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EFFECT OF INTER- AND INTRALAMINAR DAMAGE ON THE COMPRESSIVE FRACTURE OF HYPERELASTIC MATERIALS

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Summary The present analysis investigates a mechanism of compressive fracture for heterogeneous non-linear materials undergoing large deformations under uniaxial or equi-biaxial loading. Special attention is given to accounting for the presence of both, inter- and intralaminar defects. The upper and the lower bounds for the critical load are examined. The analytical solution is found for different types of interlaminar boundary conditions.

In practical cases, the assumption of perfect bonding between neighbouring layers in composites does not correspond to reality. Various cases of interlaminar adhesion breakdown may occur in real layered materials during the fabrication process or in-service. If composites are compressed along layers and, therefore, along the mentioned interlaminar defects, the classical Griffith-Irwin criterion of fracture or its generalisations are inapplicable, since all stress intensity factors and crack opening displacements are equal to zero. This fact emphasises the importance and the necessity of a most careful (possibly exact) investigation of fracture due to specific mechanisms inherent to heterogeneous materials. The loss of stability in the heterogeneous structure of composites is one of such mechanisms; the moment of stability loss in the microstructure of the material – internal instability according to Biot – is associated with the onset of fracture.

The most accurate approach to studying the internal instability is based on the model of a piecewise-homogeneous medium, when the behaviour of each component of the material is described by the 3-D equations of solid mechanics provided certain boundary conditions are satisfied at the interfaces. It was used in numerous publications on the topic – see the reviews [2,5]. Along with the exact approach, there are also approximate models proposed by Rosen and later by many other authors. Detailed comparative analysis of different approaches was given in [1,2,5]. It was concluded [2,5,6] that the approximate methods are not accurate when compared to experimental measurements and observations.

However, all works mentioned above considered *perfectly bonded layers only*. Moreover, the approaches based on the Rosen model cannot be *altogether* applied in the case of *large* pre-critical (applied) deformations. The 3-D approach presented here allows us to take into account large deformations, geometrical and physical non-linearities and load biaxiality that the simplified methods cannot consider.

This paper investigates heterogeneous *non-linear* materials under *large* deformations. The composite consists of alternating layers with thicknesses $2h_r$ and $2h_m$ (Fig. 1), which are simulated by incompressible transversally isotropic solids with a general form of the constitutive equations. Henceforth all values referred to these layers will be labelled by indices r (reinforcement) and m (matrix). The analysis finds the bounds for critical compressive loads acting on the materials with imperfect interlaminar adhesion. As an example, a change in the nature of the interlaminar contact is studied, when an interaction of the layers is implemented so, that infinitesimal sliding is allowed, but still there are no gaps between the layers (e.g., molecular chains in some kinds of glue connection, Fig. 2). This kind of the cleavage-type delaminations is called *defects with connected edges* [3,6] or *perfectly lubricated interfaces*. For these defects, the continuity at the interface is retained for normal components only. For a layered material with an unidentified set of defects with connected edges, the following estimation can be suggested to find the lower bounds for the critical loads.

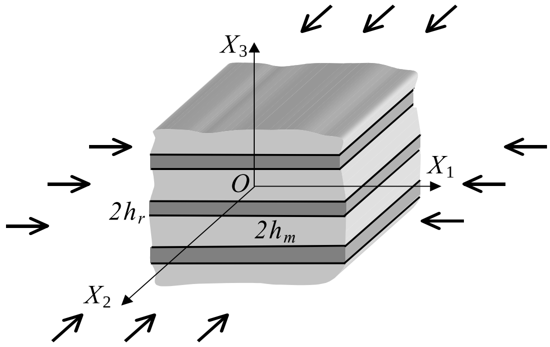

Fig. 1: The co-ordinate system and applied loads.

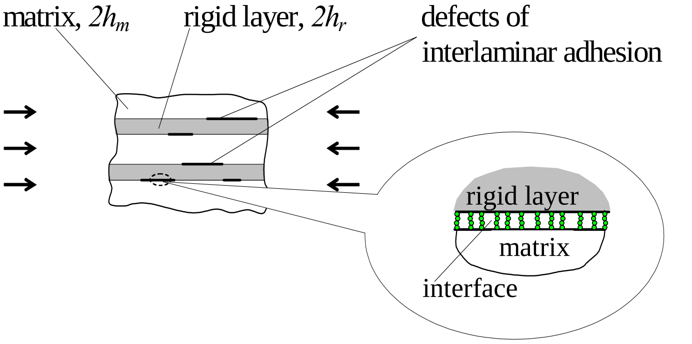

Fig. 2: An interface with a cleavage-type delamination.

Following [3], it can be said that the critical load for a material with the imperfections of interlaminar adhesion, e.g. containing the cleavage-type delaminations (P_{cr}^{imp}), must be smaller than for a material with the same internal structure with perfectly bonded layers (P_{cr}^{pb}); and must be larger than the critical load for a material with sliding layers (P_{cr}^{sl}). Hence, $P_{cr}^{pb} \geq P_{cr}^{imp} \geq P_{cr}^{sl}$, which, if written in the terms of shortening factors, λ_1, takes the form $\lambda_{cr}^{pb} \leq \lambda_{cr}^{imp} \leq \lambda_{cr}^{sl}$, since $u_i = (\lambda_i - 1)x_i$. This is true for an arbitrary set of defects with connected edges, i.e. for an arbitrary number, size and disposition of the defects. The substantiation of the bounds is based on a general principle of mechanics, which states that the release from a part of connections inside of the mechanical system cannot increase the value of the critical load.

In order to calculate the bounds, the non-axisymmetrical problem of the internal instability is considered within the model of a piecewise-homogeneous medium using the equations of the 3-D stability theory [2]. This allows us to eliminate the restrictions imposed by using the approximate theories as well as the inaccuracies they involve. The analytical solutions are found for different types of interlaminar boundary conditions, i.e. for perfectly bonded and sliding without friction layers. The characteristic determinants are derived for the first four modes, which are more commonly observed.

Of course, practical composite materials contain not only *interlaminar*, but also various sorts of *intralaminar* defects, cracks etc. The latter further complicate the problem. However, the developed method allows accounting for the presence of *intralaminar* damage by considering layers with reduced stiffness properties. The reduction in the axial material stiffness as well as in the Poisson's ratio due to matrix cracking was extensively investigated – see the review [4]. Based on the results [4,8], the effective properties of materials with intralaminar defects are calculated and incorporated into the analysis described above.

The effect of the different types of inter- and intralaminar damage, layer thickness and stiffness on the lower and the upper bounds is illustrated by several examples calculated for the particular non-linear models of materials. The obtained results show that the bounds present a good estimation. One of the examples is given below.

Let the composite (Fig. 1) consist of hyperelastic layers described by the simplified version of Mooney's potential, namely neo-Hookean potential, with the strain energy density function $\Phi = 2C_{10} I_1 (\varepsilon_{ij}^0)$, where C_{10} is a material constant, and $I_1(\varepsilon)$ is the first algebraic invariant of Cauchy-Green strain tensor. This potential is also called Treloar's potential, after the author who obtained it from an analysis of model of rubber regarded as a system of long molecular interlinking chains [8]. The upper bound for critical shortening factors is found as a result of the following procedure.

Solving the characteristic equations derived for the case of sliding layers for different modes of stability loss, the shortening factors are obtained as functions $\lambda_1^{(N)}(\alpha_r)$ of the normalised wavelength, α, where N is the number of the mode ($N = 1, 2, 3, 4$). The critical value for the particular mode, $\lambda_{cr}^{(N)}$, can be found as a maximum of the corresponding function. The maximum of these N values will be the critical shortening factor of the internal instability for the considered layered material with sliding layers, λ_{cr}^{sl} ,

$$\lambda_{cr}^{sl} = \max_N \lambda_{cr}^{(N)} = \max_N \left(\max_{\alpha_r} \lambda_1^{(N)} \right)$$

which is also the upper bound for the critical shortening factor for composites with interlaminar defects with connected edges. The example of the upper bound is given in Fig. 3. It was calculated for the typical ratios of the material constants, C_{10}^r / C_{10}^m . The value of the critical shortening factor increases with increasing relative stiffness of the layers. The increase rate is much higher for smaller values of the relative stiffness of the layers, that means $C_{10}^r / C_{10}^m < 50$. At that, the increase is very sharp for $C_{10}^r / C_{10}^m < 20$.

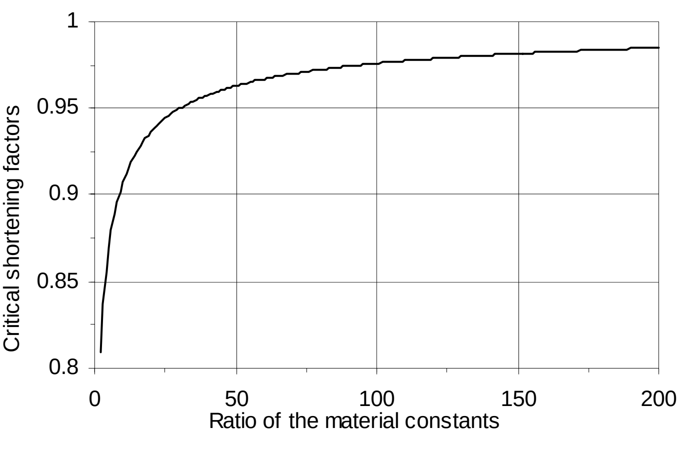

Fig. 3: The upper bound for λ_{cr} ; $h_r / h_m = 0.05$.

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