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Mesoscopic Defects of Forming and Induced Properties on the Impact of a Composite Glass/Polyester

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Abstract**—**Forming processes induce residual deformations on the reinforcement and sometimes lead to mesoscopic defects, which are more recurrent than macroscopic defects during the manufacture of complex structural parts. This study deals with the influence of the fabric shear and buckles defects, which appear during draping processes of composite, on the impact behavior of a glass fiber reinforced polymer. To achieve this aim, we produced several specimens with different amplitude of deformations (shear) and defects on the fabric using a specific bench. The specimens were manufactured using the contact molding and tested with several impact energies. The results and measurements made on tested specimens were compared to those of the healthy material. The results showed that the buckle defects have a negative effect on elastic parameters and revealed a larger damage with significant out-of-plane mode relatively to the healthy composite material. This effect is the consequence of a local fiber impoverishment and a disorganization of the fibrous network, with a reorientation of the fibers following the out-of-plane buckling of the yarns, in the area where the defects are located. For the material with calibrated shear of the reinforcement, the increased local fiber rate due to the shear deformations and the contribution to stiffness of the transverse yarns led to an increase in mechanical properties.

Keywords—Defects, forming, impact, induced properties, textiles.

I. INTRODUCTION

COMPOSITE materials with an organic matrix are increasingly used for structures in many industrial fields such as shipbuilding, aeronautics and the automotive sector due to their high performance (strength/specific mass) and their anisotropy, which can be adapted to the mechanical loadings undergone. In addition, the rapid growth in shaping techniques for composite materials has contributed significantly to their widespread use. However, the characterization and mastery of the behaviors and damage processes of these materials, taking into account the effect of the manufacturing processes, remains a challenge when they are subjected to complex mechanical loadings.

The sensitivity of composite structures to low velocity impacts, which form part of these loadings, raises many concerns and restricts their scope of application. A structure can be exposed to shocks from various foreign bodies (of varying size, shape and rigidity) during the production, maintenance or service phases. These shocks generally cause internal damage that may not be visible on the surface of the structure, often with dramatic consequences on the mechanical performance of structures in service [1]-[3]. However, to our knowledge, studies in this area do not take into account the effect of shaping processes. In general, the composite materials tested are made under ideal conditions (stratification of undeformed fabrics and resin injection) without taking into account deformations and/or defects of the fibrous network. However, the fabric is mechanically loaded (tension, shear, bending, compaction, etc.) during shaping, which can lead to residual deformations as well as the appearance of local defects on the reinforcement [4]-[6], especially when the geometry of the part is complex.

Shaping defects can be divided in two types (Fig. 1): macroscopic defects (at the fabric scale) and mesoscopic defects (at the yarn scale). Macroscopic defects (wrinkles) have been widely studied in terms of phenomenology and their effect on the behavior of the final composite. Studies have shown that wrinkling, which is an out-of-plane phenomenon, is highly dependent on the coupling of shear/tension/bending/friction behaviors of the reinforcement [5], [7], [8]. This defect, appearing at the reinforcement scale, generates a significant over-thickness that affects the geometrical tolerances and aesthetics of the final part. Furthermore, studies have shown that the mechanical performance induced on the final composite drops drastically, reaching up to 40% loss of maximum breaking stress [9]-[11].

Mesoscopic defects appear locally at the yarn scale. Among these defects, we can distinguish yarn breakage, weave pattern heterogeneity, buckles, yarn waviness, etc. [4], [5], [9], [12]. The behavior induced by these mesoscopic defects has a significant impact on the service life of the composite [13]-[15]. However, few studies deal with this aspect even though these mesoscopic defects are among the most recurrent when shaping complex preforms [5], [6], [8], [16]. In addition, when dealing with multilayer forming, inter-ply friction substantially increases their quantity and extent [6], [15], hence the importance of understanding the mechanisms involved and characterizing the criticality of these defects on the behavior of the final composite.

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The present study addresses certain aspects of this problem by investigating the effect of buckling, a mesoscopic defect, and reinforcement shear on the composite impact behavior. Calibrated defects and shear were generated on glass fabric, taking care to reproduce the amplitudes observed during the forming of complex composite parts. Glass/polyester composite plates were manufactured by the contact molding process and then tested. The results and observations were analyzed and compared with those obtained on a healthy composite material in order to assess the effect of buckles defect and reinforcement shear on the behavior and damage generated.

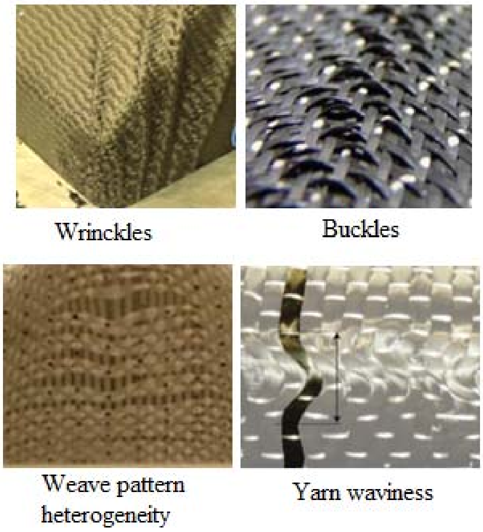


Fig. 1 Shaping defects: Macroscopic (wrinkles) and Mesoscopic

II. MATERIAL AND SPECIMEN PREPARATION

A. Material

The composite material used in this study is a glass fiber reinforced polymer (GFRP) from the company Iselman (Bejaïa, Algeria). It is mainly intended for the manufacture of marine navigation and fishing equipment. The same manufacturing process as that used by the company, namely contact molding, was used to produce composite plates with and without defects.

Three glass fabrics (two mats and one taffeta) were used to manufacture the laminates. The two mats have a real weight of 300 g/m^2 and 450 g/m^2. The taffeta has a weight of 800 g/m^2. A thermosetting unsaturated polyester resin was used to impregnate the various stacks.

To produce composite plates, a laminate of four layers, used to manufacture hulls and decks for 4.80 m fishing boats, was adopted. The order of the layers of this laminate is shown on Fig. 2. The impact tests were carried out on the outside face of the laminate (Fig. 2), which is subject to this type of loading during navigation.

B. Specimen Preparation

Plates with calibrated defects were produced in accordance with the stacking arrangement of the reference laminate. Defects were generated only on the taffeta fabric. The defects were generated in such a way as to reproduce the amplitudes observed in a feasibility study of a complex part for nautical applications. Plies were made with shear angles of 10°, 20° and 30° on each of the zones delimiting the buckle band as the amplitude of the defect is proportional to this shear (Fig. 3).

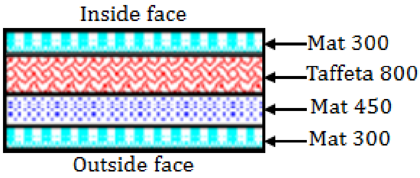


Fig. 2 Order of the reference laminate layers

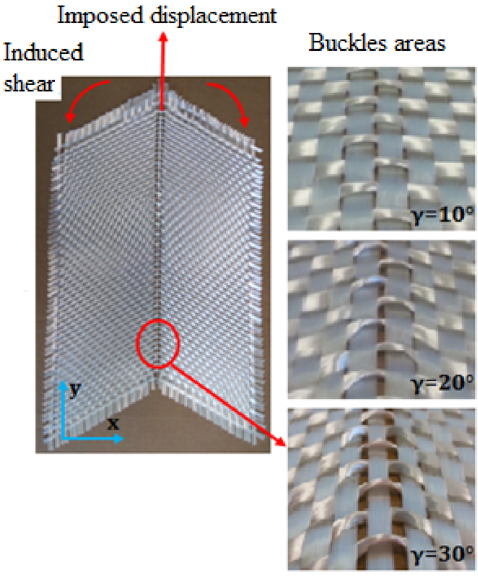


Fig. 3 Protocol for making calibrated specimens

To produce the specimens, healthy and calibrated laminates with defects and deformation were produced using the contact molding process and respecting the same order of plies as the reference material (Fig. 2). The final average thickness of the composite plates obtained was about 3.7 mm. Rectangular specimens for impact tests, measuring 150 mm x 100 mm according to ASTM D 7136/ASTM D 7136M-12 [17], were then cut out with a water jet on the plates. The longitudinal direction of these specimens corresponds to the direction of the warps. Three batches, labelled according to their area of provenance, were cut out

- Batch A: healthy specimens cut on the reference plates without defects.
- Batch AB: specimens cut from the band with the buckle defect.
- Batch AS: specimens cut on the sheared areas of the plates with calibrated defects.

III. RESULTS AND DISCUSSION

A. Reference Material

The reference laminate was tested for low impact energies to observe the evolution of its response as a function of the incident energy. Fig. 4 highlights the variation in the impact properties according to the three energies used 10 J, 20 J and 30 J.

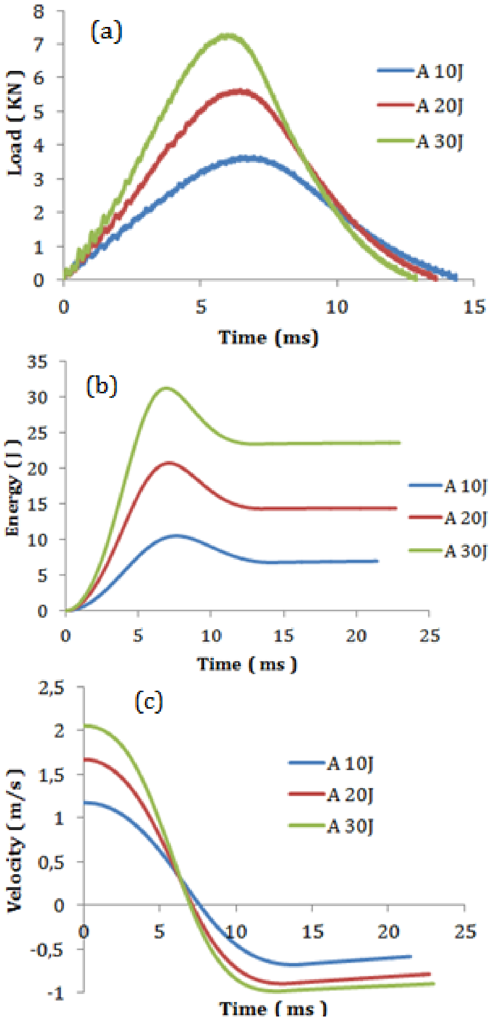


Fig. 4 Evolution of load vs. time (a), energy vs. time (b), velocity vs. Time (c), for the three levels of impact energy

The loading and unloading regions were almost symmetrical (Fig. 4 (a)), suggesting that the contact duration is almost unchanged. Higher impact velocities induced a larger impact force and therefore a larger deformation. This indicates that the impact velocity dominates the impact energy but has little effect on the contact duration, which is governed by the material properties.

The rising part of the curves (Fig. 4 (b)) corresponds to the loading phase of the material up to a maximum value equivalent to the impact energy. The impactor meets the sample and its velocity decreases until it reaches 0 m/s (Fig. 4 (c)). At that time, the impactor has reached its maximum displacement. Following this, the impactor bounces back and its velocity becomes negative (Fig. 4 (c)), which generates a decrease in energy corresponding to the unloading phase initiated by the bouncing (Fig. 4 (b)). It can also be seen that after about 14 ms the energy stabilizes, indicating that the impactor has lost contact with the sample. Some of the energy has been restored in an elastic way. The residual energy then corresponds to the energy dissipated by the damage of the laminate.

Visual analysis of the impacted areas highlights damage of the matrix and delamination areas. In addition, several fiber breakages appear from the impact energy of 20 J and 30 J (Fig. 5). Damaged areas' extent is greater in the weft direction. This is due to the presence of gaps between the wefts (and thus resin-rich regions) and the boundary conditions applied in their direction (clamping system with a rectangular window) which promotes the propagation of delamination. In contrast, the impacted face has no visible macro-cracks on the surface.

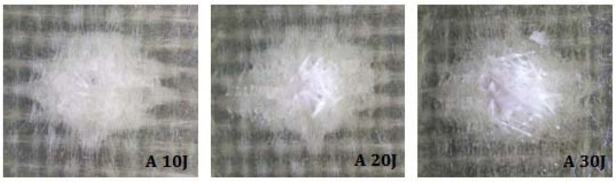
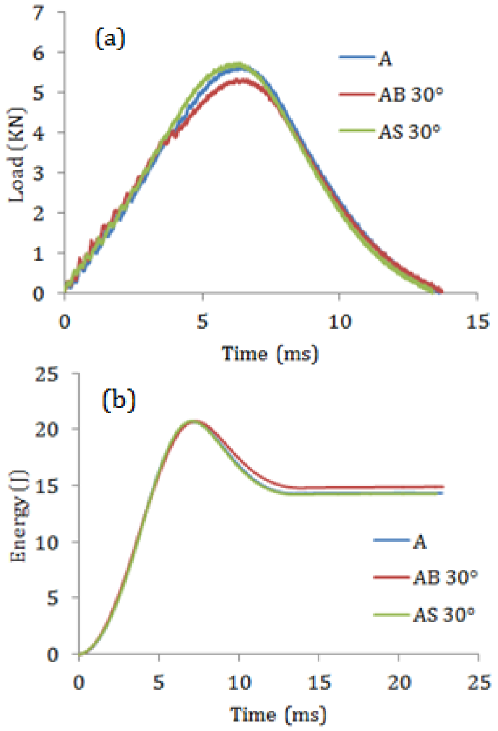


Fig. 5 Evolution of impact damages as a function of the impact energy for batch A

B. Comparison between Healthy Materials and Materials with Calibrated Defects



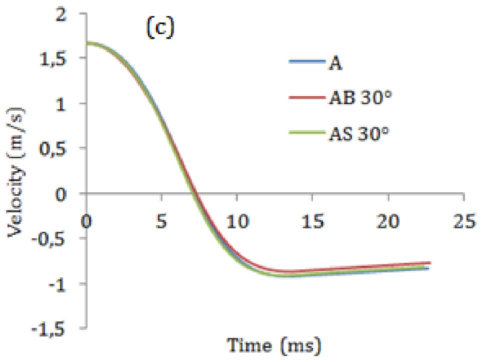


Fig. 6 Comparison of healthy material behavior/with defect/with shear: load vs. time (a), energy vs. time (b), velocity vs. Time (c)

After characterizing the behavior of the healthy composite, impact tests were conducted to characterize the properties induced by the calibrated buckling (AB samples) as well as the shear deformation (AS samples) of the reinforcement. This effect was characterized at 3 amplitude levels corresponding to shears of 10 °, 20 ° and 30 °. The comparison was done at impact conditions of 20 J.

Fig. 6 presents the impact behavior of samples with calibrated defects and shear obtained for the 30° configuration (AB30° and AS30°) compared to those of the healthy material (A). Despite almost symmetrical behavior, there is a variation in the maximum load (Fig. 6 (a)): the maximum load of the specimens with shear reinforcement (AS) is slightly higher than that measured for the reference laminate (A), which is attributed to the increase in the stiffness of the laminate. This increase in stiffness is attributed to the effect of reinforcement shear which induces an increase in fiber content (by 6.68% in this case) associated with the contribution of transverse yarns to mechanical behavior in the longitudinal direction of the material. For healthy specimens (batch A), only the yarns in the longitudinal direction contribute to the stiffness of the material in this direction, while for specimens in batch AS, the transverse yarns, being reoriented, provide additional stiffness. This is the case even if the evolution of the incidence velocity remains substantially unchanged (Fig. 6 (c)).

The trend is reversed for specimens with buckling defects (AB) where a maximum load reduction of about 5% was measured (Fig. 6 (a)). This indicates that the effect of buckling is not negligible on the mechanical impact behavior of the composite as is also the case for fatigue behavior. This effect is attributed to the nature of the defect, which consists of a local disorganization of the fibrous network, with a reorientation of the fibers following the out-of-plane buckling of the yarns. In addition, this reorganization creates a local fiber impoverishment that favors resin-rich areas (Fig. 3) at the point of impact and along the center line of the sample. All these phenomena lead to a decrease in the material's mechanical performance because the taffeta, with defects, is subjected to a tensile load as it is located on the upper part opposite the impacted side (Fig. 2).In addition, this drop in performance is associated, by the nature of the defect, with a greater predisposition to damage leading to higher absorbed energy for the laminate with defects than for the healthy material (Fig. 6 (b)).

Visual analysis of the impacted areas of the specimens highlights matrix breakage and delamination areas, as well as fiber breakage. This fact was verified with the help of the SEM observations, which were made in the thickness of the samples along planes passing through the center of the buckled regions. These observations showed the presence of significant damage, located on the opposite side, with numerous fiber breakages, multiple cracks and fragmentation of the matrix, combined with a fiber/matrix debonding (Fig. 7). These fractographies also highlighted the presence of resin-rich areas whose extent increases with the amplitude of the buckling for batch AB and fiber rich areas for batch AS.

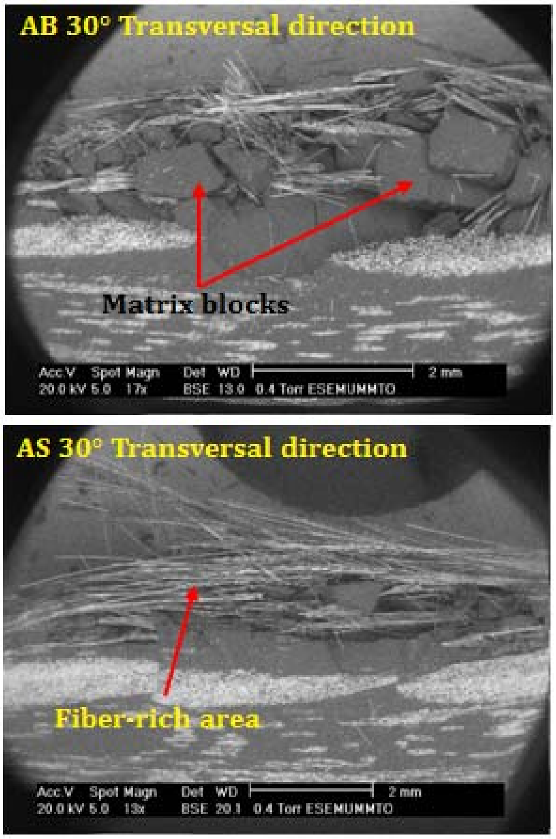


Fig. 7 SEM observation of specimens with buckles defect (AB) and shear (AS)

IV. CONCLUSION

The results of the impact tests showed that buckling has a negative effect on the elastic parameters of the material. This effect is the consequence of a local fiber impoverishment and a disorganization of the fibrous network, with a reorientation of the fibers following the out-of-plane buckling of the yarns, in the area where the defects are located. The loss of mechanical performance increases with the amplitude of the defect. On the other side, the reinforcement shear had a beneficial effect on the impact properties of the laminate, which was attributed to the increase in local fiber density.

The SEM observations made on the impacted specimens highlighted significant damage in the out-of-plane mode, both in the case of specimens with buckles and those with shear, relative to the healthy material where in-plane damage predominates. The damage is proportional to the amplitude of the defects and the shear, and leads to less circular damaged areas because of their propagation along the fibrous network that has been disorganized.

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