COMPOSITES IN CONSTRUCTIONS

Proceedings of the International Conference Composites in Constructions - CCC2003
Cosenza, Italy, September 16-19, 2003

Edited by

Domenico Bruno
University of Calabria, Italy

Giuseppe Spadea
University of Calabria, Italy

Ramnath Narayan Swamy
University of Sheffield, UK

EDITORIALE BIOS

ISBN 88-7740-358-6

Printed in Italy

The texts of the various papers in this volume were set individually by typists under the supervision of either each of the authors concerned or the editor.

Via Sicilia 5 - casella postale 528 - 87100 Cosenza (Italy)
Tel. 0984 854149 - 854512 - Fax 0984 854038
www.edibios.it
e-mail: info@edibios.it

INTERNATIONAL SCIENTIFIC COMMITTEE

Domenico Bruno, Italy, (Chairman)
Giuseppe Spadea, Italy, (Co-Chairman)
Narayan Swamy, U.K., (Co-Chairman)

Júlio Appleton, Portugal
Hojjat Adeli, Ohio, U.S.A.
Luigi Ascione, Italy
Mohammed Baluch, Saudi Arabia
Lawrence Bank, Wisconsin, U.S.A.
Ever Barbero, West Virginia, U.S.A.
Joan Casas, Spain
Alberto Corigliano, Italy
Edoardo Cosenza, Italy
Angelo Di Tommaso, Italy
Joaquim Figueiras, Portugal
Antonio Grimaldi, Italy
Patrice Hamelin, France
Thomas Keller, Switzerland
Franco Maceri, Italy
António Torres Marques, Portugal
Aftab Mufti, Canada
Antonio Nanni, Missouri, U.S.A.
Palaniappa Paramasivam, Singapore
Ghani Razaqpur, Canada
Sami Rizkalla, North Carolina, U.S.A.
Luc Taerwe, Belgium
Bjorn Taljsten, Sweden
Thanasis Triantafillou, Greece
Taketo Uomoto, Japan
Tamon Ueda, Japan
Dionys Van Gemert, Belgium
Abdul Zureick, Georgia, U.S.A.

ORGANIZING COMMITTEE

Renato Olivito, University of Calabria, Italy (Chairman)
Luís Juvandes, University of Porto, Portugal (Co-Chairman)
Raffaele Zinno, University of Calabria, Italy (Co-Chairman)

Francesco Bencardino, University of Calabria, Italy
Vincenzo Colotti, University of Calabria, Italy
Paolo Fuschi, University of Reggio Calabria, Italy
Fabrizio Greco, University of Calabria, Italy
Paolo Lonetti, University of Calabria, Italy
Luciano Ombres, University of Lecce, Italy
Nicola Totaro, University of Calabria, Italy
Venanzio Greco, University of Calabria, Italy

PREFACE

The Second International Conference on Composites in Constructions is following in the successful footsteps of the first International Conference organized in this theme and held in Porto, Portugal, October 2001.

During the last years, there has been significant progress in research and applications of advanced composite materials, especially fibre composites in Civil Engineering areas. A large number of researchers and institutions have been tirelessly working towards exploring the potential of such new materials and the successful integration of these modern materials to structural engineering design. In fact the matching of composite material with traditional material and their innovative application, provides economically sound and attractive solutions for structural strengthening and rehabilitation as well as new construction components and structural solutions.

In spite of the advantages that are offered by the use of fibre composites, the significant number of case studies and innovative experiences already gathered, many issues need further studies, both from a theoretical and a practical point of view, for the reliable and safe application of modern composites in the construction industry.

A total of 200 papers have been submitted to the conference, but only 115 are included in the proceedings, which have been selected after revision process by the Scientific Committee. The book contains selected and revised papers on different topics related to the use of composites in different research fields and it addresses the following ten important themes:

1) *Damage mechanics, fatigue and fracture;*
2) *Developments in composite materials;*
3) *Experimental techniques;*
4) *Innovations in design concepts and practical applications;*
5) *Non-destructive testing and evaluation of damage;*
6) *Rehabilitation; strengthening and seismic retrofitting;*
7) *Structural dynamics, vibration, buckling;*
8) *Structural modeling;*
9) *Micromechanics;*
10) *Structural health monitoring.*

We would like to gratefully thank all the authors for their attendance and their collaboration in the efforts towards the success of the Conference and the reviewers for their accurate selection and review of the manuscripts and their positive criticism.

Finally we would like to thank to all the Institutions and the Sponsors for their support to the Conference and to all those which contributed to the organization of the CCC 2003 edition.

Domenico Bruno
Giuseppe Spadea
Ramnath Narayan Swamy

Damage Mechanics, Fatigue and Fracture

Composites in Construction, Bruno et al (eds), ©2003, Editoriale Bios

A mechanical model for mixed-mode delamination growth in composite laminates under cyclic compression

Stefano Bennati & Paolo S. Valvo
University of Pisa, Dept. of Structural Engineering, Pisa, Italy

ABSTRACT: The paper presents a mechanical model for describing the buckling-driven mixed-mode delamination growth in composite laminates subjected to cyclic compressive loads. The laminate is modeled as the union of two sublaminates, partly bonded together by an elastic interface, i.e. by a continuous distribution of normal and tangential linear elastic springs. The model, already introduced in previous papers by the authors, allows for the determination of the explicit expressions of the normal and tangential interlaminar stresses, exerted between the sublaminates at the delamination front. Hence, the mode I and II contributions to the energy release rate and the mode-mixity angle can be deduced. Based on the above results, a mode-dependent fatigue growth law is applied. Thus, for any load level, predictions can be made on the number of cycles needed to grow a delamination to a given length. Results help to shed light on some experimentally observed phenomena of delamination growth and highlight the possibility of some very insidious failure modes.

1 INTRODUCTION

Fibre-reinforced composite laminates are used in many civil and industrial engineering applications, where, thanks to their very high strength and stiffness and their low specific weight, they are gradually supplementing, or even replacing, traditional structural materials. In contrast, composite laminates are also very sensitive to damage by environmental factors or localized defects. Of these latter types of damage, delaminations are both very dangerous and very common, as they may arise due to manufacturing errors (e.g., by an imperfect curing process) or in-service accidents (e.g., by low-velocity impacts) (Garg 1988, Abrate 1991, Bolotin 1996).

When a laminated plate containing a delamination is loaded in compression, local instability phenomena can promote further crack growth and, in some cases, lead to final failure. In order to model the process, loss of stability can be treated through the methods of non-linear structural analysis, while delamination growth can be described by applying some typical fracture mechanics tools (Chai et al. 1981, Kachanov 1988, Storåkers 1989). In the earliest studies on the subject, the total potential energy release rate, G, is assumed as the parameter pointing out the onset of crack growth. Actually, G is often preferred with respect to other parameters, such as stress-intensity factors, since its calculation is easier (e.g., by means of invariant integrals) (Yin & Wang 1984). However, experimental studies have proven that delamination growth always involves simultaneously the three classical modes of crack propagation: mode I, or opening, mode II, or sliding, and mode III, or tearing. Therefore, delamination growth is more properly described by a mixed-mode criterion, whose application requires the energy release rate to be split into the sum of the contributions G_I, G_{II} and G_{III}, related to the three typical propagation modes (Whitcomb 1981, Hutchinson & Suo 1992).

In previous works (Valvo 2000; Bennati & Valvo 2001, 2002), a mechanical model of a delaminated plate, subjected to monotonic compression, was introduced. The plate is modeled as the union of two sublaminates, partly bonded together by an elastic interface, consisting of a continuous distribution of normal and tangential linear elastic springs (Vizzini & Lagace 1987, Bruno & Grimaldi 1990, Corigliano 1993, Point & Sacco 1996). The model allows for the determination of the explicit expressions of the normal and tangential interlaminar stresses, exerted between the sublaminates at the delamination front. Hence, the mode I and II contributions to the energy release rate and the mode-mixity angle can be deduced. Finally, a mixed-mode growth criterion can be applied to predict the phenomena of delamination buckling and growth, under static compressive load.

In the present paper, the above model is extended to include the case of delamination growth under cyclic compressive loads. In this case, as the delaminated plate undergoes repeated buckling and unloading, a progressive accumulation of damage at the delamination front takes place. As a consequence, an existing delamination can grow even if the static growth criterion is not satisfied (i.e. if the energy release rate is less than the critical value). In what follows, a fatigue growth law, based on a mode-dependent critical energy release rate, is applied (Kardomateas et al. 1995). Thus, the number of cycles needed to grow a delamination to a given length can be predicted. Results help to shed light on some experimentally observed phenomena of delamination growth and highlight the possibility of some very insidious failure modes.

2 THE ELASTIC INTERFACE MODEL

Let us consider a rectangular laminated plate of length $2L$, width B, and thickness H, affected by a central, through-the-width delamination of length $2a$. The laminate is subjected to two compressive loads of intensity P acting in the axial direction. The material is supposed to be homogeneous and linearly elastic, with orthotropy axes aligned with those of the global reference system $OXYZ$.

The elastic interface model (Fig. 1) conceives of the delaminated plate as the union of two sublaminates, partly bonded by a continuous distribution of linear elastic springs. The two sublaminates are referred to as the 'film', included between the delamination plane and the nearest external surface (thickness H_f), and the 'substrate' (thickness $H_s = H - H_f$). The interfacial springs are active in both the directions normal and tangential to the interface plane, where they are characterized by the elastic constants, k_Z and k_X, respectively. The width B is assumed to be 'very large', so the sublaminates can be modeled as beam-plates. Hence, the 'reduced' Young modulus $E_X{}^* = E_X / (1 - \nu_{XZ}\, \nu_{ZX})$ is introduced, and all calculations refer to a unit width. According to the classical laminated plate theory, $\mathsf{A}_f = E_X{}^* H_f$ and $\mathsf{D}_f = E_X{}^* H_f^3 / 12$ are the extensional and bending stiffness of the film, respectively; $\mathsf{A}_s = E_X{}^* H_s$ and $\mathsf{D}_s = E_X{}^* H_s^3 / 12$ are those of the substrate, and $\mathsf{A} = E_X{}^* H$ and $\mathsf{D} = E_X{}^* H^3 / 12$ are those of the base laminate.

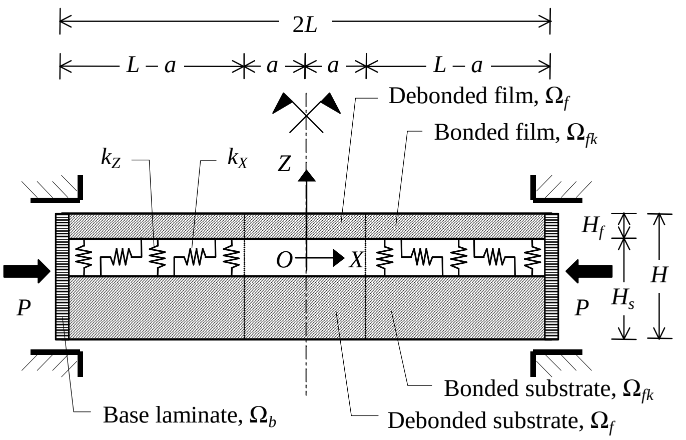

Figure 1. The elastic interface model.

With these assumptions, the differential equations of the equilibrium problem, according to von Kármán's plate theory, have been derived and solved completely in closed form. The explicit expressions of the solution, in the pre- and post-buckling phases, are reported in the above-cited works (Valvo 2000, Bennati & Valvo 2001, 2002). Here, we limit ourselves to recalling the fundamental results.

The pre-buckling phase is characterized by a linear relationship between the applied load, P, and the end displacement of the plate, u. During this phase, the sublaminates undergo uniform shortening and the axial force is distributed between them in proportion of their extensional stiffness. This behavior ceases when the axial force in the debonded film, Ω_f, equals the buckling load of the sublaminate. This is determined by solving numerically a non-linear transcendental equation. Consequently, the buckling load of the delaminated plate, P_B, i.e. the load applied to the base laminate at the incipient buckling of the film, is deduced.

During the post-buckling phase, the substrate experiences only axial shortening, while the film undergoes shortening and bending as well. Because of the different displacements of two laminates, non-zero stresses arise in the interfacial springs. Moreover, the energy release rate, $G = -\partial\Pi/\partial a$ (Π is the total potential energy of the system), which is zero throughout the pre-buckling phase, starts to increase.

G is the sum of the mode I and II contributions:

$$G = G_I + G_{II} \tag{1}$$

which are:

$$G_I = \frac{k_Z a_{fk}^2}{2} \frac{8\lambda}{\dfrac{2a}{\lambda} - \sin\left(\dfrac{2a}{\lambda}\right)} \left(a + \omega \tanh \frac{L-a}{\omega} \right) \frac{P - P_B}{\mathsf{A}_s}$$

$$G_{II} = \frac{k_X}{2} \left(\omega \tanh \frac{L-a}{\omega} \frac{P - P_B}{\mathsf{A}_s} \right)^2 \tag{2}$$

where $\lambda^2 = (\mathsf{A}\,\mathsf{D}_f) / (\mathsf{A}_f\, P_B)$; $\omega^2 = [k_X\, (\mathsf{A}_f^{-1} + \mathsf{A}_s^{-1})]^{-1}$; and a_{fk} is a dimensionless integration constant.

Finally, the mode-mixity angle,

$$\psi = \arctan \sqrt{\frac{k_X}{k_Z} \frac{G_{II}}{G_I}} \tag{3}$$

which conventionally measures the relative amount of fracture modes, by ranging from 0° (pure mode I) to 90° (pure mode II), is deduced.

3 STATIC DELAMINATION GROWTH

According to Griffith's classical criterion, crack growth is to be expected when G equals a critical value, G_C. In the original and simplest formulation, G_C is a material constant, measuring the so-called ‘toughness’. Nevertheless, for anisotropic materials, such as composite laminates, experimental determinations of G_C are markedly dependent on the propagation mode (I or opening, II or sliding, III or tearing) active in the test performed. Actually, the critical value measured in a pure mode III test, $G_{III\,C}$, is usually greater than that obtained in a pure mode II test, $G_{II\,C}$, which may, in turn, be much greater than the value measured in a pure mode I test, $G_{I\,C}$.

Under mixed-mode conditions, as all propagation modes are simultaneously active, the toughness equals an intermediate value. Thus, in order to predict crack growth, a mixed-mode criterion is to be adopted, by considering G_C as a function of the relative amount of the different propagation modes. In particular, for plane problems, the critical energy release rate,

$$G_C(\psi) = \frac{G_{I\,C}}{1+(\gamma-1)\sin^2(\psi)} \tag{4}$$

where $\gamma = G_{I\,C} / G_{II\,C}$, may be conveniently defined as a function of the mode-mixity angle (Hutchinson & Suo 1992).

For the present model, as shown by Equations 2 and 3, the energy release rate, G, in the post-buckling phase is an increasing function of the applied load, P; also, the mode-mixity angle, ψ, increases as either the load or the delamination length grows. For any assigned delamination length, it is possible to determine the load, $P_G(a)$, at which $G = G_C(\psi)$ and static delamination growth is expected. Figure 2 shows the buckling load of the delaminated plate, P_B, and the static delamination growth load, P_G, as functions of the delamination half-length, a. The following numerical values have been adopted: L = 100 mm, H = 10 mm and H_f = 1 mm; E_X = 54 GPa and ν_{XZ} = 0.25; k_X = 17284 N/mm^3 and k_Z = 23333 N/mm^3; $G_{I\,C}$ = 100 J/m^2 and $G_{II\,C}$ = 1000 J/m^2. Loads have been divided by the Euler load, $P_{\mathrm{eul}} = \pi^2\, D / L^2$ = 4535.8 N/mm, and the delamination half-length has been divided by L.

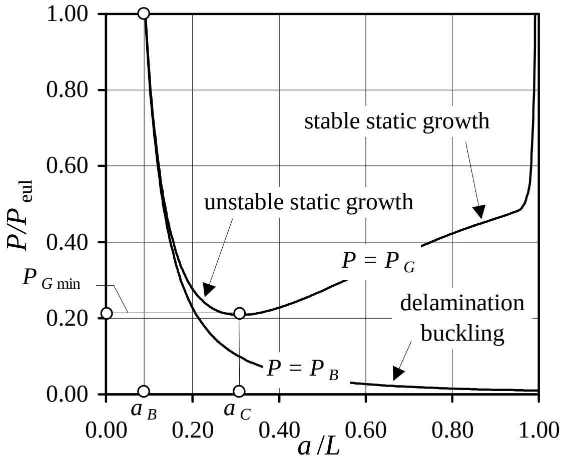

Figure 2. Buckling load of the delaminated plate and static delamination growth load vs. delamination half-length.

Two significant values of the delamination half-length have been highlighted in the figure: a_B, at which $P_B = P_{\mathrm{eul}}$, and a_C, at which P_G reaches a local minimum, $P_{G\min}$. If the length of the existing delamination is such that $a < a_B$, then local buckling phenomena and related delamination growth are not to be expected (although global instability can obviously occur); if, on the other hand, $a_B < a < a_C$, then delamination buckling and growth will be possible, the latter resulting in an unstable process; finally, if $a_C < a$, then delamination buckling and growth will be possible, but as a stable process.

For what follows, it is useful to introduce an equivalent alternative formulation of the growth criterion. To this aim, the energy release rate is normalized with respect to the mode-dependent toughness:

$$\hat{G} = \frac{G}{G_C(\psi)} \tag{5}$$

Consequently, under static loading, the condition for delamination growth becomes $\hat{G}$ = 1; instead, no growth is predicted for $\hat{G}$ < 1. With reference to Figure 2, the static growth condition is fulfilled by points belonging to the ‘growth curve’, $P = P_G$; on the other hand, points located below or on the ‘buckling curve’, $P = P_B$, furnish $\hat{G}$ = 0; finally, for all points in the region included between the above two curves, $0 < \hat{G} < 1$. In this region, no static growth is expected; however, as explained in the next paragraph, delamination growth under cyclic loads is possible. Finally, we might also notice that for all points located above the growth curve, $\hat{G}$ results to be grater than 1. This means that these points are not reachable by a quasi-static load history. Therefore, they have no meaning within the present model, which does not account for any dynamic effects.

4 FATIGUE DELAMINATION GROWTH

Moving on to examine the case of fatigue delamination growth, we consider a laminated plate affected by a delamination, whose initial half-length is a_0. We assume the applied compressive load varies cyclically between $P_{\min}$ and $P_{\max}$, so that the energy release rate will vary between $G_{\min}$ and $G_{\max}$. In these cases, experimental studies show that delamination growth can occur, because of the progressive accumulation of damage at the delamination front, as the delaminated plate undergoes repeated buckling and unloading.

According to Kardomateas et al. 1995, a fatigue growth law can be postulated,

$$\frac{da}{dN} = c(\psi)\frac{\left(\Delta\hat{G}\right)^{m(\psi)}}{1-\hat{G}_{\max}} \tag{6}$$

where N is the number of load cycles performed, and

$$\Delta\hat{G} = \frac{G_{\max} - G_{\min}}{G_C(\psi)} \tag{7}$$

is the range in the normalized energy release rate; in turn, $c(\psi)$ and $m(\psi)$ are two mode-dependent parameters to be determined by experiment. In particular, the multiplicative factor is

$$c(\psi) = c_I\left[1 + (\kappa - 1)\sin^2(\psi)\right] \tag{8}$$

where $\kappa = c_{II} / c_I$; c_I and c_{II} are the values measured in pure mode I and II tests, respectively. Analogously, mode dependence is introduced for the exponent, by setting

$$m(\psi) = m_I\left[1 + (\mu - 1)\sin^2(\psi)\right] \tag{9}$$

where $\mu = m_{II} / m_I$; m_I and m_{II} are the values measured in pure mode I and II tests, respectively. Numerical values used in all the figures below are: c_I = 50 mm/cycle and κ = 10; m_I = 10 and μ = 0.50.

In what follows, we will assume that cycles are performed with $G_{\min} = 0$, so that $\Delta\hat{G} = \hat{G}_{\max}$ and the fatigue growth rate becomes:

$$\frac{da}{dN} = c(\psi)\frac{\left(\hat{G}_{\max}\right)^{m(\psi)}}{1 - \hat{G}_{\max}} \tag{10}$$

This assumption, however, does not necessarily imply $P_{\min} = 0$, but just $P_{\min} \le P_B$, since $G = 0$ in the pre-buckling phase.

The fatigue growth rate, da/dN, is a positive and increasing function of $\hat{G}_{\max}$. Moreover, because of the denominator of Equation 10, as $\hat{G}_{\max}$ approaches unity, the growth rate goes to infinity, so that instant (static) growth is predicted (Fig. 3). Also, da/dN is an increasing function of ψ (Fig. 4). Therefore, since the mode-mixity angle increases as the delamination grows longer (Bennati & Valvo 2001), the growth rate is expected to become higher and higher as the process of fatigue growth itself develops.

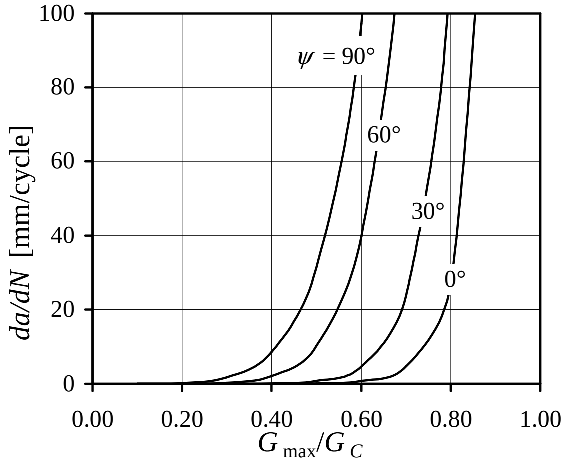

Figure 3. Fatigue growth rate vs. normalized energy release rate, at constant mode-mixity angle.

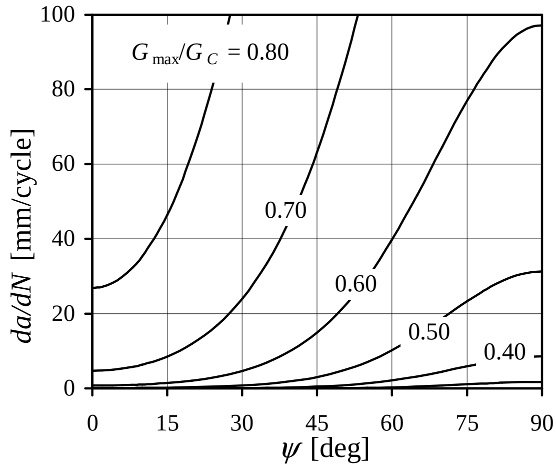

Figure 4. Fatigue growth rate vs. mode-mixity angle, at constant normalized energy release rate.

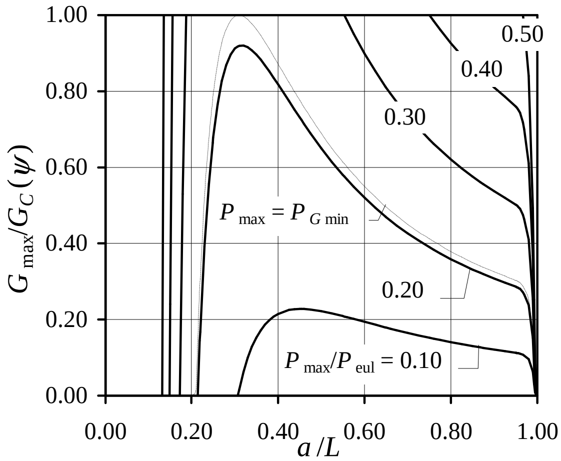

Figure 5. Normalized energy release rate vs. delamination half-length, at constant maximum load.

Figure 5 shows $\hat{G}_{\max}$ as a function of the delamination half-length. The dashed curve is for $P_{\max} = P_{G\min}$: at this load level, $\hat{G}_{\max}$ features a local maximum equal to 1. Curves below the dashed one are for $P_{\max} < P_{G\min}$: here it is always $\hat{G}_{\max} < 1$. Finally, curves above the dashed one are for $P_{\max} > P_{G\min}$: at these load levels, some values of $\hat{G}_{\max}$ are greater than unity and, therefore, must be excluded.

Figure 6 represents da/dN as a function of the delamination half-length. Again, the dashed curve is for $P_{\max} = P_{G\min}$: for this and all the higher load values, da/dN shows a vertical asymptote. Instead, for $P_{\max} < P_{G\min}$, the curves have a local maximum.

The number of cycles needed to grow the delamination from its initial length, $2a_0$, to an actual length, $2a$, is given by:

$$\Delta N(a_0, a) = \int_{a_0}^{a} \frac{dN}{d\bar{a}}\, d\bar{a} = \int_{a_0}^{a} \frac{1}{c(\psi)} \frac{1 - \hat{G}_{\max}}{\left(\hat{G}_{\max}\right)^{m(\psi)}}\, d\bar{a}\,. \tag{11}$$

Because of the analytical complexity of Equation 11, the integration is to be carried out numerically. In what follows, two cases are considered separately.

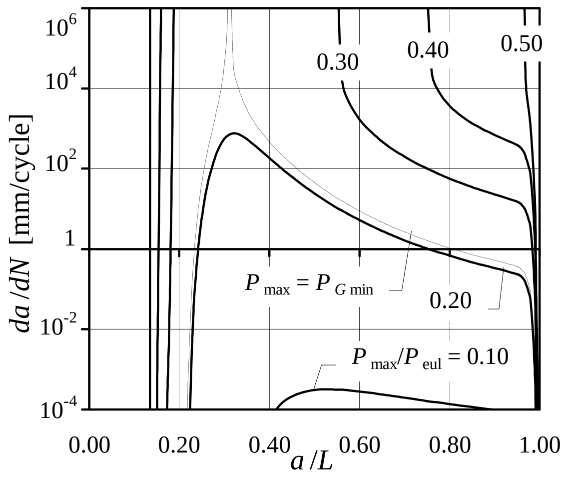

Figure 6. Fatigue growth rate vs. delamination half-length, at constant maximum load.

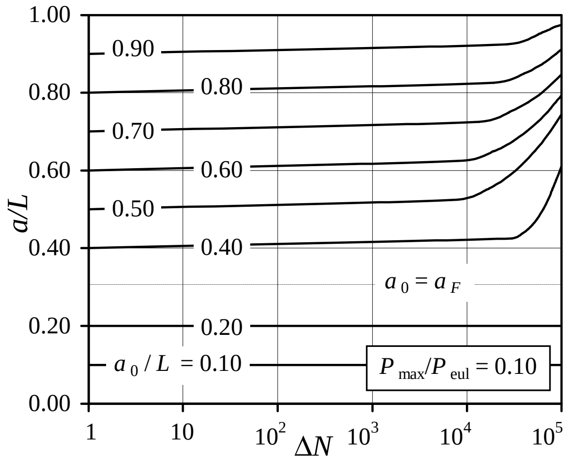

Figure 8. Delamination half-length vs. number of load cycles, at constant maximum load ($P_{\max}/P_{\mathrm{eul}}$ = 0.10).

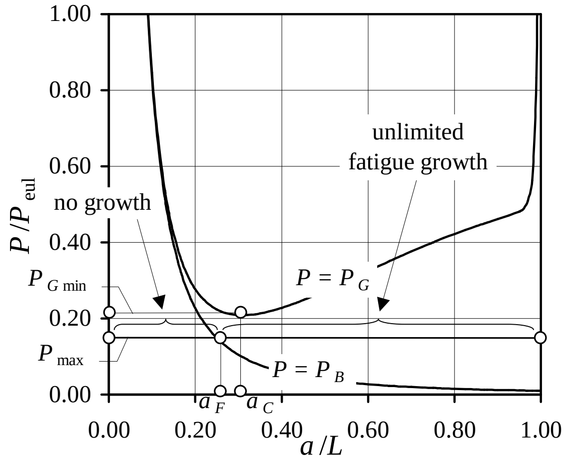

Figure 7. Fatigue growth: case a).

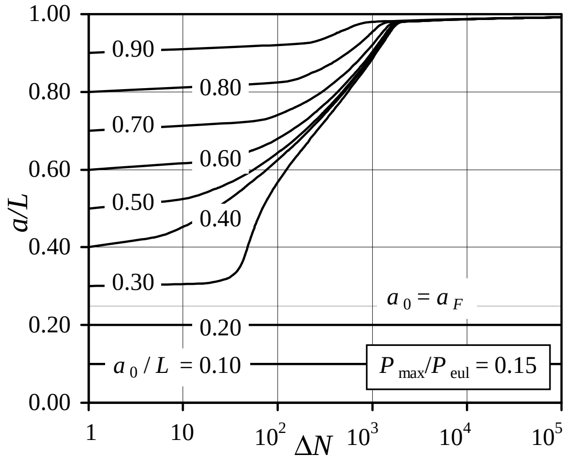

Figure 9. Number of load cycles vs. delamination half-length, at constant maximum load ($P_{\max}/P_{\mathrm{eul}}$ = 0.15).

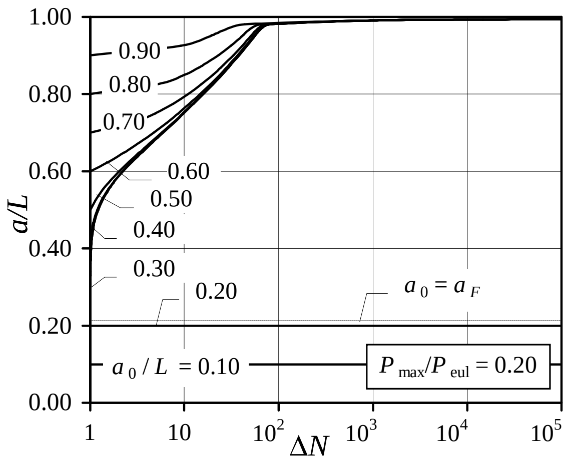

Figure 10. Number of load cycles vs. delamination half-length, at constant maximum load ($P_{\max}/P_{\mathrm{eul}}$ = 0.20).

4.1 *Case a)* $P_{\max} \leq P_{G\min}$

We consider first the case when the maximum load, $P_{\max}$, is less than the minimum load at which static growth can occur, $P_{G\min} = P_G(a_C)$ (Fig. 7). In this case, the straight line, $P = P_{\max}$, intersects the buckling curve, $P = P_B$, at one point, where the delamination half-length, a_F, is such that $P_B(a_F) = P_{\max}$. If the initial delamination length is such that $a_0 \leq a_F$, then no fatigue growth is expected, since no local buckling will take place; instead, if $a_0 > a_F$, then fatigue growth is predicted. Moreover, fatigue growth will be 'unlimited', since in theory it can continue until the plate is completely delaminated.

The following three figures show the delamination half-length as a function of the number of load cycles, for a range of values of the initial delamination length. A dashed line marks the value, a_F, under which no fatigue growth occurs. The qualitative trend of the fatigue growth process is very different in the three cases considered, which refer to increasing values of the maximum load. In Figure 8, the load level is quite low ($P_{\max}/P_{\mathrm{eul}}$ = 0.10) and the delamination does not increase relevantly in length until more than 10^4 cycles have been performed.

In Figure 9, the maximum load is at an intermediate value ($P_{\max}/P_{\mathrm{eul}}$ = 0.15): here, the delamination does not grow relevantly until about 10^2 load cycles have been performed. Afterwards, it develops rapidly until the plate is completely delaminated (notice, however, that a logarithmic scale is used for N).

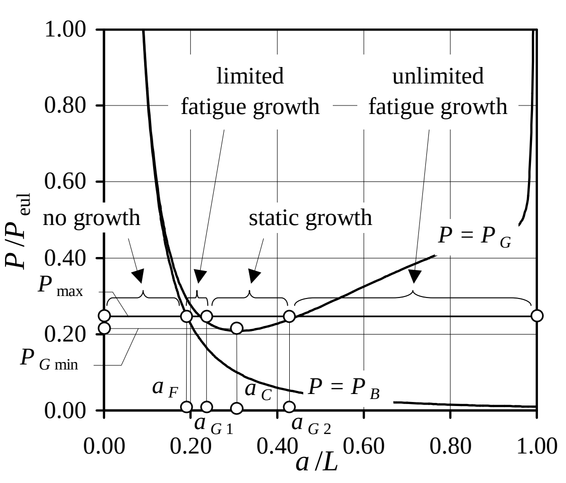

Figure 11. Fatigue growth: case b).

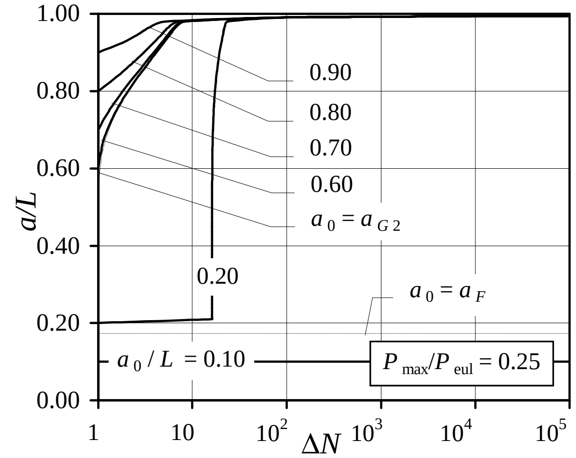

Figure 12. Number of load cycles vs. delamination half-length, at constant maximum load (P_{max}/P_{eul} = 0.25).

Finally, in Figure 10, the maximum load ($P_{max}/P_{eul} = 0.20$) is very close to the minimum static growth load ($P_{Gmin}/P_{eul} = 0.2084$): here, a rapid fatigue growth takes place, leading to complete delamination for a number of load cycles less than 10^2.

4.2 *Case b)* $P_{max} > P_{Gmin}$

When the maximum load, P_{max}, is greater than the minimum static growth load, P_{Gmin}, the straight line, $P = P_{max}$, intersects the buckling curve, $P = P_B$, at a_F; also, it intersects the growth curve, $P = P_G$, at two points, where the delamination half-length is, respectively, a_{G1} and a_{G2} (Fig. 11).

As well as in the previous case, if the initial delamination length is such that $a_0 \leq a_F$, then no fatigue growth is expected since no buckling will occur. Likewise, if $a_0 > a_{G2}$, then 'unlimited' fatigue growth will take place. Instead, a different behavior emerges in the range such that $a_F < a_0 < a_{G1}$: here, fatigue growth is possible, but 'limited'. In fact, after a finite number of cycles have been carried out, at $a = a_{G1}$, the conditions for static growth are fulfilled and the process can possibly continue in the form of static growth until $a = a_{G2}$.

The last plot (Fig. 12) shows the delamination half-length as a function of the number of load cycles. For $a_0 > a_{G2}$, a very rapid fatigue growth is expected, leading to complete delamination for less than 10 cycles. A peculiar behavior is predicted by the curve for $a_0 = 0.20$, which is in the range of the 'limited' fatigue growth. Accordingly, the delamination begins to grow very slowly, but suddenly, at $a = a_{G2}$, it undergoes a long jump leading to complete delamination. It is predictable that, in a real structure, this kind of behavior may result in a very insidious and dangerous mode of failure.

REFERENCES

Abrate, S. 1991. Impact on laminated composite materials. *Applied Mechanics Reviews* 44(4): 155-190.

Bennati, S. & Valvo, P.S. 2001. A mechanical model for mixed-mode buckling-driven delamination growth. In *Atti del XV Congresso Nazionale AIMETA '01 (Taormina, 26-29 settembre 2001).*

Bennati, S. & Valvo, P.S. 2002. An elastic-interface model for delamination buckling in laminated plates. In *Proceedings of the 5th Seminar on Experimental Techniques and Design in Composite Materials (Cagliari, Italy, September 28-29, 2000), Key Engineering Materials* 221-222: 293-306.

Bolotin, V.V. 1996. Delaminations in composite structures: its origin, buckling, growth and stability. *Composites Part B: Engineering* 27(2): 129-145.

Bruno, D. & Grimaldi, A. 1990. Delamination failure of layered composite plates loaded in compression. *Int. J. of Solids and Structures* 26: 313-330.

Chai, H., Babcock, C.D. & Knauss, W.G. 1981. One dimensional modelling of failure in laminated plates by delamination buckling. *Int. J. of Solids and Structures* 17(11): 1069-1083.

Corigliano, A. 1993. Formulation, identification and use of interface models in the numerical analysis of composite delamination. *Int. J. of Solids and Structures* 30: 2779-2811.

Garg, A.C. 1988. Delamination – A damage mode in composite structures. *Engineering Fracture Mechanics* 29(5): 557-584.

Hutchinson, J.W. & Suo, Z. 1992. Mixed mode cracking in layered materials. *Advances in Applied Mechanics* 29: 63-191.

Kachanov, L.M. 1988. *Delamination buckling of composite materials*. Dordrecht-Boston-London: Kluwer Academic Publishers.

Kardomateas, G.A., Pelegri, A.A. & Malik, B. 1995. Growth of internal delaminations under cyclic compression in composite plates. *J. of the Mechanics and Physics of Solids* 43(6): 847-868.

Point N. & Sacco E. 1996. A delamination model for laminated composites. *Int. J. of Solids and Structures* 33: 483-509.

Storåkers, B. 1989. Nonlinear aspects of delamination in structural members. In *17th Int. Congress of Theoretical and Applied Mechanics*: 315-336.

Valvo P.S. 2000: *Fenomeni di instabilità e di crescita della delaminazione nei laminati compositi* (in Italian). Ph.D. Dissertation: University of Florence.

Whitcomb, J.D. 1981. Finite element analysis of instability related delamination growth. *J. of Composite Materials* 15: 403-426.

Yin, W.-L. & Wang, J.T.-S. 1984. The energy-release rate in the growth of a one-dimensional delamination. *ASME J. of Applied Mechanics* 51(4): 939-941.