Damage Evolution in Woven Composite Laminates under Fatigue Loading

M. Quaresimin and M. Ricotta

University of Padova - Department of Management and Engineering, Stradella S.Nicola 3, - 36100 Vicenza – ITALY
E-mail: marino.quaresimin@unipd.it, mauro@gest.unipd.it,

ABSTRACT. *The results of an experimental investigation oriented to the analysis of the fatigue damage evolution in plain woven composite laminates subjected to tension-tension and tension-compression fatigue loading are presented and discussed. T300/ET442 carbon/epoxy prepregs were used in the autoclave moulding of the laminates, which were laid up in three stacking sequences, namely* $[0]_{10}$, $[45]_{10}$ *and* $[0_3/45_2]_s$. *The main fatigue damage mechanisms, identified by means of microscopic observation, are: transverse matrix cracking, layer delamination and fibre failure. The sequence of appearance of the different mechanisms depends both on laminate lay-up and type of loading whereas the laminate final failure is generally controlled by a predominant damage mechanism only.*

INTRODUCTION

The analysis and evaluation of damage mechanisms and patterns during fatigue loading of composite laminates represent the starting point for the development of physically based, mechanistic life prediction criteria. Moreover, even for phenomenological criteria, the full understanding of the damage mechanics and the assessment of the critical damage modes are required to formulate a reliable model and to its validation.

The first, brilliant example of this approach is represented by the work of Talreja [1], where the *Fatigue Life Diagrams* were formulated after a detailed study and discussion on the damage mechanic of unidirectional laminates. The correlation between a macroscopic damage parameter, like the axial stiffness, and the fatigue life is another possible way to obtain semi-empirical models [2, 3]. Analytical models of the damage evolution can also be developed on the basis of experimental evidences [4, 5].

In this frame, the paper aims to investigate the fatigue damage mechanics in woven composite laminates. After an extensive analysis and description of the influence of laminate's lay-up and loading conditions on the damage patterns and evolution, the results are summarised with the help of the crack density curves which turned out to be useful tools for describing and explaining the fatigue damage mechanics.

MATERIALS AND TEST PROCEDURES

SEAL - TEXIPREG® CC 206 - ET442 (twill 2x2 T300 carbon fibre fabric, CIBA 5021 toughened epoxy matrix, V_f = 60%) prepregs were used in the laminates manufacturing. The laminates were produced by vacuum bag autoclave moulding with a curing cycle at 120° C and 0.6 MPa of pressure for 60 minutes. With the aim to investigate the failure modes of the material associated to fibre-dominated and matrix-dominated behaviour, three different laminates were considered, namely $[0]_{10}$, $[45]_{10}$ and $[0_3/45_2]_s$, and the specimens were subjected to tension-tension (R=0.05) and tension-compression (R=-1) fatigue loading.

The dimensions of the specimens, shown in Figure 1, are those suggested by ASTM D3039-00, D3479-96 and D3410-95 Standards and by the experimental results already presented in [6]. All the specimens were tested at room temperature on a servo-hydraulic MTS 809 machine with 10/100 kN load cells. The tests were carried out under load control, with a sinusoidal wave and a test frequency variable in the range of 1 o 10 Hz depending on lay-up and loading conditions. For the analysis of the fatigue damage evolution, the laminates were subjected to constant amplitude blocks of loading up to failure; at the end of each block damage patterns and crack density were analysed by means of microscopic observation of the polished edges of specimens.

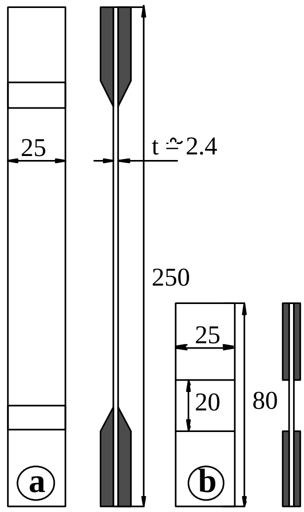


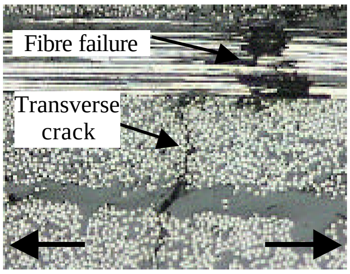
Figure 1. Specimens for:
a) tensile, b) compressive tests.

DAMAGE ANALYSIS

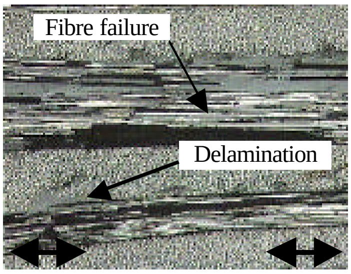
The analysis of the fatigue behaviour of the materials was carried out both at macroscopic and microscopic level: the macroscopic analysis provided the fatigue curves [6] and the hysteresis cycles [6, 7] while the microscopic observation of the polished edges of the specimens during the fatigue life allowed to identify damage patterns and main damage mechanisms for the different lay-ups and loading conditions. As usual, macroscopic and microscopic analyses turned out to be complementary and evidenced a strong fibre-dominated behaviour for the $[0]_{10}$ and $[0_3/45_2]_s$ lay-ups while the matrix properties seems to have more influence in the behaviour of the $[45]_{10}$.

The hysteresis cycles analysis, reported in [7] for the different materials, confirms an almost perfectly linear behaviour up to failure for the fibre-dominated laminates under tension-tension loading, while for the $[45]_{10}$ lay-up the behaviour, controlled by the matrix, is less linear also with an evident influence of the applied mean stress. Under tension-compression loading there is an evident loss of linearity for all the lay-ups indicating the more important role played by the matrix in the overall laminate behaviour, as well as that of the 45° layers, when present. The greater sensitivity to the fatigue damage is also evidenced by a change in the average slope of the hysteresis cycles as the fraction of life increases, corresponding to a remarkable axial stiffness reduction.

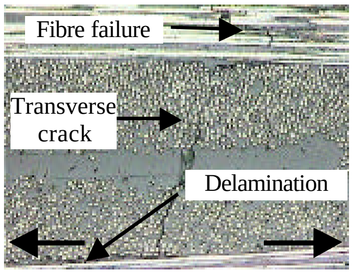
By means of microscopic observations, three main fatigue damage mechanisms have been identified: transverse matrix cracking, layer delaminations and fibre failure. The sequence of appearance of the different mechanisms depends, however, both on laminate lay-up and type of loading but not on the stress level, whereas a dominant damage mechanism only is responsible of the laminate final failure. Examples of the damage mechanisms are shown by the micrographs in Fig. 2 and a careful description of the fatigue damage evolution is reported in the following paragraphs for each lay-up.



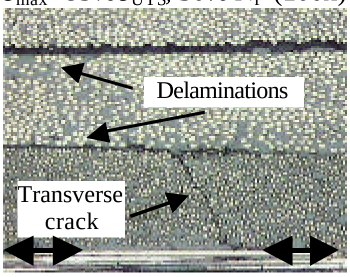
(a): $[0]_{10}$ R=0.05; σ_{max}=85%σ_{UTS}; 30% N_f (100x)



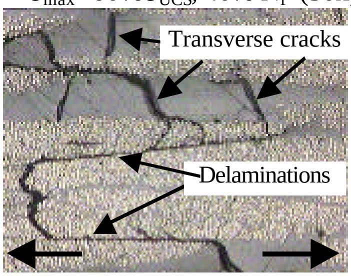
(b): $[0]_{10}$ R=-1; σ_{max}=60%σ_{UCS}; 40% N_f (50x)



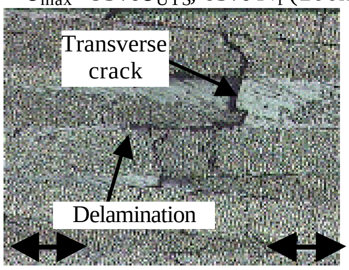
(c): $[0_3/45_2]_s$ R=0.05; σ_{max}=85%σ_{UTS}; 65% N_f (100x)



(d): $[0_3/45_2]_s$ R=-1; σ_{max}=65%σ_{UCS}; 50% N_f (100x)



(e): $[45]_{10}$ R=0.05; σ_{max}=55%σ_{UTS}; 83% N_f (50x)



(f): $[45]_{10}$ R=-1; σ_{max}=45%σ_{UCS}; 80% N_f (50x)

Figure 2. Microscopic observation of the main fatigue damage mechanisms.

$[0]_{10}$ Laminates

Under tension-tension loading the fatigue damage begins with the appearance of transverse matrix cracks (Fig.3a). In agreement with the observations already reported in [2], these cracks nucleate in the higher points of the weft's bundles, oriented at 90° with respect to the loading direction, and their density increases with the number of fatigue loading cycles. As it will be illustrated below, the transverse crack nucleation proceeds continuously during the fatigue life. The damage evolution continues with the failure of warp fibres and this mechanism characterises the laminate behaviour at failure. Due to the brittle behaviour of the fibres, on the specimen edges is visible a random distribution of broken fibres up to the moment when the damage concentrates in a specific section where the final, sudden failure takes place (Fig.3b). An almost complete absence of delaminations was observed in this case.

Under tension-compression loading, the beginning of the fatigue life is not characterised by a prevailing damage mechanism: at the same load level, in fact, delaminations can appear followed by the onset of transverse cracks or vice versa. The delamination growth can be driven by two distinguished effects, which induce intralaminar or interlaminar delamination, respectively. In the first case, the bundles waviness combined with the compressive load induce a localised buckling and out-of-plane stress components, which tend to separate weft from warp (point X of Fig. 4). In the second case, instead, the delamination grows from the higher points of the weft's bundles as the effect of stress concentration at the transverse crack tip (point Y of Fig. 4). The presence of the first delaminations induces further local buckling effects and increases the local stress level, with a rapid diffusion of the damage through the specimen and a deterioration of its strength properties. The overall effect is a greater sensitivity to the fatigue damage with respect to the tension-tension loading condition. In the second half of the fatigue life, even the fibres start to fail and this remains the mechanism which controls the final failure of the laminate.

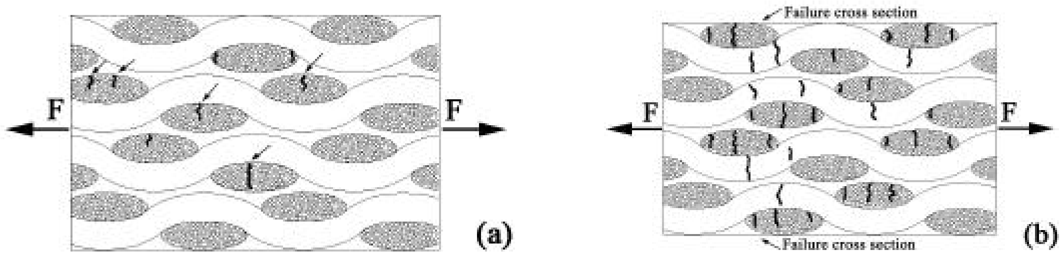


Figure 3. Damage patterns under tension-tension loading, lay-up $[0]_{10}$.

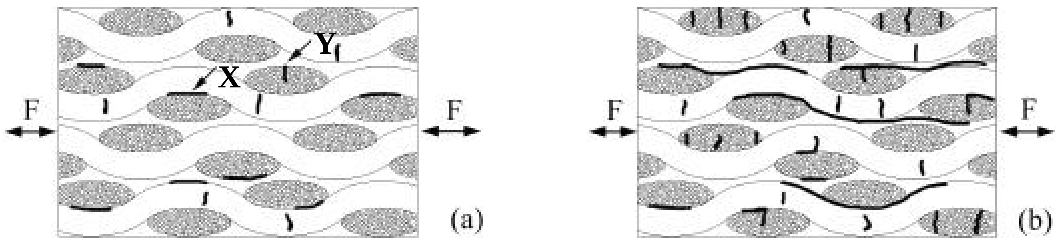


Figure 4. Damage patterns under tension-compression loading, lay-up $[0]_{10}$.

$[45]_{10}$ Laminates

Under tension-tension loading, the first damage mechanism to appear is the onset of transverse matrix cracks in the resin rich areas at the bundle apexes; growing along the bundle these cracks evolve, subsequently, in delaminations (Fig.5a).

At the beginning, the onset of new cracks is more evident than the delamination growth; with the increase of the fraction of life spent, the delaminations start to grow, both at interlaminar and intralaminar level, and also the transverse cracks start to coalesce in a unique, larger crack. The consequence of this particular damage evolution is a relative axial and angular displacement between bundles of warp and weft, with consequent development of both the delaminated zone and length of the cracks, which increase the distance between their surfaces. The damage localisation in a specific section of the specimen brings to the final failure that consists in a relative displacement of the bundles with a reduced quantity of broken fibres (Fig. 5b).

Under tension-compression loading, the fatigue damage evolution begins with the appearance of delaminations between warp and weft and between plies. The delamination growth and propagation are facilitated, in comparison to the case of tension-tension loading, by the combined effects of bundle weavings and the compressive component of the load cycle, and they are preponderant with respect to the formation of transverse cracks which appear again in the resin rich areas at bundles' apexes but only later, at about the 25% of the fatigue life. Once formed, the cracks propagate as described earlier for the tension-tension loading, inducing also further delaminations (Fig. 6b). With the evolution of the fatigue life, both the growth of delaminations and the coalescence of the transverse cracks increase, up to specimen failure. The failure happens in compression when the delamination prevails, in tension when the transverse cracks are more concentrated in a specific section. In both cases and as previously described, the failure consists in a relative displacement of bundles without broken fibres.

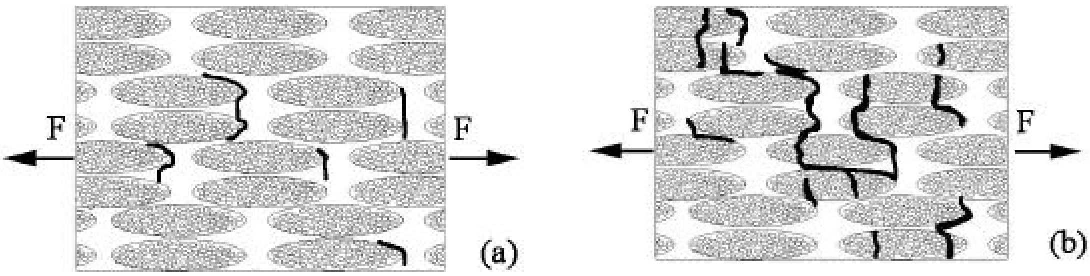


Figure 5. Damage patterns under tension-tension loading, lay-up $[45]_{10}$.

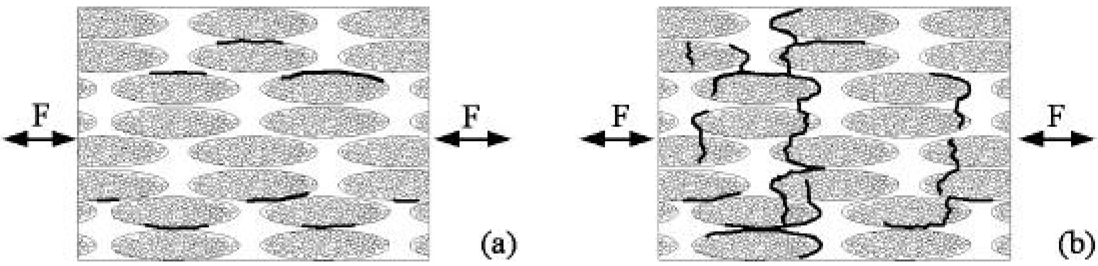


Figure 6. Damage patterns under tension-compression loading, lay-up $[45]_{10}$.

$[0_3/45_2]_s$ Laminates

In the case of tension – tension loading, after few fatigue cycles all the damage mechanisms previously described for the $[0]_{10}$ and $[45]_{10}$ laminates are active (Fig. 7a): in fact, both transverse cracks in the weft of the 0° layers and transversal cracks, with consequent growth of delamination, in the 45° layers appear. The peculiarity of this lay-up is the 0°/45° layer interface where, since the first cycles, an important delamination grows parallel to loading direction. With the increase of the loading cycles, the damage grows in the 0° layers and the delamination at the 0°/45° interface layers increases. On the other hand, the fatigue damage evolves slowly in the 45° layers, due to the reduced stress level. As previously discussed, the laminate behaviour is almost perfectly linear up to failure, as the in $[0]_{10}$ laminate, since the behaviour is controlled by the load-bearing 0° layers. The final failure takes usually place in a section where the crack density is greater with respect to others zones of laminate; as a result of the 0° layer failure, the applied load is transferred to 45° layers, which have neither enough strength nor the time to develop their typical damage mechanisms, resulting in a brittle failure.

Under tension-compression loading (Fig. 8), the specimen starts to delaminate in the inner 45° plies and this delamination grows all along the specimen. Also a reduced number of transverse cracks is present in the early phase of the fatigue life. Even in this case, in fact, the compressive component of the loading cycle tends to facilitate the delamination with respect to the onset of transverse cracks. The damage evolves with the growth of delamination and transversal cracks both in 0° and 45° layers. As for the tension-tension loading the damage mechanisms developed are those typical of the layers the laminate is constituted of; the mechanism controlling the laminate final failure remains the fibre failure.

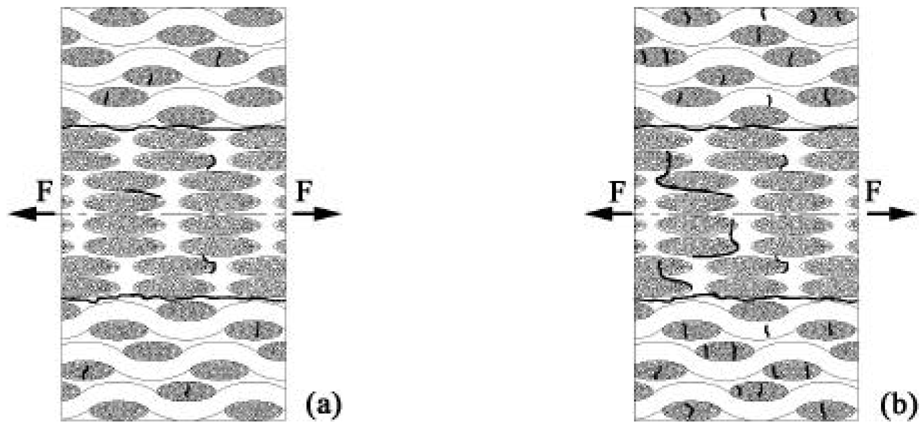


Figure 7. Damage patterns under tension-tension loading, lay-up $[0_3/45_2]_s$.

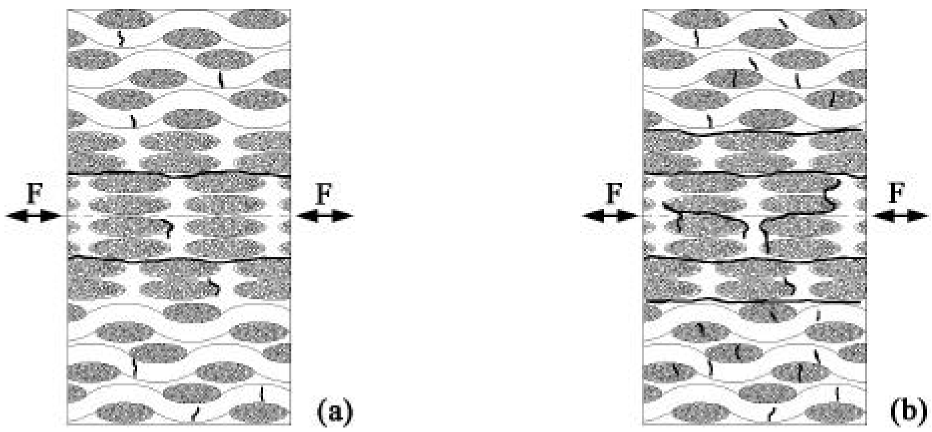


Figure 8. Damage patterns under tension-compression loading, lay-up $[0_3/45_2]_s$.

CRACK DENSITY ANALYSIS

The fatigue damage evolution can be characterised by the crack density curves, which present the density of the transverse cracks evaluated on the specimen edges as a function of the normalised fatigue life, as shown in Figure 9. The analysis of the different curves allows to identify the main damage mechanisms and to describe their evolution. The fibre-dominated behaviour, for tension-tension loading, is characterised by monotonically increasing curves, Fig.9a and Fig.9c, since the transverse matrix cracking is the more evident damage mechanism. For the $[0_3/45_2]_s$ laminates, the delamination gives a greater contribution to the fatigue damage with respect to the case of the $[0]_{10}$ laminates and this effect is clearly indicated by the lower crack density values of the $[0_3/45_2]_s$ laminates, at the same fraction of life.

The curve for the matrix-dominated $[45]_{10}$ laminates (Fig.9b) under tension-tension loading presents a particular trend, with a peak at the beginning of the fatigue life and a subsequent decrease. As previously described, a great number of transverse cracks nucleates in the initial fraction of life and the delamination appears only later; the apparent reduction of the crack density is simply the effect of coalescence of many cracks in a unique, larger fracture.

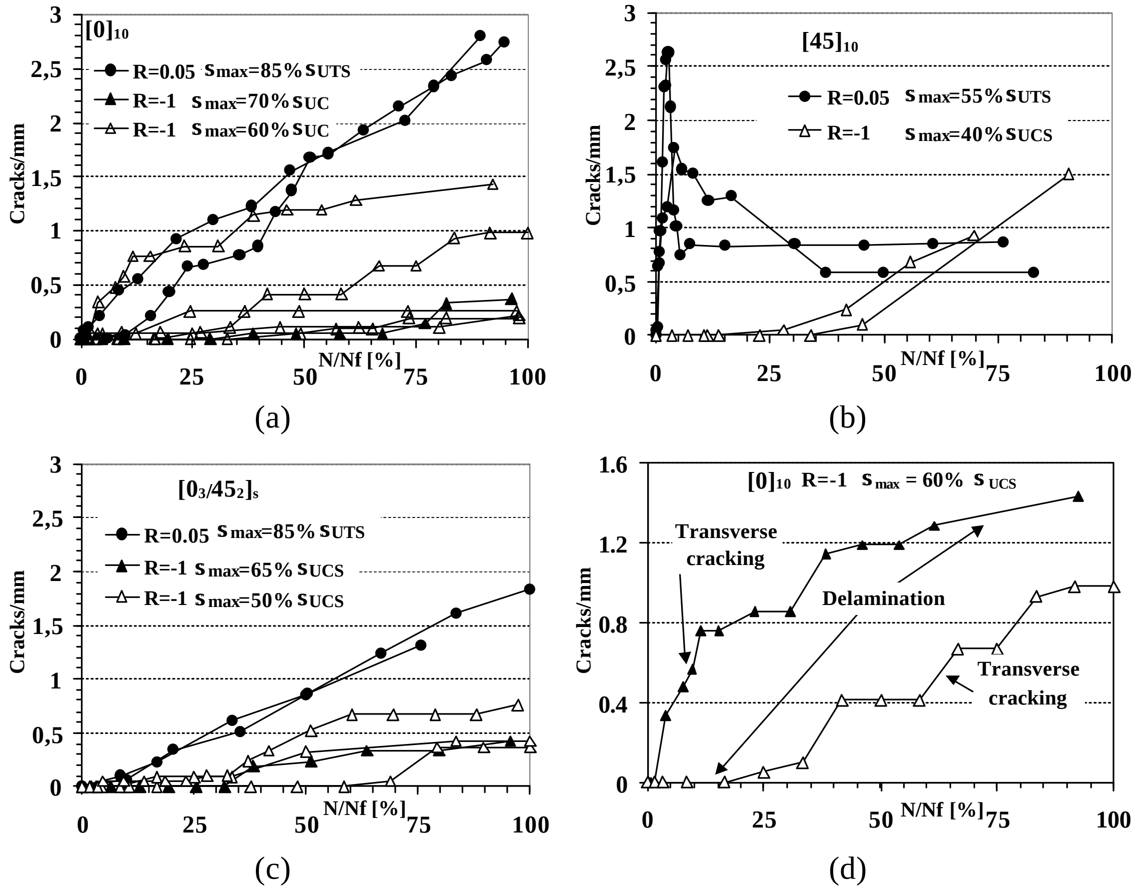


Figure 9. Crack density vs normalised fatigue life.

In the case of tension-compression loading (R=-1) the crack density trends are less influenced by the laminate lay-up. For all the lay-ups, in fact, the damage evolution is characterised in the first part of the fatigue life, by the onset and growth of delaminations, facilitated by the compressive component of the loading cycle and by the fabric architecture. This effect is quite evident in all the R=-1 curves: the almost flat trend in the first part of the fatigue life indicates the predominance of delamination onset and growth with respect to the formation of transverse cracks, which on the contrary appear later as shown by the rise of the crack density values in the second part of the fatigue life.

The crack density curves are also capable to describe the prevalence of one damage mechanism with respect to another: the trends recorded during tension-compression tests at the same stress level on two $[0]_{10}$ specimens, plotted in Fig.9d, clearly highlights the predominance, in the early fraction of life, of transverse cracking in one case and delamination in the other.

As a further consideration, it is interesting to note that the crack-density values at failure, measured in the present work, significantly differ from those reported in the literature, being greater than those measured for CFRP non-woven laminates $[0_2/90_2]_s$, $[0/45/90/-45]_s$, $[45/0/-45/90]_s$ in [8, 9] and for satin woven laminates $[0]_6$ in [10]. The reduced presence of delamination, due to both the fabric architecture and the toughened matrix, could be a possible reason of this difference.

REFERENCES

1. Talreja, R. (1981) *Proc. R. Soc. Lond.* **A378**, 461-475.
2. Pantelakis, Sp. G. and Kyriakakis Em. Ch. (1999) *Theoretical and Applied Fracture Mechanics* **32**, 37-46.
3. Van Paepegem, W. and Degrieck , J. (2002) *Composite Science and Technology* **62**, 687-696.
4. Akshantala, N. V. and Talreja, R. (1998) *Mechanics of Materials* **29**, 123-140.
5. Bartley-Cho, J., Lim, S.G., Hahn, H.T. and Shyprykevich, P. (1998) *Composite Science and Technology* **58**, 1535-1547.
6. Quaresimin, M. (2002) *Proceedings of 10th European Conference on Composite Materials* - ECCM10 Bruges - June 3-7, 2002.
7. Quaresimin M. and Ricotta M. (2002) *Proceedings of Manufacturing and Design of Composites* Piteå, Sweden June 17-18 – 2002.
8. Akshantala, V. and Talreja, R. (2000) *Materials Science and Engineering* **A285**, 303-313.
9. Ogihara, S., Takeda, N., Kobayashi, S. and Kobayashi, A. (1999) *Composites Science and Technology* **59**, 1387-1398.
10. Song, D. Y. and Otani, N. (1998) *Materials Science and Engineering* **A254,** 200-206.