Non conventional fracture tests of heterogeneous and anisotropic paperboard composites

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ABSTRACT. Non-conventional experimental procedures have been designed in order to characterize the overall constitutive properties and to follow the evolution of the damaging phenomena leading to fracture of heterogeneous and anisotropic paperboard composites. Specimens are monitored all along the tests, either by digital image correlation or by laser profilometry, in order to recover qualitative and quantitative information about the material deformation in the different considered experimental configurations. The interpretation of the results is supported by the numerical simulation of the tests.

SOMMARIO. Sono state concepite delle prove sperimentali non-convenzionali, che permettono di determinare le proprietà globali (su scala macroscopica) dei compositi laminati a base di carta qui considerati e che permettono altresì di analizzare la comparsa e lo sviluppo dei fenomeni di danneggiamento che inducono la rottura del materiale. La deformazione dei campioni sottoposti a prova è stata determinata mediante un monitoraggio continuo, basato su tecniche di profilometria laser o di correlazione d'immagini digitali che restituiscono informazioni quantitative, oltre che qualitative. L'interpretazione dei risultati sperimentali è stata inoltre supportata dalla simulazione numerica di ciascun test.

KEYWORDS. Fracture tests; Experiments; Modelling; Paperboard composites.

INTRODUCTION

Materials widely exploited in food packaging industry consist of layered composites, made of paperboard foils coupled with aluminium and polymer plies. Paperboard production process consists of the lamination of a network of interconnected fibres, which induces a preferential orientation in the lamination (machine) direction. Thus, the material presents anisotropic overall characteristics, which are transferred to the layered composite formed by further lamination. The final packaging material is also inhomogeneous, due to the different ply sequence provided, e.g., in correspondence of the cap opening zone. It must meet several functional requirements; in particular, the mechanical properties should be adequate to sustain the stresses induced by folding, forming and filling industrial processes without apparent damaging.

Non-conventional testing procedures have been designed in order to characterize the overall constitutive properties and to follow the evolution of the damaging phenomena leading to failure both of the paperboard and of the aluminium-polymer laminate that constitutes the cap opening area. In the considered experimental configurations, tests are continuously monitored either by digital image correlation or by laser profilometry, in order to recover qualitative and quantitative information about the displacement fields developing in the specimens. The interpretation of the experimental results and the identification of the local damaging processes and of their progressive evolution has been supported by the numerical simulation of the tests. The experimental and numerical methods exploited in this investigation are briefly summarised in the following.

EXPERIMENTAL PROCEDURES

The mechanical characteristics of paper – based materials is usually recovered from tensile tests, performed on strips of standard dimensions (15×180 mm) cut out of the investigated batch along directions parallel, orthogonal and rotated by 45° with respect to the lamination direction [1]. The test is ended by the fracture of the specimen, which systematically occurs orthogonally to the applied load. An overall measure of the material strength under a more general load combination, closer to that corresponding to the actual working conditions, is provided by the standardised bursting test [2], which inspired the non-conventional experimental set-up described in [3]. A prototype of the relevant instrumentation is at present available at the Stazione Sperimentale Carta, Cartone, Pasta per Carta (Milano, Italy).

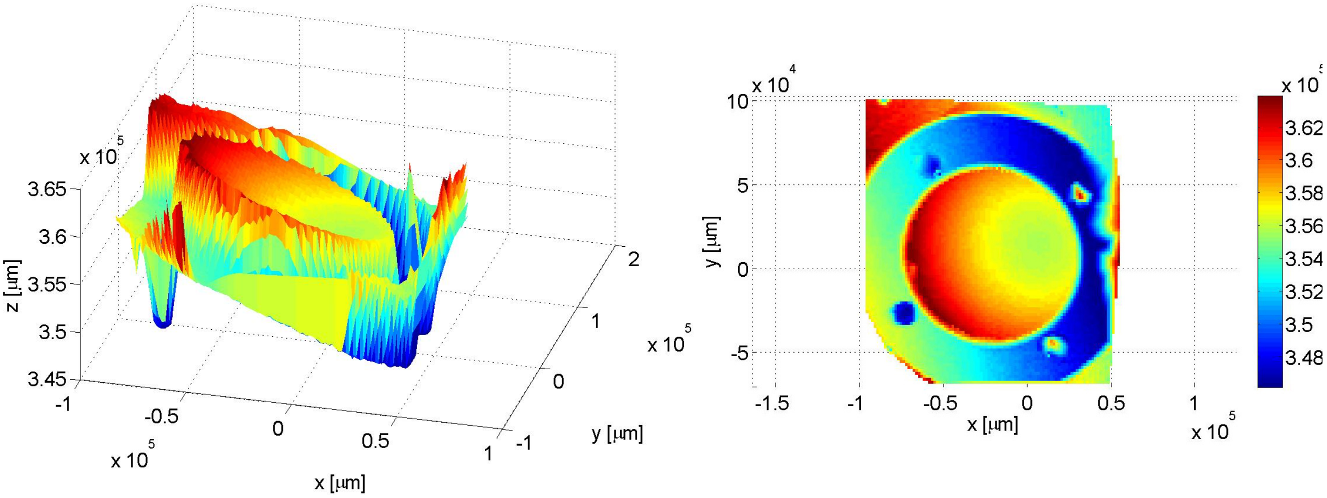

Figure 1: Graphical representation of the data returned by laser profilometry concerning the deformed foil hold by the partly visible circular bolt flange.

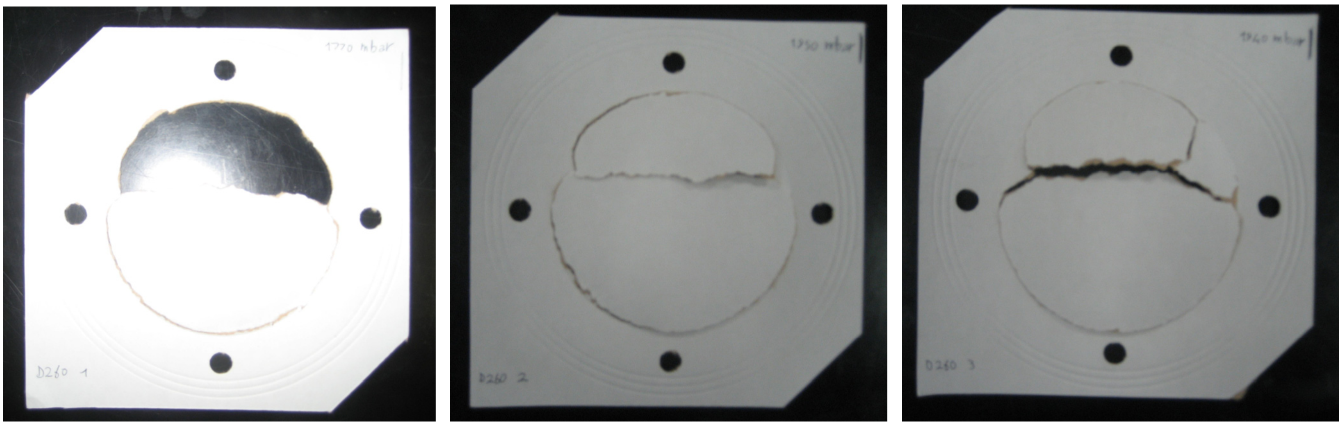

Figure 2: Failure of paperboard specimens.

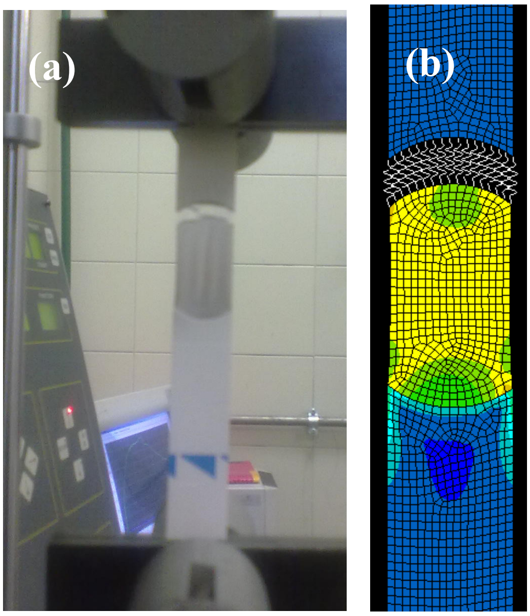

Figure 3: Failure of a heterogeneous specimen under tensile test (a) and the finite element simulation of the experiment (b).

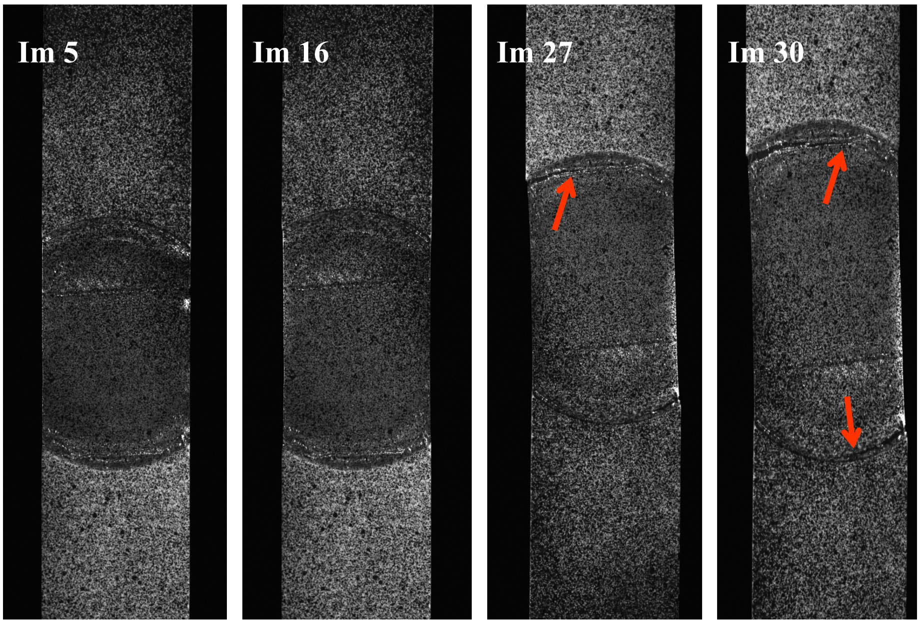

Figure 4: Sequence of digital images showing crack appearance and evolution during the test.

During the test, a foil specimen is inflated by a sequence of increasing pressure levels and the shape of the deforming membrane is determined by laser profilometry. The relevant geometrical data, stored in digitalized form as graphically shown in Fig. 1, may represent the basis of identification procedures; see, e.g. [4]. For the present application, the applied pressure has been increased up to the failure of the specimens, in most cases conforming with the fracture pattern shown in Fig. 2.

The inhomogeneous material, made of the paperboard composite containing an inclusion of the aluminium-polymer laminate that protects the packaging content in the cap opening area, can be tested with the same experimental setup. Further information about the fracture resistance of this material can be collected by tensile tests, performed on the specimens shown in Fig. 3(a). The experiment is monitored by a digital camera, which returns a sequence of images, partially represented in Fig. 4. The deformation history of the specimen can then be quantitatively evaluated by digital image correlation techniques, as in applications [5] and [6]. The whole displacement field can then be recovered as shown e.g. in Fig. 5, obtained by the comparison of images 5 and 16 in Fig. 4. It can be easily seen that most deformation concentrates in the area of the aluminium laminate inclusion, while the stiffer paperboard composite transfers the load undergoing an almost rigid body motion. The progressive appearance and evolution of the interfacial cracks, which lead to the ultimate failure of the specimen, are clearly evidenced in images 27 and 30 of Fig. 4 and in the corresponding deformation maps.

SIMULATION OF THE LABORATORY TESTS

The interpretation of the experimental results can be supported by the numerical simulation of the test, performed in all considered situations by exploiting the features available in a widely used finite element (FE) commercial code [7]. In particular, all analyses have been performed within the large strain / large displacement framework. Huber-Hencky-Mises and Hill's elastic-plastic constitutive models have been selected to simulate the response of the isotropic aluminium laminate and of the anisotropic paperboard material, respectively.

The FE model and a typical simulation result of the inflation test are represented in Fig. 6. The analysis permits to gather a better understanding of the load carrying mechanism in this strongly anisotropic material, which presents quite different mechanical behaviour along machine and cross direction (the former being stronger, stiffer and much less ductile than the latter) and on the alternative and competitive failure criteria that can be hypothesized in this situation.

Tensile tests, performed on the heterogeneous material strips visualised in Fig. 3(a), induce the fracture of the aluminium layer at the boundary with the paperboard composite, as also shown by the sequence of digital images in Fig. (4). This phenomenon does not necessarily imply complete material separation, since the polymer plies may still transfer some load. The process can be simulated by the FE model of Fig. 3(b), which implements non-linear spring elements with properly calibrated cohesive-crack models, as in [8].

CLOSING REMARKS AND FUTURE PROSPECTS

The combination of experimental information gathered from properly designed laboratory procedures and the numerical simulation of the tests constitutes the basis of inverse analysis techniques [9], which are widely exploited to material characterization purposes also in fracture mechanics context [10] and which constitute the future development direction of the present work. On the other hand, the selected numerical models can be validated (or improved) on the basis of the large amount of information collected during the experiments by the considered full-field monitoring techniques.

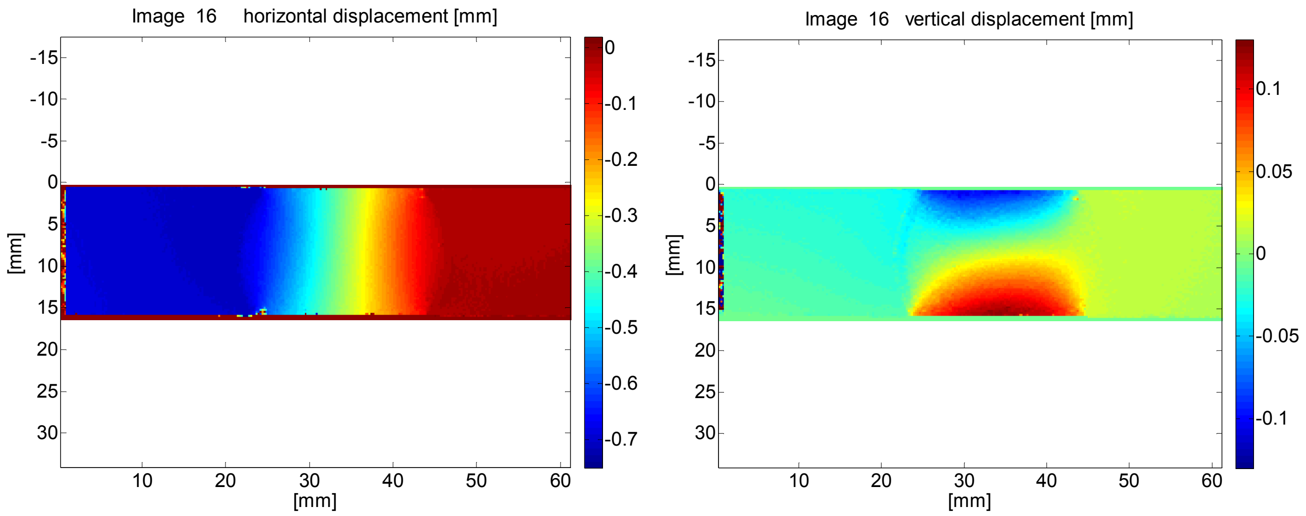

Figure 5: The displacement field in the heterogeneous specimen under tensile test, reconstructed by digital image correlation techniques (loaded specimen head on the left, fixed on the right).

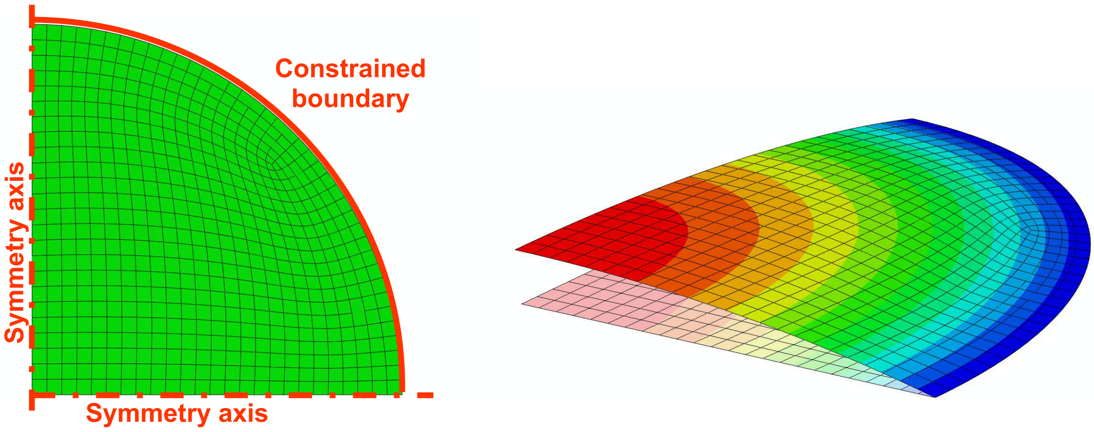

Figure 6: FE model and typical simulation result of the inflation test.

ACKNOWLEDGEMENTS

The financial and technical support, through a research grant and the re-design and realization of part of the membranometric instrumentation, of Tetra Pak Packaging Solutions (Modena, Italy) is gratefully acknowledged. Thanks are also due to our Colleagues at the Stazione Sperimentale Carta, Cartone, Pasta per Carta (Milano, Italy) for hosting the experiments in their labs and letting their equipment available for the present investigation.

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