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Mechanical Performance of Incrementally Formed Flax Fiber-Reinforced Polypropylene Caps

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Abstract. Incremental forming represents a versatile and cost-effective alternative to conventional sheet forming processes. In recent years, its application has been extended to polymers and composite materials. Among these, natural fiber-reinforced thermoplastics offer several advantages, as natural fibers are widely available, contribute to the semi-biodegradability of the composites, and serve as effective reinforcements for polymer matrices. This experimental study examines the mechanical properties of flax woven fabric-reinforced polypropylene composites, fabricated via compression molding, and their suitability for producing spherical caps through cold incremental forming. A range of features was investigated to assess the effectiveness of incremental forming on these biobased composites and to compare the mechanical performance of undeformed and deformed laminates.

Introduction

Incremental sheet forming is a manufacturing technique originally developed as an alternative to conventional forming methods, particularly for shaping flat metal sheets into complex three-dimensional profiles [1]. The core principle of this technique involves the progressive deformation of a clamped sheet of material by a forming tool, which is controlled by a computerized numerical control (CNC) machine. The tool follows a programmed path, gradually shaping the sheet into its final geometry [2]. In recent years, its scope has expanded to include polymers and composite materials, broadening its applicability to lightweight and sustainable engineering solutions.

Composite materials are used in various fields, thanks to their outstanding properties [3]; the use of natural fibers as an alternative to conventional synthetic reinforcements (particularly glass and carbon fibers) has garnered increasing attention in both research and industrial contexts, owing to their low-cost, biodegradability, renewability, and non-toxicity [4-6].

Hemp and flax are among the most widely available and commonly used natural fibers in Europe. Their complex microstructure [7, 8] contributes to their superior mechanical properties, making them the strongest and stiffest natural fibers [9], and thus ideal candidates to produce biocomposites [10].

Polypropylene, alongside polyethylene and polyvinyl chloride, is among the most used polymer matrices for natural fiber composites [11]. As the world's second-most widely produced synthetic polymer, polypropylene is extensively employed across various industrial sectors, including the fabrication of advanced composite materials [12, 13].

A previous study by the authors [14] demonstrated the feasibility of incremental forming (conducted at room temperature and without the use of dedicated dies) for natural fibre-reinforced polymer composite laminates. This enabled the fabrication of components that are typically challenging to produce due to the intrinsic characteristics of the materials involved. Moreover, the low forming force requirements suggest promising implications for energy efficiency, aligning with sustainable manufacturing objectives.

This study presents an experimental campaign focused on the manufacture of spherical caps via incremental forming with a partial counter die, starting from flax fiber-reinforced polypropylene laminates. The forming process was conducted without localized heating [15] to preserve its operational flexibility and ease of implementation. The composite laminates were produced through compression molding using flax woven fabrics, without the application of fiber treatments or coupling agents, thereby maintaining the environmental advantages associated with natural fibers.

Following the mechanical characterization of the laminates, the study investigates key aspects of the incremental forming process applied to biocomposites, including geometrical accuracy, forming forces, power, and energy consumption, as well as the post-forming mechanical performance of the spherical caps. These components are considered for potential applications such as the shaping of stiffening ribs in structural panels in the automotive, aerospace, and marine sectors [16].

Materials and Methods

Laminates consisting of polypropylene reinforced with flax fibers in fabric form, with a thickness of 2.2 mm, were manufactured using neat polypropylene films (supplied by GDC S.r.l.; thickness: 0.5 mm) and a woven flax fabric (supplied by FIDIA S.r.l. - Technical Global Services; areal density: 320 g/m^2). The fabric, whose main properties are detailed in [14], was not subjected to any chemical or surface treatment prior to processing. To eliminate residual moisture, it was dried at 60°C for 12 hours before the molding procedure.

The laminates were produced via compression molding using a conventional hydraulic press. The stacking sequence consisted of five layers: the outermost layers (two on each side) were polypropylene films, while the central layer was a woven flax fabric. The molding process was conducted at a temperature of 200°C, with a total cycle time of 300 s (comprising an initial dwell time of 120 s) followed by the application of 4 MPa pressure for 180 s through the press plates.

The resulting reinforced laminates, containing 15.6 wt.% flax fiber, were characterized by tensile testing. Compared to neat polypropylene [17], the reinforced laminates exhibited enhanced tensile properties, as summarized in Fig. 1.

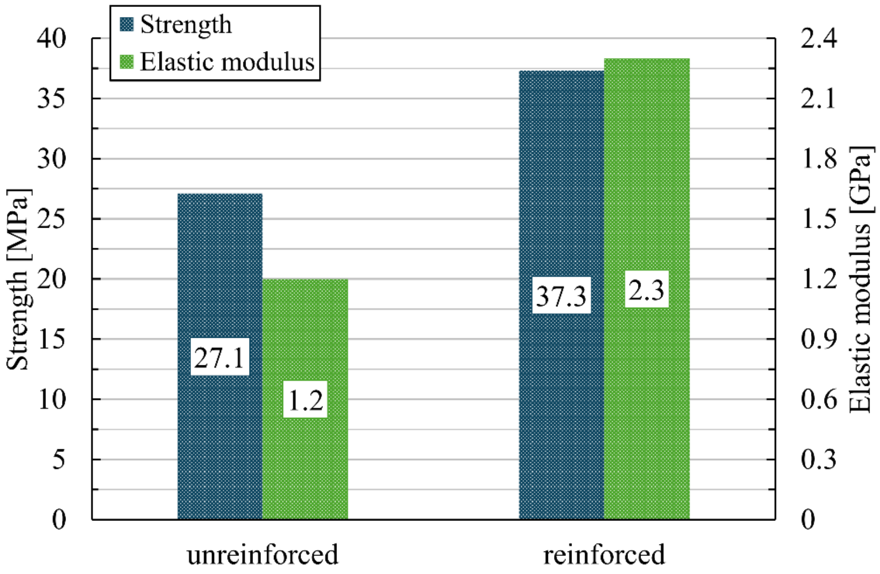

Fig. 1. Tensile properties of unreinforced and reinforced laminates

Spherical caps with a base radius of 40 mm and a polar angle of 50° were fabricated from the flax-reinforced polypropylene laminates using cold negative incremental sheet forming. This kind of geometry, with decreasing wall angle and deformation states, was chosen because it can be used for applications such as shaping stiffening ribs for different applications and does not show formability problems (the ISF process applied to the material under investigation highlighted a maximum wall angle of less than 50° [14]). To mitigate bending defects near the base of the caps, a partial counter die was employed, consisting of a hollow cylinder with internal and external diameters of 80 and 100 mm, respectively.

The forming process was carried out using a non-rotating stainless-steel stylus with a hemispherical head of 10 mm in diameter, which progressively deformed the laminate. It was constrained by a clamping frame with a square working area of 100 × 100 mm^2. The forming tool was operated by a C.B. Ferrari high-speed four-axis vertical machining center at a nominal feed rate of 1000 mm/min, following an alternating helical toolpath with 1° angular step-down (i.e. the angular increment per full revolution). This strategy significantly reduced the likelihood of twisting [18], as previously observed in the incremental forming of metallic [2] and polycarbonate sheets [19]. The process was conducted under lubricated conditions using Boelube 70104 (100A) lubricant (supplied by Orelube) to minimize the risk of failure and defects.

A schematic representation of the forming setup is provided in Fig. 2.

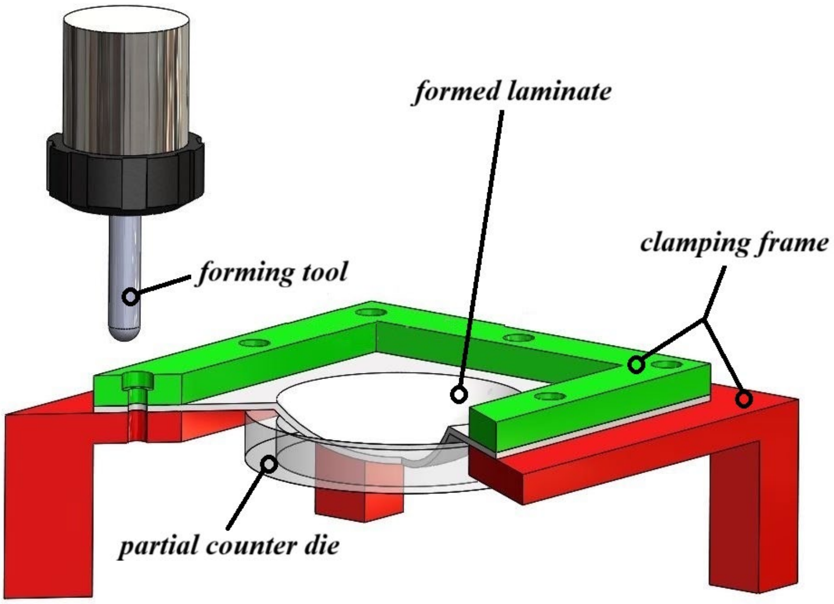

Fig. 2. Schematic of the incremental sheet forming process

Several parameters were evaluated, including geometrical accuracy, forming forces, power and energy consumption.

Geometrical accuracy was assessed by comparing the shape of the formed caps to the target geometry using a Zeiss DuraMax coordinate measuring machine (measurement accuracy: 2.4 µm) and Calypso software.

Forming forces were recorded at a sampling rate of 50 Hz using a K-MCS10 multicomponent sensor, integrated with the QuantumX MX840B data acquisition system and Catman Easy AP software. These force measurements were also used to calculate power and energy consumption, following the methodology described in a previous study by the authors on the incremental forming of flax and hemp fiber-reinforced polypropylene composites [20]. This approach enables estimation of the actual energy required for the forming process, which constitutes only a small fraction of the total energy consumed (most of which is attributed to auxiliary functions of the equipment [21]).

To compare the mechanical performance of undeformed and post-formed laminates, flexural and penetration tests were also conducted.

Flexural tests, including both simply supported and fixed-end configurations, were performed using an MTS Alliance RT/50 universal testing machine. Loading and supporting pins with a diameter of 10 mm were employed. For the fixed-end tests, the supporting pins were replaced by the clamping frame used during the incremental forming process, with only the two edges parallel to the loading pins being constrained.

Penetration tests were conducted using a spherical cap with a base radius of 20 mm and a polar angle of 70°, employed as the loading tool to test specimens constrained along their periphery. The remaining equipment was identical to that used for the incremental forming tests. Failure zones resulting from these tests were examined using a Hirox RX-100 digital microscope.

All tests were performed on specimens with a square working area of 100 × 100 mm^2. The testing machines imposed a vertical displacement on the loading tools at a nominal speed of 60 mm/min.

Results and Discussion

Two tests for each different case were performed; Given the limited variability observed among repetitions, only representative curves and average values of the investigated features are reported for the sake of conciseness. The incremental forming process was successfully conducted without the occurrence of typical defects such as twisting and wrinkling. An example of a formed spherical cap is shown in Fig. 3a, while Fig. 3b presents a comparison between the actual and target profiles. Two key geometrical features are highlighted: the deviation in maximum height and the gap observed at the intersection between the base of the cap and the flange. The components exhibited good surface quality and satisfactory geometrical accuracy, especially considering the cold nature of the process and the use of a partial counter die rather than a dedicated forming die.

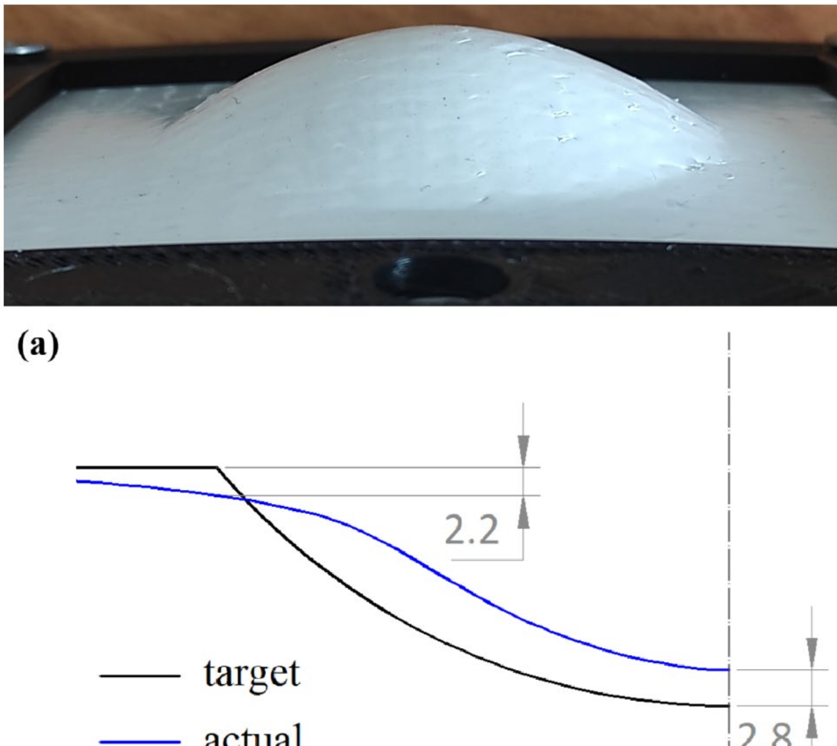

Fig. 3. Spherical cap (a) and comparison between actual and target profiles (b)

The incremental forming process was characterized by low forming forces, with a maximum value of 536 N. Consequently, both the peak power and the energy consumption were limited, amounting to 2 W and 563 J, respectively. These values indicate non-severe operating conditions, which enable the use of non-dedicated tools and machinery for the incremental forming of biobased composite materials.

Simply supported flexural tests were performed on undeformed laminates and deformed laminates with specimens oriented both concave side up and concave side down (see schematic in Fig. 4a). As shown in Fig. 4b, the concave side up configuration resulted in superior mechanical performance, with a maximum load of approximately 120 N, compared to about 70 N for both the concave side down and undeformed configurations.

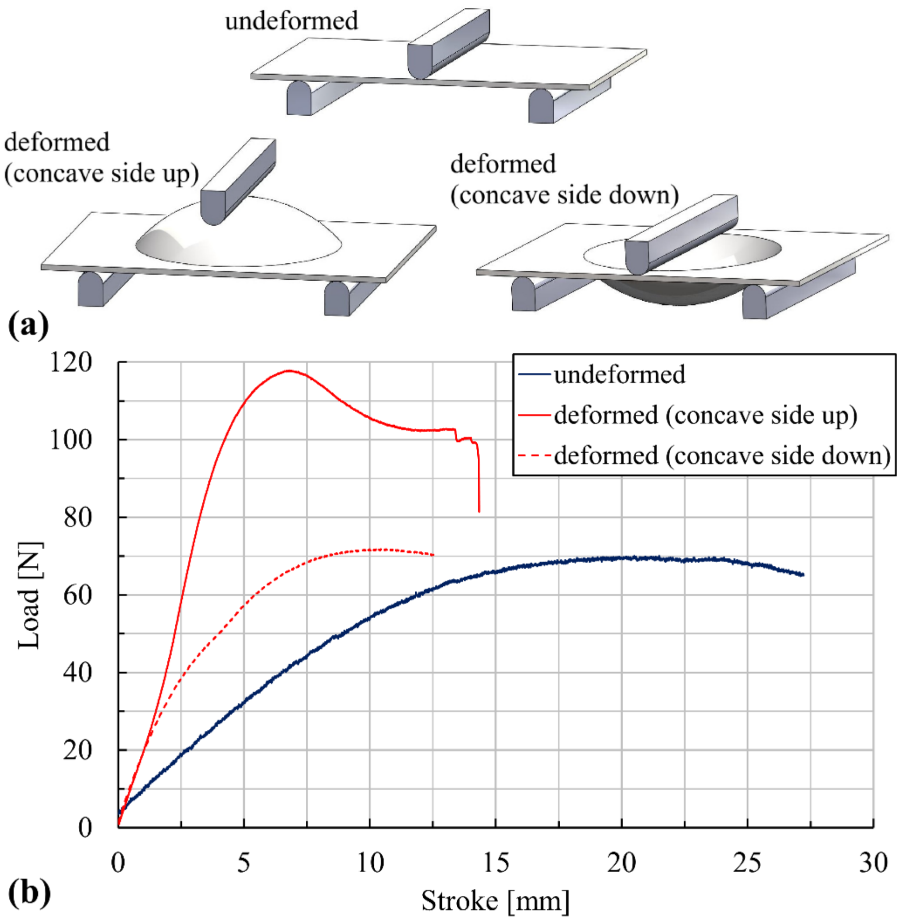

Fig. 4. Simply supported flexural tests: Schematic (a) and load-stroke curves (b)

Based on the previous findings, fixed-end flexural tests on the deformed laminates were conducted exclusively on spherical caps oriented with the concave side up (see schematic in Fig. 5a). As shown in Fig. 5b, this configuration proved effective, with the maximum flexural force increasing from approximately 3200 N for undeformed laminates to about 4000 N for the deformed ones.

Fig. 6 presents the results of the penetration tests, which were performed on undeformed and deformed specimens, with the caps clamped in the concave side up configuration (see schematic in Fig. 6a). Fig. 6b highlights the enhanced strength of the spherical caps: the penetration force (corresponding to the peak of the load-stroke curve) resulted more than doubled compared to the undeformed laminate, rising from approximately 2000 N to 4000 N. In terms of penetration energies, the values increased from 17 J for the undeformed specimens to 115 J for the deformed ones.

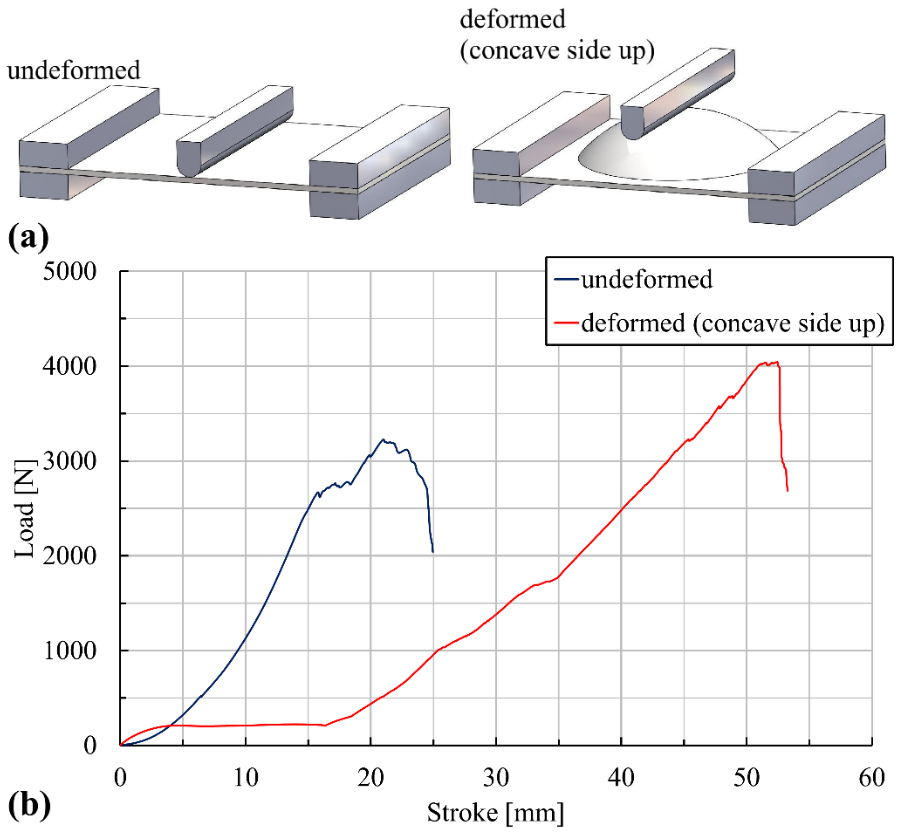

Fig. 5. Fixed-end flexural tests: Schematic (a) and load-stroke curves (b)

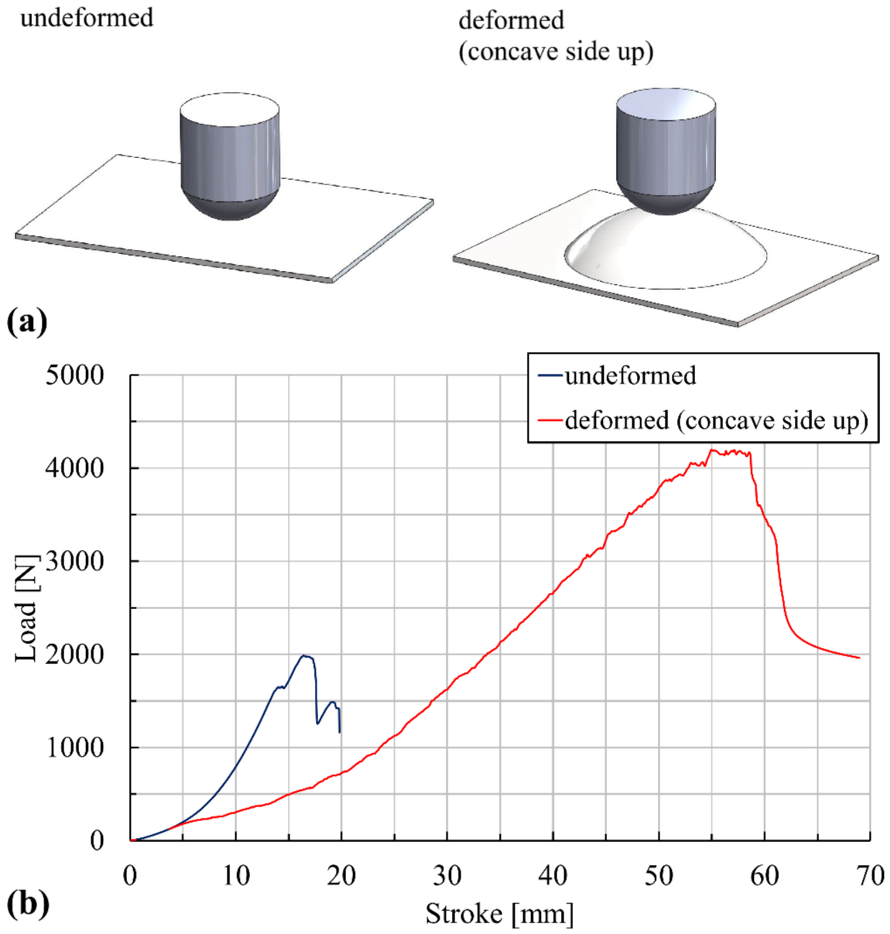

Fig. 6. Penetration tests: Schematic (a) and load-stroke curves (b)

Fig. 7 presents a 50× magnification of the failure surface obtained from a penetration test on a deformed laminate. The image reveals poor fiber/matrix adhesion, which is characteristic of this composite system, particularly in the absence of fiber surface treatments and coupling agents [22]. Consequently, stress transfer between the matrix and the fibers is primarily governed by mechanical interlocking, facilitated by the relatively large mesh size of the flax fabric.

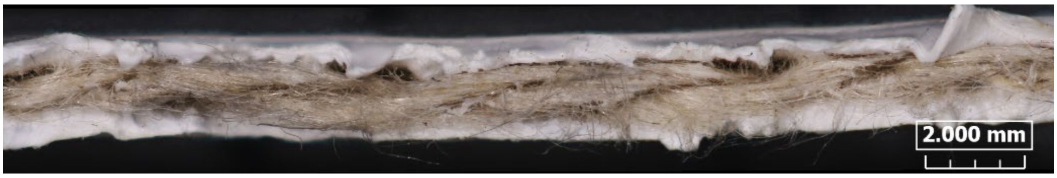

Fig. 7. Failure surface from a penetration test on a deformed laminate

Conclusions and Future Work

This study presents an experimental investigation on cold incremental forming with a partial counter die, applied to flax woven fabric-reinforced polypropylene laminates produced via compression molding, without the use of fiber treatments or coupling agents. The mechanical characterization of the resulting spherical caps was also performed.

The results demonstrate that incremental sheet forming is effective for biobased composites, offering satisfactory geometrical accuracy while requiring relatively low forming forces and power levels.

Furthermore, the incrementally formed spherical caps exhibited improved mechanical performance compared to the undeformed laminates.

Future research could focus on the remolding potential of incrementally formed laminates and the evaluation of their residual mechanical properties. Additionally, the incremental forming of fully natural composite laminates may provide further insights into sustainable manufacturing strategies.

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