (structures [0/90°], [±θ°/0/90°]), its growth is usually stable under tension, heating and increasing humidity ([40]—FEM, [91,93]—experiment).

When the plate is bent, the free nature of the growth of the delamination edge ($G \approx \text{const}$) is revealed in experiments [63] and in FEM calculations [92], not only in plates of the above structures, but also in plates of [0/θ°] and [±θ°/90°] structures. The dependence of G_{II} of l_c, with an increase in delamination in a three-layer beam under bending, was studied in [12].

In [31], it was proposed to take into account the visco-plastic effects at the tip of the delamination edge crack, which allows for the extension of the results to $l_c \to 0$. This is analogous to "cutting off" the yield stress of the stress curve—the crack length in classical crack mechanics is close to $l_c = 0$.

The development of delamination in multidirectional composite plates near circular holes under tension has been studied analytically [22] and with the FEM [91,93]. At the final width of the plate, the fracture zones from the hole, after the stage of steady growth, begin to interact with the fracture zones from the free edges, and the growth becomes unstable [60]. The experimental study of the development of delamination from the hole under compression and low-speed impact was studied in [66]. Qualitatively, the results are similar to [60].

Theoretically and experimentally, [21,22] investigated the shear cracks Mode II and Mode III in three-point bending of a composite plate with elliptical delaminations. The distribution of G_{II} and G_{III} were by contour.

The bending of arbitrary transversally isotropic plates with circular closed delaminations (Modes II, III) and their growth conditions were analyzed in [74,75], orthotropic plates in [76], and plates with a hole surrounded by a delamination in [85]. It was found that the influence of the delamination on the stress–strain state of the plate in bending rapidly decreases with distance from it. Closed delamination in Mode II tends to increase in the direction of the maximum bending moment gradient, in particular, toward the near plate boundary [75] and in an orthotropic plate, mainly in the direction of the axis of greater stiffness [76]. The presence of a hole in the plate surrounded by a circular delamination removes G_{II} and G_{III} on the delamination contour. However, with the growth of delamination, the crack front ceases to "feel" the hole. The situation on the delamination contour [85] is significantly mitigated by rejecting the hypothesis of a common straight normal and applying the Reissner-type shear theory of plate bending. Delamination growth is usually unstable.

The FEM solution of an axisymmetric plate bending problem with several delaminations of different radii [73] showed that the crack of the smaller radius grows first. However, this conclusion is not sufficiently justified, especially if the delamination of a smaller radius is not in the middle of the plate in thickness, where G is extreme [74].

The growth of delamination in plates in the residual stress field was studied in [31]. In this case, the kinetics of residual stress formation and strength change, and the heterogeneity of the undisturbed field of the delaminated part stressed in the SSS, whether it is unloaded or not, is essential for the growth. In particular, the edge decomposition of a circular plate in the residual stress field can be stable [25].

Model problems of interactions between intralayer cracks along fibers and interlayer delaminations in [0/90°] composites under tension (load-oriented layer) were considered in [21,30]. The FEM [93] was used to find that elliptical delamination at the intersection of intralayer cracks tends to grow perpendicularly to the load, mainly in Mode III. A delamination from two parallel intralayer cracks in 90° layers growing toward each other mainly proceeds according to Mode III [21]. However, if the intralayer cracks are near the rod surface, then a significant component of Mode I is involved.

In [29,94], the influence of load-transverse intralayer cracks (in layers of 90° orientation) and the delaminations that develop from them on the nature of the nonlinearity of the $\sigma - \varepsilon$ tensile diagram in composite rods of [±θ°/90°/0] structures was studied experimentally and theoretically (FEM). Here too, the delaminations grow mainly according to Mode II.

The interaction of intralayer cracks in delaminations in the rods of [0/90°] structures during bending was studied in [54,63]. The fracture process usually begins with the formation of intralayer cracks in the dangerous section of the 90° layer, with the largest positive deformations. Then, delaminations appear that interact with each other (Figure 8). The processes of unstable to stable delamination growth are usually followed by stable growth.

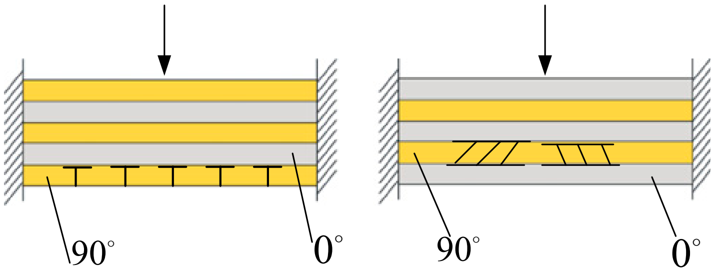


Figure 8. Interaction of intralayer cracks in delaminations in the rods of [0/90°] structures during bending.

The stability of delamination growth from the ends of a transverse crack in a layered arbitrarily loaded composite was analytically studied in [73]. It was found, in particular, that a small deviation in the external load from the direction of reinforcement leads to instable delamination growth (Figure 9).

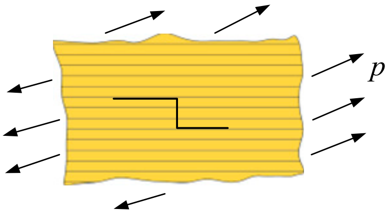


Figure 9. Transverse crack in a layered arbitrarily loaded composite.

3.2. Durability (Material Resistance)

3.2.1. Delamination Resistance

Delamination in composites is referred to as near-surface delamination of relatively small thickness. When a structural element is deformed, the delamination may bulge out (a local form of loss of stability) (Figure 10). This does not always lead to failure, but it can degrade the performance of the product [23,30]. The literature on delamination stability in rods, plates and shells is analyzed in [23,32,38]. In this review, we will focus on the general characterization of approaches, and some of the stability problems and critical behavior that are characteristic of composites.

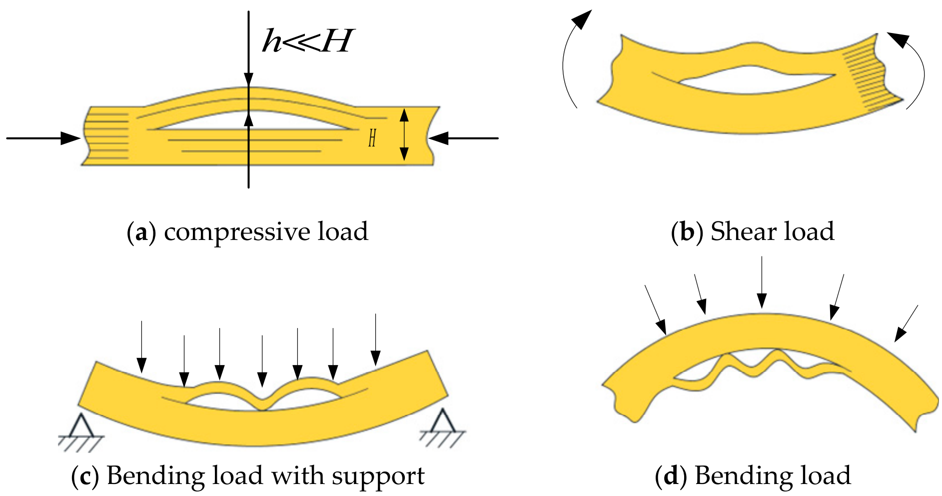


Figure 10. Delamination in composites.

As in traditional problems, the issues of delamination stability are reduced to eigenvalue problems [11,40,49] or energy methods [14,15,23,50,56,57,63,77]. At the same time, nonlinear technical theories of plates [15,77] and shells [11,50,63] are used, as well as the FEM [91,94].

Analytical approaches are usually limited to one-member approximations, taking into account the conditions of rigid clamping on the contour of the bulging delamination [11,27,32,50,56,57,63,68,77]. In a momentless undisturbed state (compression), bulging delamination is the only option when the load increases. If the subcritical state is momentary, then, depending on the properties and geometry, total failure in the delamination area or its growth without bulging is possible [74,75,77].

Delaminations that are anisotropic [25,38,39] have initial deflections due to residual stress, impact [15,61,72] or heating [17,30], and delaminations with incisions (which are "pocket-like") [65,66] bulge out without bifurcations under compression or shear pressure.

The results of an experimental study on the stability of delaminations in composites are provided in [64,68].

The problem of delamination stability depends on the behavior of the delaminated bearing layer in three-layer thin-walled structural elements [27,82]. The peculiarity in this analytical study is to take into account the strong difference in the mechanical properties of the aggregate in the bearing layer. As a rule, the critical values of compressive forces in the bearing layer are lower than those in the multilayer composite [109].

3.2.2. Closing Delamination Behavior

Under loading, the closure exhibits increased normal displacements, alterations in shape and a growth in delamination size; these are characteristic traits of laminated composites. Most studies primarily focus on the problem of delamination growth. Comprehensive reviews can be found in [32,63,70,94].

The quasi-static critical growth problem of one-dimensional and two-dimensional delamination in plates has been discussed in [63,68], while in shells, it is covered in [11,56,57]. The delamination state is described using geometrically nonlinear approximations, as per the Karman and Mindlin theories [11,56,57,68], or through the Finite Element Method (FEM) [91–94].

The increase in the size of the detachment is determined by criterion (2) or (5), with the separation of modes as mentioned in other studies. The contribution of Mode III is usually neglected.

The following conclusions can be drawn from the results of theoretical studies on closure and experimental research [64,66]. In the uniaxial compression of a plate or cylindrical shell, delamination in the form of an ellipse with axes that do not differ much grows mainly in directions that are perpendicular to the compression [56,57,64,68]. In the case of orthotropic detachment under biaxial compression, growth occurs mainly in the directions of greater stiffness [71]. With an increase in the size of the delamination, the ratio $\frac{G_I}{G_{II}}$ decreases, which, in the case of thermosetting binders (characterized by $G_{Ic} \ll G_{IIC}$), can affect the direction of delamination growth [17,55].

All of this applies to the case of hard loading (specified deformations)—the growth of delamination size is usually stable [56,68]. Under soft loading, growth occurs most often [17,30].

The compression of plates with orthotropic delaminations can cause secondary intralayer cracks [66] along the reinforcement—a closed delamination will become open. In the case of a delamination that is elongated in one direction, the loss of stability and closure can occur with the formation of several waves during compression along it [71]. The reason for the shape with several waves can be the curvature of the shell [32] (Figure 10d), the nature of the load [78,83] (Figure 10c) and the possible restructuring of the closed-state shape during quasi-static loading.

4. Summary and Outlook

Technological factors contributing to composite material delamination involve challenges in manufacturing processes, such as component selection, interface formation and curing time, as well as temperature, humidity, pressing force and tape tension during product winding. Delamination in composite materials can be attributed to various factors such as the free edge, joints, shock and cyclic loads, fiber layer ruptures, intralayer cracks throughout the fiber thickness and rotations of adjacent layers with differing reinforcement orientations. Insights into the methodological and technological dimensions of delamination are derived from an extensive compilation of scientific and literary contributions.

This article is devoted to a review of composite fracture mechanics, i.e., the macroscopic fracture that is the last stage before failure, the survivability stage. The product life cycle also includes the accumulation of damage, i.e., the dispersive fracture stage—fractures at the micro- and meso-levels of the material. Future research in composite materials should focus on improving manufacturing techniques to reduce delamination risks, strengthening interfaces between layers, optimizing curing processes, developing more effective non-destructive testing methods, exploring tougher resin matrices, utilizing advanced simulation and modeling for prediction and prevention, enhancing the characterization of damage at micro- and meso-levels, innovating composite repair technologies, studying environmental impacts and developing multiscale models to better understand delamination from micro- to macro-levels. These directions will advance our knowledge and technologies, ultimately increasing the durability and reliability of composite structures.

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