RESEARCH ARTICLE

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# Toughened CFRPs via PEO Nanofibers: Effect of Water Ageing on Delamination

*Emanuele Maccaferri,* Jacopo Ortolani, Laura Mazzocchetti, Tiziana Benelli, Tommaso Maria Brugo, Andrea Zucchelli, and Loris Giorgini*

**Delamination is a common failure mechanism affecting composite laminates. Thermoplastic poly(ethylene oxide) (PEO) nanofibers are recently proposed for toughening carbon fiber reinforced polymers (CFRPs), obtaining promising results. In the present work, PEO-modified epoxy CFRPs underwent ageing in water for 1 month, and the interlaminar properties are assessed via double cantilever beam (DCB) and end-notched flexure (ENF) tests. The Mode I delamination behavior of both PEO-modified and unmodified commercial composite plates is compared. Water ageing slightly affects the mechanical properties of the nano-modified laminates, though the interleaved nano-reinforcement is water-soluble. The achieved results are very encouraging and pave the way to the use of PEO nanofibrous mats for hindering delamination in composite laminates.**

## 1. Introduction

Carbon fiber reinforced polymers (CFRPs) are largely used for their excellent mechanical properties and lightweight. Despite these benefits, they suffer from delamination, which may lead to the complete failure of the structure.[1] The integration of sensors, even nanostructured,[2] can help monitoring the composite health, but often the original interlaminar properties worsen.[3] For increasing the safety of structures and components, the improvement of the interlaminar properties is of paramount importance. Since two decades, nanofibers were proposed for hindering delamination;[4] Polyamides (Nylons) and polyesters (e.g., polycaprolactone, PCL) are the most used.[5] Recently, also rubbery nanofibers based on Nitrile Butadiene Rubber (NBR), (e.g., NBR/PCL,[6] NBR/Nomex,[7] and NBR-coated Nylon 6,6[8] nanofibers) were proposed as very effective toughening interlayers. More recently, poly(ethylene oxide) (PEO) nanofibers, usually used for biomedical applications,[9,10] were successfully proposed for reinforcing epoxy CFRP composite laminates.[11] While thermoplastics like Nylons and PCL are insoluble in water, PEO is water-soluble, making its use for reinforcing composite laminates potentially problematic.

In the present work, an epoxy CFRP laminate nano-modified with electrospun PEO nanofibrous mats was conditioned (aged) in water for 1 month and its delamination behavior compared with the ones of the commercial laminate and the 'as-produced' PEO-modified CFRP.

## 2. Results and Discussion

Delamination tests were carried out to evaluate the composite behavior under Mode I and Mode II loadings (**Figure 1**).

The performance of PEO-modified laminates, both 'as is' and after 1 month of conditioning (aged) in water, was compared with the unmodified commercial CFRP.

PEO nanofibers effectively toughen the epoxy laminate, as clearly displayed by load-displacement trends and confirmed by energy release rate (G) values. In particular, in Mode I (opening) the $G_I$ achieves a +41% in initiation and a +114% in propagation.

Water conditioning strongly affects the performance of the commercial CFRP, resulting in a halved $G_I$ after immersion for 1 month at room temperature, while the PEO-modified laminate maintains the delamination resistance high.

As previously demonstrated[11] by SEM images of DCB delamination surfaces, there is a sort of "coating" of the PEO (arranged into spheres) by the hosting epoxy resin, thus preventing PEO dissolution in water. Therefore, water ageing does not lead to reduced CFRP interlaminar properties.

E. Maccaferri, J. Ortolani, L. Mazzocchetti, T. Benelli, L. Giorgini
Department of Industrial Chemistry "Toso Montanari"
University of Bologna
Viale Risorgimento 4, Bologna 40136, Italy
E-mail: emanuele.maccaferri3@unibo.it

E. Maccaferri, J. Ortolani, L. Mazzocchetti, T. Benelli, T. M. Brugo, A. Zucchelli, L. Giorgini
Interdepartmental Center for Industrial Research on Advanced Applications in Mechanical Engineering and Materials Technology
CIRI-MAM
University of Bologna
Viale Risorgimento 2, Bologna 40136, Italy

T. M. Brugo, A. Zucchelli
Department of Industrial Engineering
University of Bologna
Viale Risorgimento 2, Bologna 40136, Italy

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/masy.202300253



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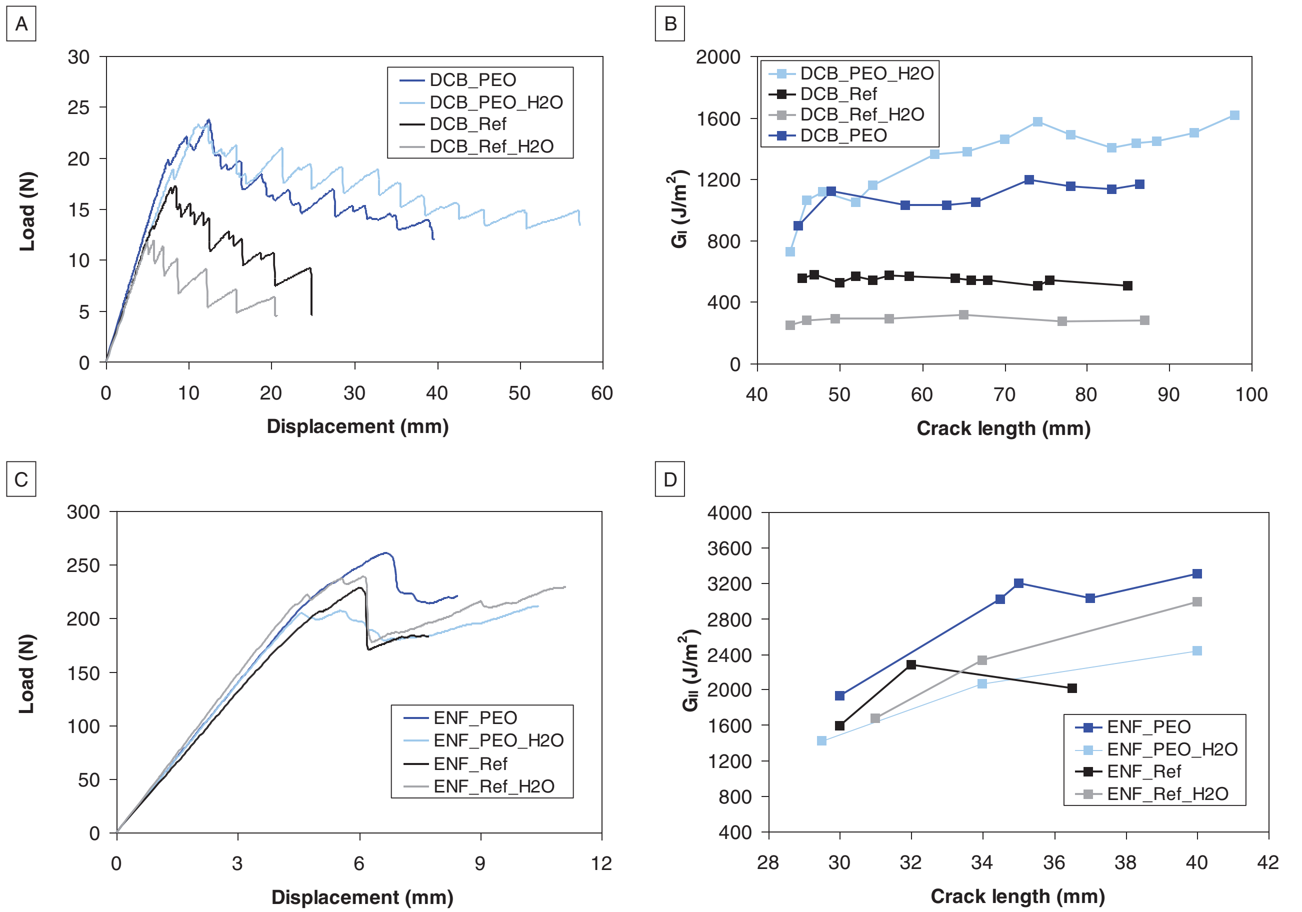


**Figure 1.** CFRPs' delamination behavior: top, DCB test (Mode I); bottom, ENF test (Mode II). (A,C) load-displacement profiles, (B,D) G vs. crack length.

The PEO effect on Mode II (sliding) delamination is practically absent after water immersion: the found $G_{II}$ is comparable with the one of unmodified CFRP.

## 3. Conclusion

The present work demonstrates that PEO nanofibers effectively hinder delamination in epoxy-based CFRP laminates, even after 1 month of material's water conditioning (ageing).

In particular, PEO addition can contrast the loss in Mode I delamination properties displayed by commercial CFRP (≈50% in $G_I$) conditioned in water, achieving a good toughening effect (up to +114% in $G_I$).

The effect of the nanofibrous polyether on the Mode II delamination is negligible after water immersion, while PEO nanofibers contribute to slightly increasing the $G_{II}$ of the 'as produced' laminate (up to +48%).

These results are very encouraging and pave the way to safely using PEO membranes to prevent delamination in epoxy CFRP laminates.

## 4. Experimental Section

Poly(ethylene oxide) (PEO), $M_w$ 400,000 Da, was purchased from Sigma-Aldrich and used without any preliminary treatment or purification. Plain weave carbon fabric, 200 g m$^{-2}$, in epoxy matrix prepreg (GG204P IMP503Z-HT, G. Angeloni s.r.l.) was used for the laminate fabrication.

PEO solution for electrospinning was prepared by dissolving the polymer (6% wt) in distilled water under magnetic stirring for a minimum of 2 h. The solution was electrospun using a four-needles electrospinning machine (Spinbow) equipped with a drum collector rotating at low speed to avoid nanofibers' alignment, using the following process parameters: flow rate 1.20 mL h$^{-1}$, electric potential 18 kV, distance 17 cm. The final membrane thickness is 40 μm on average.

CFRP panels for DCB and ENF tests were produced via hand lay-up, stacking 14 prepreg plies, and interleaving a nanofibrous mat in the central interface; a Teflon film was added as a crack trigger. Before laminate curing (2 h at 135 °C, 6 bar), the panels underwent a preliminary treatment of 2 h at 40 °C to favor the impregnation of the nanofibrous mat. Unmodified panels were also produced for the sake of comparison. The ageing of the CFRPs, both modified and unmodified, was carried out by immersing the specimens in distilled water at room temperature for 1 month.

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## Conflict of Interest

The authors declare no conflict of interest.

## Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Keywords

composite, electrospinning, interlaminar fracture toughness, nanofiber, polyethylene oxide, water ageing

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