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A PCCL vezetésével a projektben résztvevő osztrák cégek és kutatóintézetek ez évben elnyerték az osztrák Gazdasági és Munkaügyi Minisztérium egyik STRAPAMO (stratégiai projekt az unióhoz csatlakozó kelet- és közép-európai államokkal) projektjét, ami Matelcomp néven fut és a következő résztvevőkkel indul várhatóan még ebben az évben:
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Interlaminar mode I and mode II fracture toughness and intralaminar damage of textile composites

Dan Mihai Constantinescu[**+] – **Mircea Găvan**[**] – **Nicolae Constantin**[*] – **Hans Christian Goetting**[#]

Összefoglalás

Textil kompozitok rétegközti törési szívósságának kísérleti meghatározása I. és II. terhelési módban

Az egy irányban rétegzett kompozitok rétegközti törési szívósságát a G_c kritikus energiafelszabadulás-sebességgel fejezik ki [(1) egyenlet].

A törésmechanikai vizsgálatokat – az ASTM és ESIS ajánlásainak megfelelően – az I. terhelési módban az ún. DCB kettős konzolos próbatestekkel, míg a II. terhelési módban az ún. ENF végein bemetszett három ponton hajlított próbatestekkel végezték *(2. és 3. ábra)*. A próbatesteket rendezetlen és szőtt üvegszálakkal erősített poliészter illetve epoxigyanta kompozitból, valamint poliészter bőrből és rendezetlen üvegszál-szövetből rétegelt, poliuretánhab magú szendvics anyagból készítették, míg a mesterséges kezdő repedést (bemetszést) 10 μm vastag műanyag fólia beágyazásával létesítették. A vizsgálatokat univerzális gépen, kezdetben, 10 mm repedésnövekmény eléréséig, 0,5 mm/min, majd 1 mm/min terhelési sebességgel végezték. Az erő–elmozdulás diagramot in situ adatgyűjtő rendszerrel rögzítették. A réteges elválás kezdetét a diagramon az iránytangens megváltozása jelzi. A G_c értékét az összetartozó erő és elmozdulás adatokból határozták meg.

Az I. terhelési módban végzett vizsgálatok a különböző anyagmintákra várt eltérő viselkedést igazolták. Jellemző erő–elmozdulás diagramokat a *4.* és az *5. ábra* szemléltet. A stabil repedésterjedést és az R-görbéket még részletesen elemezni kell. A II. terhelési módban végzett vizsgálatoknál némelykor mutatkozott a repedés keletkezése és némi terjedése, más esetekben viszont csak nagy lehajlást követően, de a repedés terjedése nélkül *(6. és 7. ábra)*. Vagyis, az ENF próbatestben gyakran nehéz a repedést megindítani. Úgy tűnik, hogy a négypontos hajlítási vizsgálat ígéretesebb.

A szendvics próbatestekben tapasztalt rétegen belüli károsodás *(9. és 10. ábra)* összetett jelenség, amely több kísérleti megfigyelést, gondos elemzést és numerikus modellezést igényel. A DCB próbatest érdekes szívóssági viselkedése *(8. ábra)* a helyi nemlineáris törési és károsodási mechanizmusnak tulajdonítható.

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Introduction

The fracture behaviour of high performance composite laminates is a complex issue, involving both intralaminar damage mechanisms (e.g. matrix cracking, fibre cracking) and interlaminar damage (delamination). Some progress has been made lately in the development of analytical tools for the prediction of intralaminar damage growth, but similar tools for delamination characterisation are still not available. Without a better understanding of progressive failure, the fracture criteria and predictive capabilities will be limited. Delamination is one of the predominant forms of failure in laminated composites due to the lack of reinforcement in the thickness direction. The analysis of delamination is commonly divided into the study of initiation and the monitoring of the propagation of an already initiated defect. Delamination initiation is usually based on analysis of stresses in conjunction with a characteristic distance. This distance is a function of specimen geometries and material properties, and its determination always requires extensive testing. Crack propagation is usually predicted using the Fracture Mechanics approach, which eliminates the difficulties associated with the stress singularity at the crack front, but requires the presence of a pre-existing delamination whose exact location may be difficult to determine in real applications. It is also essential to develop computational methods for the simulation of the delamination growth and the intralaminar damage mechanisms. In order to do this it is important to carefully observe and understand the fracture processes to be simulated.

Interlaminar fracture toughness of unidirectional laminated composites is usually expressed in terms of the critical energy release rate, G_c [1]. For Mode I the commonest test uses the double cantilever beam (DCB) specimen, according to ASTM D 5528 – 94a standard [2] for unidirectional fibre reinforced polymer matrix composites. It looks like major problems associated with this kind of test are the occurrence of fibre bridging across the crack as the crack moves above and bellow bundles of fibres and the fact that the *R*-curves associated with this phenomena are not intrinsic material properties, but they frequently depend on specimen stiffness. However, O'Brien [3] noted that fibre bridging, and consequently the *R*-curve effect are artefacts of the DCB specimen and do not occur in structural composite laminates. There are many other aspects to be discussed about the tests of unidirectional and multidirectional laminates, but it is not the case to do it here. For Mode II there are four test specimens considered for the measurement of interlaminar fracture toughness which have received most attention: three-point loaded end-notched flexure (ENF) test, the stabilized end notched flexure specimen (SENF – used in the Japanese standard), the end-loaded split (ELS), and, more recently, the four-point end-notched flexure (4ENF) test. Although the ENF test specimen has received the most attention, it has problems associated with the unstable crack propagation for short crack lengths. The Japanese JIS K7086, [4], standard can be used to establish both Mode I and Mode II interlaminar fracture toughness of carbon fibre reinforced plastics. Alternatively, one can use the European Structural Integrity Society (ESIS) protocol for interlaminar fracture testing of composites as for: Mode I on DCB [5], and Mode II, on ELS, [6]. The main problems [7, 8] associated with Mode II testing are the definition of the type of starter defect, the definition of crack initiation, the stability of the test, frictional effects on the crack faces and the data analysis. Mode II fracture toughness is typically much higher [9] and has more scatter than the Mode I fracture toughness: for epoxy matrix composites the G_{IIc}/G_{Ic} ratios typically exceed a value of 2. There are some differences in the recommended conditions of testing in between various documents, and there is a need to try to unify all these procedures, as it was already done in Mode I by the International Organisation of Standardisation, [10]. A clear picture of the current state of the art in the Delamination Fracture Mechanics of unidirectional composites is presented in [11].

However, one should mention that the used standards and protocols have been established and evaluated in 'round-robin' trials by standards organizations only for unidirectional fibre reinforced layered composites. Preliminary tests for multidirectional laminates have resulted in significantly higher values of G_{Ic} compared with unidirectional laminates.

The purpose of this research is to establish the fracture toughness of glass epoxy and polyester textile composites with roving and satin fibre fabrics, very much used in engineering applications. The main goal is to test multilayered laminates and sandwich specimens with a rigid core foam, to observe the interlaminar and intralaminar failures, and to try to understand most of the local processes. More developments are expected after being able to perform correctly the numerical simulation of delamination growth.

Theoretical approach

The DCB specimen is shown in *Fig. 1*, where $2h$ is the thickness of the specimen, is the initial delamination length, is the length of the propagated crack, and is the crack opening under the applied wedge forces P towards the edge of the specimen by which both sides of the specimen are loaded. The energy release rate in a DCB is defined in a usual way:

$$G = -\frac{\partial \Pi}{b \partial a}, \quad (1)$$

where b is the width of the specimen, Π is the potential energy accumulated in the system. The potential energy of a linear elastic system is equal to

$$\Pi = \frac{1}{2}\int_v \sigma_{ij}\varepsilon_{ij} dv - \int_0^u P(u)du, \quad (2)$$

where σ_{ij} and ε_{ij} are the stress and strain, v is the volume, and $P(u)$ is the force applied, which is a function of displacement. The first term is an energy stored in the linearly elastic body and the second one is the work produced by the applied external force. The displacement u is the full opening of the DCB specimen where the force P is applied. The first term is also expressed through the force acting on the system,

$$\Pi = \frac{1}{2}Pu - \int_0^u P(u)du. \quad (3)$$

From Eqs. (1) and (3) it follows that

$$G = -\frac{1}{2b}\frac{\partial P}{\partial a}u - \frac{1}{2b}P\frac{\partial u}{\partial a} + \frac{1}{b}P\frac{\partial u}{\partial a} = \frac{1}{2b}\left(P\frac{\partial u}{\partial a} - u\frac{\partial P}{\partial a}\right) \text{ or}$$

$$G = \frac{P^2}{2b}\frac{\partial c}{\partial a}, \quad (4)$$

where $c = u/P$ is the compliance of the system. The formula (4) is general, well-known, and widely used. No assumption about the crack type structure was made, and should be valid for any bridging law and specimen shape. But the G values obtained can be functions of the specimen shape, and not only of the characteristics of the material. G depends on the compliance $c = u/P$ which is measured experimentally or calculated theoretically.

Neglecting the possible bridging effect in unidirectional composites, the deflection of an ideal cantilever beam (as having a fixed end at the crack front), with length a and bending stiffness EI, under load P is equal to $Pa^3/3EI$. The full opening of the DCB equals the doubled deflection [9],

$$d = \frac{2Pa^3}{3EI} \quad (5)$$

and the compliance is

$$c = \frac{2a^3}{3EI} \quad (6)$$

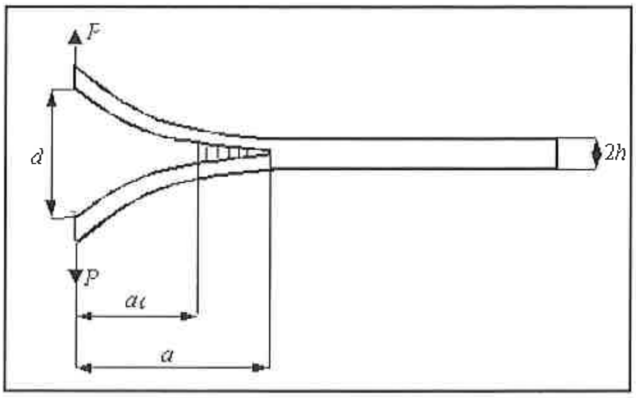

Fig. 1 The specimen geometry of the DCB.
1. ábra. A kettős konzolos, DCB próbatest alakja és méretei

Using Eqs. (4) and (6), the mostly known formula for the DCB is obtained

$$G(P,a) = \frac{P^2a^2}{EIb}. \quad (7)$$

Combining Eqs. (7) and (5), we get three another modified formulae for G:

$$G(P,a,d) = \frac{3Pd}{2ba}, \quad (8)$$

$$G(P,d)=\frac{P^2}{EIb}\left(\frac{3EId}{2P}\right)^{2/3}, \qquad (9)$$

$$G(a,d)=\frac{9EId^2}{4ba^4}. \qquad (10)$$

Applying Eqs. (7) – (10) to an ideal isotropic cantilever beam, equal results will be obtained. But, strictly speaking, they are all invalid for DCB specimens since boundary conditions at the end of the cracked part of specimen are not the same as for the clamped end of the cantilever beam. As a result, the deflection of a real specimen for a given load and crack extension will always be greater when established experimentally, than it is predicted by beam theory (Eq. (5)). The deflection is even higher for unidirectional composites since in this equation we neglect the interlaminar shear. The error is big for a short crack and diminishes when the crack propagates. From previous experience it looks like formula (9) performs better even for short cracks [7]. This is probably because formula (9) is written in term of compliance, as it was before derivation in (4).

If large displacements occur, the deflection d will be less than that predicted by small displacement theory owing to the shortening of the lever arm. An approximate correction factor is suggested in [2]. The same correction factor can be used to yield the corrected compliance. However, both ASTM standard and ESIS protocol recommend that the correction factor should be considered to be 1 if the load P is applied through hinges; another possible fixture to the end of the DCB is the end block; this is rigid and stiffens the specimen, and can rotate thus shortening the lever arm – in this case the correction factor should be used.

Experimental procedure

Experiments were done on glass epoxy and polyester woven fabrics, DCB specimens for Mode I *(Fig. 2)*, and ENF specimens for Mode II *(Fig. 3)*. The polyester skin/core/skin sandwich specimens were tested both in Mode I and Mode II. The large variety of tested samples consists of:

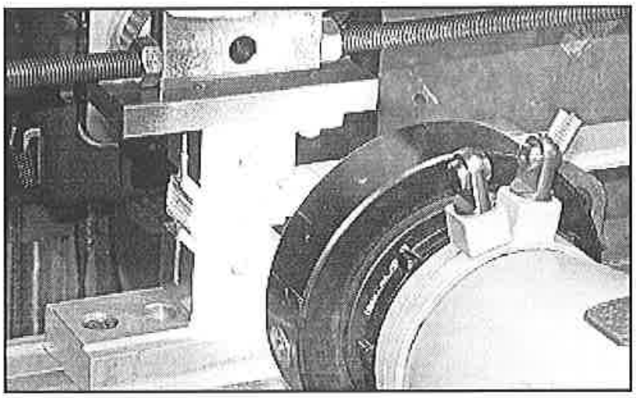

Fig. 2 Mode I testing on DCB specimen
2. ábra. A DCB próbatest vizsgálata I. terhelési módban

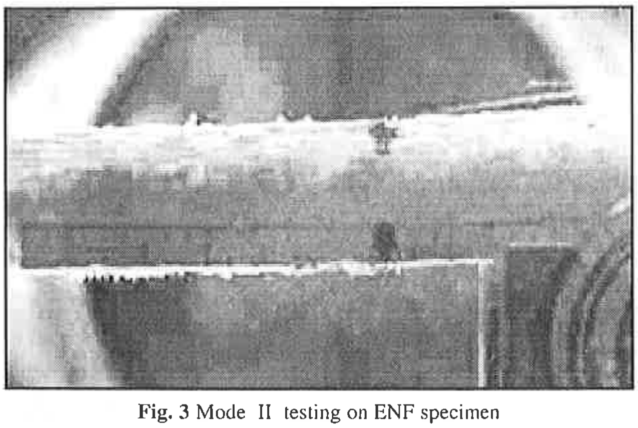

Fig. 3 Mode II testing on ENF specimen
3. ábra. Az ENF próbatest vizsgálata II. terhelési módban

– laminates made from polyester and epoxy resins, reinforced with roving and satin glass fibre fabrics;

– sandwich specimens with roving glass fibre fabric and polyester laminated skins, and rigid polyurethane (Coremat) foam core.

All specimens (manufactured in Romania) have an artificially introduced delamination (insert) by a plastic film of thickness about 10 mm, an initial length of 200 mm and a width of 20 mm. Thickness varies on the type of specimen used for testing, between 3.5 and 9 mm. Tests were done in displacement control, the delamination length and growth were monitored on an optical microscope and the whole test was recorded by a video-camera, in order to make possible a better surveillance of the damage and crack initiation, propagation and failure processes.

The tests to establish the interlaminar fracture toughness and intralaminar damage and fracture processes were done on different specimens and abbreviated as follows:

- Mode I testing: 12FER5 and 12RT350 (polyester layered roving fabrics), E020 (satin texture and epoxy matrix), 6FER5/Coremat/6FER5 and 6RT350/Coremat/6RT350 (sandwich type – in sequence skin/core/skin);
- Mode II testing: FER3 (roving texture and epoxy matrix), E020 (satin texture and epoxy matrix), and sandwich 6RT350/Coremat/ 6RT350.

By 12 or 6 are denoted the total number of layers of the multilayered specimens or the number of layers in the skin of the sandwich specimen. The initial delamination is inserted in the middle of the layered composites, or as two initial delaminations for the sandwich specimens in between both skins and the core.

The side of each specimen is coated with white tape and pencil marks are done every 2 mm from the tip of the initial delamination in order to measure better and follow damage and crack propagation. For the sandwich specimens engineering paper is glued on the lower skin as not to cover the core and obstruct the observation of the fracture processes in that area.

Additionally, tensile tests up to the ultimate failure were conducted on roving glass fibre fabric/polyester laminates 6FER5 and 6RT350.

Force–crosshead displacement diagrams are plotted in-situ by the acquisition system. Values of force, displacement, and time from the beginning of the test are measured at every 0,2 seconds (in *Figs. 4* and *5*), and a force–time or displacement–time plot is also possible. Initial crack length (delamination) is $a_0 = 50$ mm. At the beginning of the test the specimen is loaded at a constant crosshead speed of 0,5 mm/min [2] for $\Delta a = 10$ mm crack propagation, then 1 mm/min up to $\Delta a = 40$ mm. The crack propagation path is observed during the test and recorded on short VCR films for 2 seconds at an interval of 30 seconds. Unloading is done at 4 mm/min [3]. Subsequently, many other tests were done with a constant crosshead speed of 1 mm/min up to $\Delta a = 25$ mm followed by a rapid unloading.

In order to identify the delamination "initiation" one may consider: initiation by visual observation (delamination is seen to grow from the insert on either edge of the specimen), initiation determined by deviation from linearity (the point of non-linearity of the load–displacement curve), or initiation from 5% offset/maximum load (intersection of the load deflection curve with a line drawn from the origin and offset by a 5% increase in compliance from the original linear portion of the load–displacement curve; if the maximum load occurs before the point of intersection, then the maximum load and the corresponding displacement should be used to calculate G_c). Visual inspection of crack propagation onset can be correctly noticed with an optical microscope, but is highly operator dependent. Deviation from linearity looks to be a clear enough indication in our force–displacement curves but gives conservative values of the toughness, as in all our tests is reached at the lowest value of the force. Especially for sandwich specimens we believe that this point is not at all conclusive, as the later shape of the force-displacement diagram show some other interesting features. We have finally chosen the visual onset of delamination (VIS) as representative for the calculation of fracture toughness.

Results on mode I and mode II interlaminar fracture toughness

Mode I and mode II interlaminar fracture behaviour is quite different with respect to the material. Only as some examples, one test of each kind are presented hereby. Figures show the behaviour at crack initiation and stable propagation. *Figs. 4* and *5* are for interlaminar Mode I testing.

As there are so many values measured during the test (every 0,2 seconds) a moving average trend line is chosen to smooth the fluctuations in data, thus showing the trend of the variation more clearly. Crack initiation appears where the first change of the slope in the diagrams is visible. All jumps in the diagram are indicating sudden crack propagation. As specimens for both materials are the same, in comparing the previous figures it is evident that 12RT350 behaves in a more brittle manner, and when delamination initiation is produced this also means sudden crack propagation with Δa = 12 mm at a crosshead displacement d = 5,56 mm *(Fig. 5)*, but at a force about being the same as for 12FER5 when deviation from linearity appears *(Fig. 4)*. Such a stick-slip behaviour may in fact not be valid to establish the fracture toughness as the force-displacement curve needs to be continuous [2, 5].

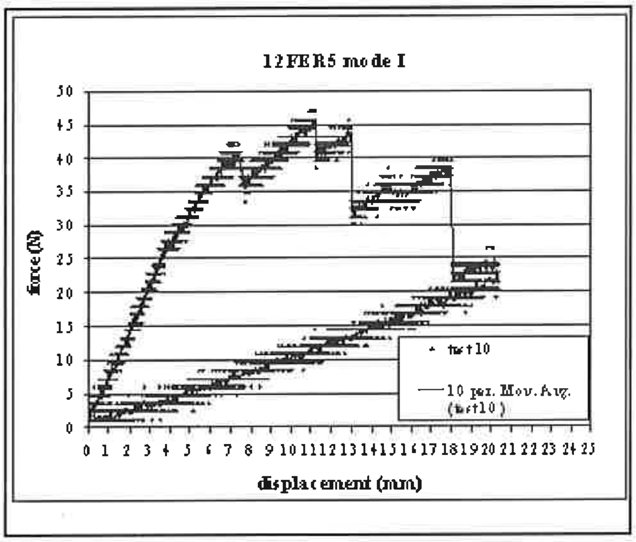

Fig. 4 Force–displacement diagram for Mode I tetsing on 12FER5 specimen
4. ábra. Az I. terhelési módban vizsgált 12FER5 próbatest erő–elmozdulás diagramja

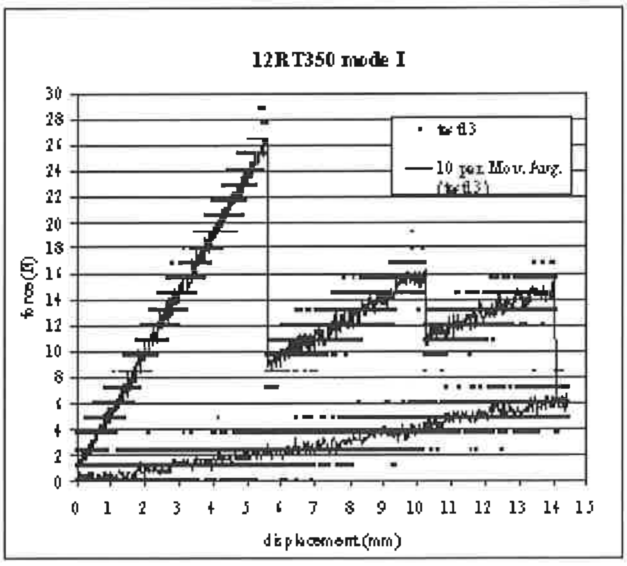

Fig. 5 Force–displacement diagram for Mode I testing on 12RT350 specimen.
5. ábra. Az I. terhelési módban vizsgált 12RT350 próbatest erő–elmozdulás diagramja

Mode II tests are sometimes capable of showing crack initiation, but in other cases only large deflection of the specimen in three-point bending (3PB) is to be obtained without any crack extension. As an example, in *Fig. 6*, delamination initiation starts at a crosshead displacement of about d = 7 mm, and this corresponds to a force of about 110 N, which will give a bigger value of the interlaminar fracture toughness than in Mode I – in fact this point is not far away from a deviation from linearity in the force-displacement curve. Also large deflections of the 3PB specimen are noticed; this means that a correction factor is also needed. Anyhow, for the ENF specimen care should be taken in setting the distance from the edges of the specimen till the supports in order to avoid the possibility of the specimen to slip at larger deflections. In *Fig. 6* this is to be seen and results in a sudden drop of the force at a crosshead displacement of about 24 mm.

As for a Satin/Epoxy specimen (here denoted E3 in *Fig. 7*) one may notice that the visual onset of delamination (VIS) is reached at a force greater than for the deviation from linearity. In fact the VIS point is very close to the one at which the maximum force is reached; from this point on the crack faces are in full contact, large deflection of the specimen appears, and we may even reach the failure of the specimen without any crack extension. In other tests there is no visible onset of delamination due to a complete closure of the artificial insert.

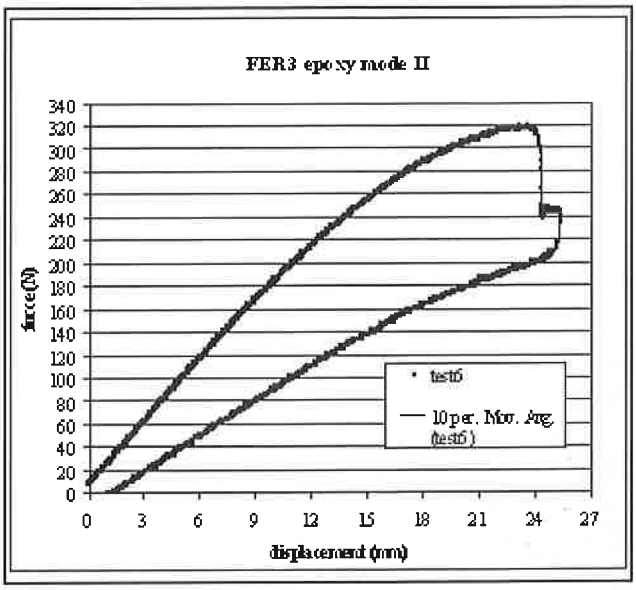

Fig. 6 Force–displacement diagram for Mode II testing on FER3/Epoxy material
6. ábra. A II. terhelési módban vizsgált FER3/Eposy anyag erő–elmozdulás diagramja

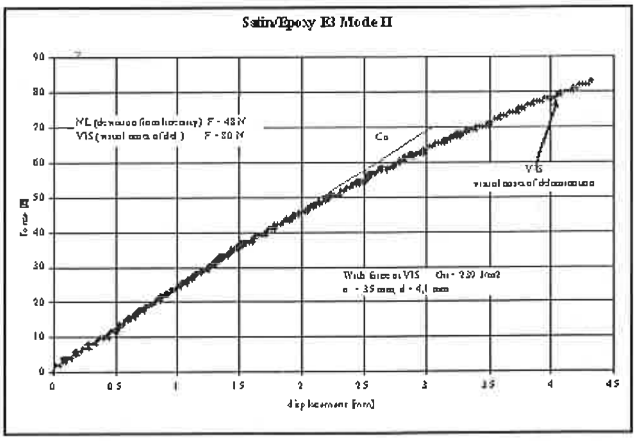

Fig. 7 Force–displacement diagram for Mode II testing on a Satin/Epoxy material
7. ábra. A II. terhelési módban vizsgált Satin/Eposy anyag erő–elmozdulás diagramja

Results on mode I and mode II intralaminar damage

When a sandwich type specimen is tested the artificial plastic insert is on both sides, in between the skins and the core (Coremat material). From the beginning, in Mode I – *Fig. 8*, the delamination on one side starts to open, and the crack will leave the interface and propagate slowly in the rigid foam of the core, as an intralaminar damage in front of the main interface crack. In the initial stages, a careful observation under the microscope will show that after a deviation from linearity, the appearance of microcracks and voids will coincide with the start of a "toughening" behaviour of the specimen. All the processes of intralaminar damage are becoming highly non-linear and, probably, this increase of slope in the force-displacement diagram is due to the local mechanisms of failure. With the force at VIS one can calculate the corresponding toughness of the core with the modified beam theory (MBT), or corrected beam theory (CBT), or experimental compliance calibration (ECC), [2].

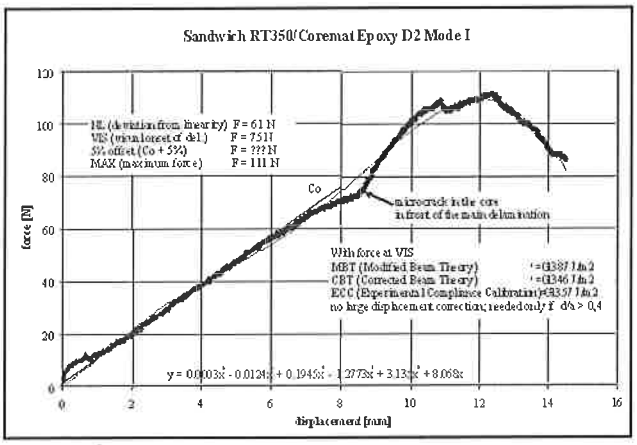

Fig. 8 Mode I force-displacement diagram for a sandwich RT350/Coremat/RT350 specimen

8. ábra. Az I. terhelési módban vizsgált RT350/Coremat/RT350 szendvics próbatest erő–elmozdulás diagramja

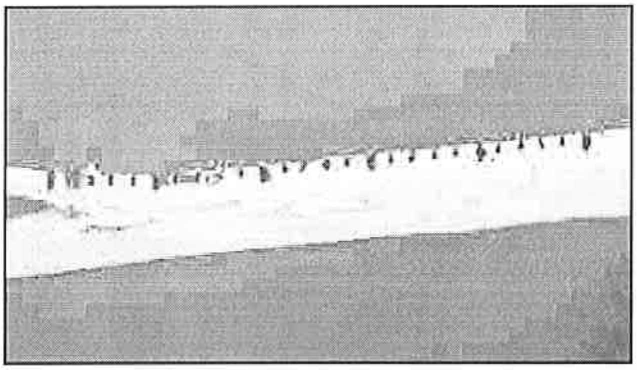

Fig. 9 Intralaminar matrix damage in a 6RT350/Coremat/6RT350 specimen

9. ábra. Rétegen belüli (intralamináris) matrix károsodás a 6RT350/Coremat/6RT350 próbatestben

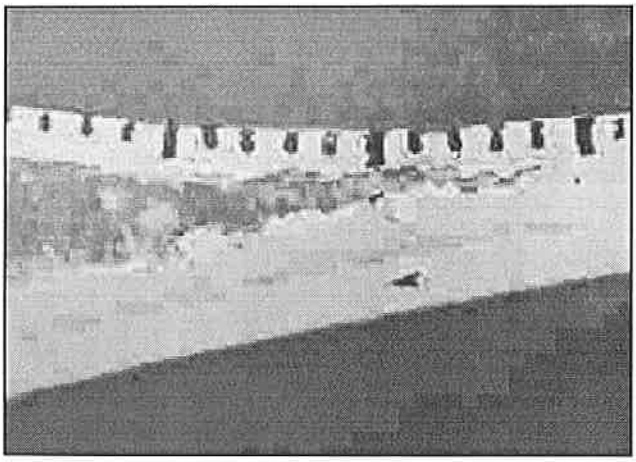

Fig. 10 Extensive damage and zigzag crack propagation

10. ábra. Kiterjedt károsodás és cikcakkban terjedő repedés

The damage extension and crack path are very interesting to be monitored, as they are characterized by crazing with initiation of the new microcracks in front of the main crack *(Fig. 9)*, followed by their coalescence in a zigzag pattern *(Fig. 10)*.

For Mode II tests it is again, in most cases, difficult to propagate the crack. Some voids appear in the core, in front of the artificial insert, and the force at which the visual onset of delamination is achieved is greater than the one at which the deviation from linearity is noticed in the force-displacement curve.

Conclusions

Interlaminar Mode I and Mode II fracture toughness experiments showed for Mode I tests pertinent results, thus giving clear evidence on the different behaviour of the tested materials; the stable crack propagation and the *R*-curves have to be further analyse in detail. For Mode II, it is in many situations difficult to drive the crack for an ENF specimen. It looks like a four-point bending test is more promising.

Intralaminar damage occurring in sandwich specimens is a complex phenomena which needs more experimental observation, and careful analytical and numerical modelling. A very interesting "toughening" behaviour of the DCB specimen is attributed to the local non-linear fracture and failure mechanisms.

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