Crush core forming: An innovative technology to manufacture structural sandwich parts with variable thickness

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Abstract. Sandwich structures, constituted in honeycomb core and skin in composite material, are usually employed to produce parts having a constant thickness or simple shape. Indeed, sandwich components with complex shapes, curvature or varying thickness are costly to manufacture due to the preliminary machining operations required on the core prior the molding process. A novel approach to manufacture complex sandwich structures, knows as Crush Core Forming (CCF) process, consisting in press-forming simultaneously the core material and the skins into the shape is under study. Such a method is potentially able to increase the production rate and lowering the overall costs. The present work aims to develop an experimental route to produce sandwich panels by means of CCF process and build a FE model of the forming process and validate it against the experimental studies. Experimental study was conducted to derive the fundamental parameters and properties for core and skins to be added in the FEM model of the CCF process. After, the numerical model was implemented to simulate the forming of the core and skins. Finally, a laboratory scale sandwich part was produced to validate the model outputs and assessing the reliability of the proposed approach.

Introduction

Composite sandwich structures offer opportunities of lightweight design and sustainable mobility thanks to their high strength-to-weight ratio, especially bending and torsional stiffness. Sandwich panels are currently employed in several fields, from aeronautics, to automotive and marine transportation [1]. Examples of application include aircraft interior, car body panel, boat hulls [2]. Sandwich panels usually are produced by means of autoclave processes bonding the composite skins with the core under the action of pressure and heat, however in the last years new pre-pregs, which can be processed by out-of-autoclave (OoA) techniques and can be cured under vacuum condition and with conventional ovens, have been commercialized [2,3]. Moving from the autoclave manufacturing toward OoA processes allows to significant cost saving and faster production routes without sacrificing the performances of the components [4–7]. Despite these progresses, composite sandwiches are commonly produced only in simple shape and have constant thickness.

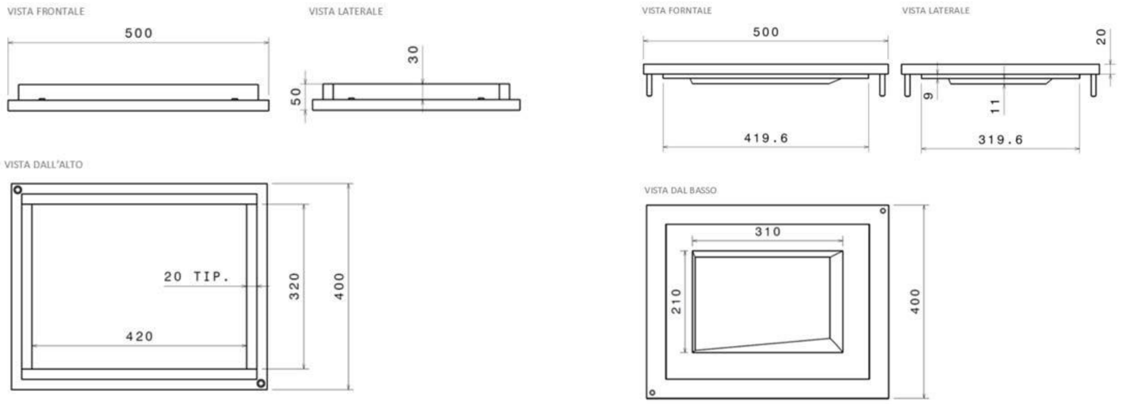
For the manufacturing of more complex shape structural panels, the core is generally obtained through machining operations, while the bonding and curing of the skins are made as subsequent steps [8]. Recently, the use of additive processes allows to realize core with high strength-to-weight ratio and with more complex shapes known as lattice structures [9,10]. However, the low production rate does not allow the development of such technology for series products.

Recently, in high-volume production application, such as lightweight automotive interiors, a reduction in production time is required to manufacture sandwich structures compatible with market demands. For this purpose, first studies on core crushing are present in scientific literature [11,12]. Forming behavior of curved sandwich plates differ from that observed in monolithic sheet material and in composite panels due to the presence of the core material, which affects the overall deformation of the sandwich plate and the occurrence of surface defects [12]. During the manufacturing core and skins are subject to complex load and multi-axial deformations, including in-plane tension/compression and shear and out-of-plane bending [12].

Typical issues observed during the forming process are surface waviness, local buckling, fracture of the skins as well as crushing of the core structure, and they were ascribed as the main factors limiting the formability of thin sandwich panels [11–15]. Optimization of the core design, so that it can provide sufficient resistance against skin buckling and core cell collapsing, demonstrated to be able to mitigate these defects and, therefore, plastic forming method could be used to produce complex shaped panels from flat sandwich plates [12]. In this context, development of numerical simulation techniques for the sandwich forming process able to predict the forming behaviors of core and skins and the forming-induced defects would be helpful. In very recent works, Cai et al. [12] and Chen et al. [11] proposed finite element models and analytical models to determine the main failure factors in plastic forming of curved sandwich panels. The first authors investigated the multi-point forming of sandwich structures having polyurethane egg-box-like core and aluminum face sheets. They observed that the limits in formability are mainly related to occurrence of wrinkling or dimpling on the face sheets, while the core cell fracture has lower influence [12]. The other authors developed a multiscale model of the sandwich structure having composite skins and honeycomb cellular core. The results indicate that the formability of sandwiches with complex curvature is due to the local crushing of the core. In the authors' best knowledge, besides these few contributions no other works dealing with numerical simulation or experimental approach are available for the published literature, especially in the case of composite skinned sandwiches for structural applications. Moreover, there are no studies that investigate not only the plastic forming process of the core but also the efficacy of the bonding between skins/core and the resin cure of the skins in a one-shot forming process of structural parts. In the present manuscript a novel approach to manufacture complex sandwich structures, knows as Crush Core Forming (CCF) process, consisting in press-forming of both core and skins in a one-shot operation, is under study. Such a method is potentially able to increase the production rate and lowering the overall costs. The present work aims to develop an experimental route to produce sandwich panels by means of CCF process and build a FE model of the forming process and validate it against the experimental studies. In fact, compression tests were performed on the honeycomb core to estimate the deformability and the densification of the core material under the action of the forming load, while the composite skins were subjected to bias extension and cantilever test to assess their formability. These properties were used as input data for the FEM model developed to simulate the forming of the core and skins and estimate the occurrence of forming-induced defects. A laboratory scale sandwich part was produced to validate the model outputs and assessing the reliability of the proposed approach.

Materials and Methods

Fig. 1 shows the case study designed for the investigation of the CCF process. For the forming process, a press system was used with heated plates up to 250°C with dimensions 400x400 mm^2. EP121-68-40 fiberglass prepreg impregnated with 40% epoxy resin from Gurit Ltd was used as face sheets for the sandwich panels. It is a prepreg with 8H satin texture and a resin cure temperature of 120°C. The skins were produced with 2 plies layered with rolling direction in the direction of the long side of the panel.



a) b)

Fig. 1. Scheme of the upper half mold (a) and lower half-mold (b) for the case study considered (dimensions in mm).

The hexagonal cell honeycomb HRH10-3.2-48 from Hexcel HexWeb was adopted as core. It is a core in Nomex that has cell dimensions of 3.2 mm, height of 19 mm and a density of 48 kg / m^3. The characterization of the core was conducted according to ASTM C365 along the thickness of the core, both at room temperature and at the prepreg cure temperature of 120°C. The compression tests were conducted with three replicas for each test temperature (see Fig. 2).

a) b)

Fig. 2. Compression test of the core: a) During test; b) at the end of the test.

The formability of prepreg skin was assessed by bias extension test (Fig. 3) and by cantilever testing, respectively for the in-plane shear behavior and the out-of-plane bending behavior. The specimens for the bias extension test are 50 mm x 200 mm in dimension and were tested at testing speed of 50 mm/min. Three replications were considered for the test. ASTM D1388 standard was adopted for the cantilever test, which recommends specimens with size of 10x100 mm^2 and an overhang length of 50 mm. Five replications were considered.

Fig. 3. Bias extension test per EP121-68-40.

Once the single parts of the sandwich have been characterized, the CCF process was conducted. The optimal process parameters were determined by the trial-and-error method, evaluating the goodness of the adhesion between skin and core through ultrasonic non-destructive testing. The process parameters, which resulted in free-defects sandwich panels, are: 100 kN closing force, molds temperature of 120°C, holding time of 90 min. The temperature trend on the mold was measured by using J-type thermocouples placed inside the mold as shown in Fig. 4. Once the cure of the skins was completed, the mold was opened, and the component extracted.

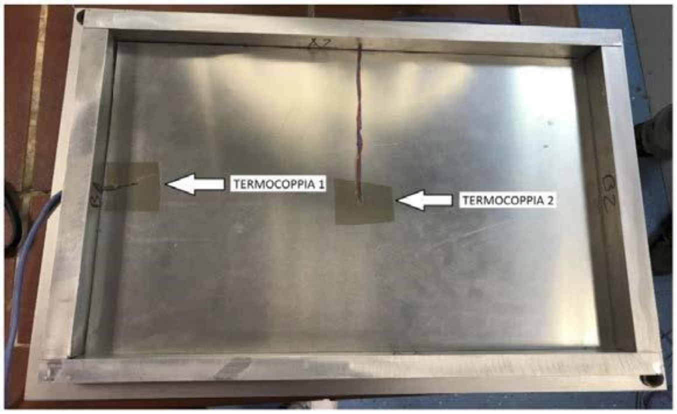


Fig. 4. Locations of the thermocouples on the surface of upper half-mold.

The numerical analysis was conducted by adding the properties of the materials, derived from the experimental characterization in the PAM-FORM software developed by Esi Group. For the present case study, brick-type and shell elements were considered for the core and skins, respectively (see Fig. 5 and 6). Specifically, for the skins and tools Belitschko-Tsai type 4-node square elements were used, while Flanagan-Belytschko type 8-node elements were used for the core. The tools were modeled as rigid bodies, while the mechanical behavior of the core and skins was implemented in the software as a point list.

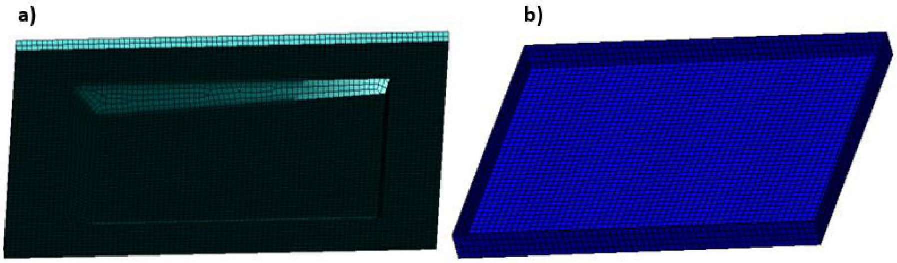


Fig. 5. CAD tools in PAM-FORM environment: a) upper mold; b) lower mold.

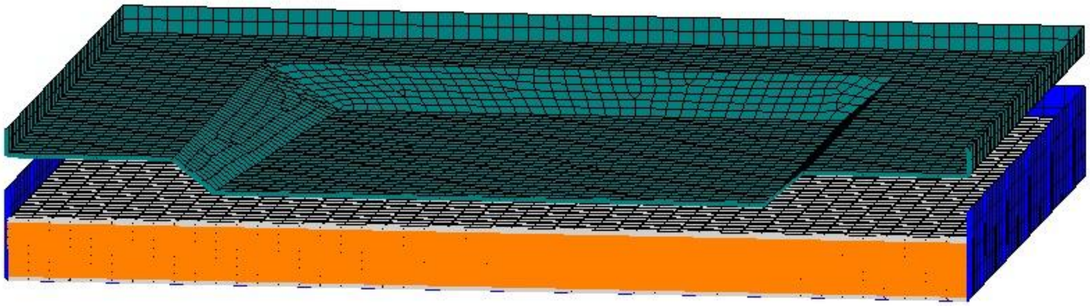


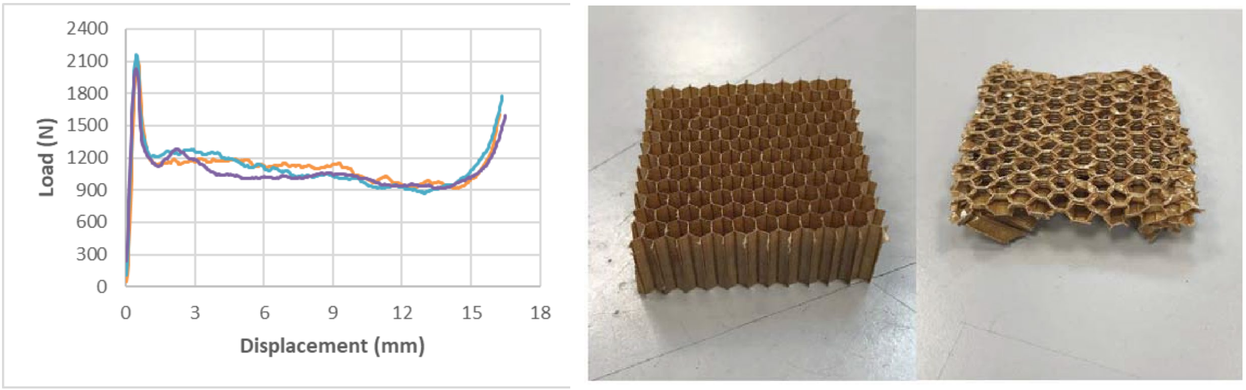
Fig. 6. Section view of CCF process developed for the case study in PAM-FORM environment.

Results and Discussion

In this section the results from the experimental characterization and numerical analysis of CCF process are reported and discussed

Compression test.

Fig. 7 report the force/displacement curves acquired during the compression tests on the three specimens and the photos of core before and after the test. By analyzing the curves, it is possible to observe a first peak of mechanical resistance of about 2100 N, after which there is a collapse of the load and a plateau up to an overall displacement of 14 mm of the upper plate. In this stage of the test, the failure of the core cells occurred, which, once completed, led to a new increase in measured load. Therefore, the investigated core is compressible up to a thickness of about 5 mm, lower than that necessary for the realization of the case study of the present work. Tests conducted at 120°C showed the same results, but with about 30% lower initial stiffness and strength.



a) b)

Fig. 7. Compression test results on the core material: a) Load-displacement curves; b) specimen image before and after the compression tests.

Cantilever test.

The results from the cantilever tests on prepreg laminates are shown in Fig. 8. From these it is possible to observe that the flexural stiffness of the prepreg EP121-68-40 at room temperature varies between 22 and 28 kPa. In the case of tests conducted at the forming temperature, the flexural stiffness has lower values between 17 and 18 kPa. In the latter case, the tests showed a greater repeatability of the measurement with a limited scattering.

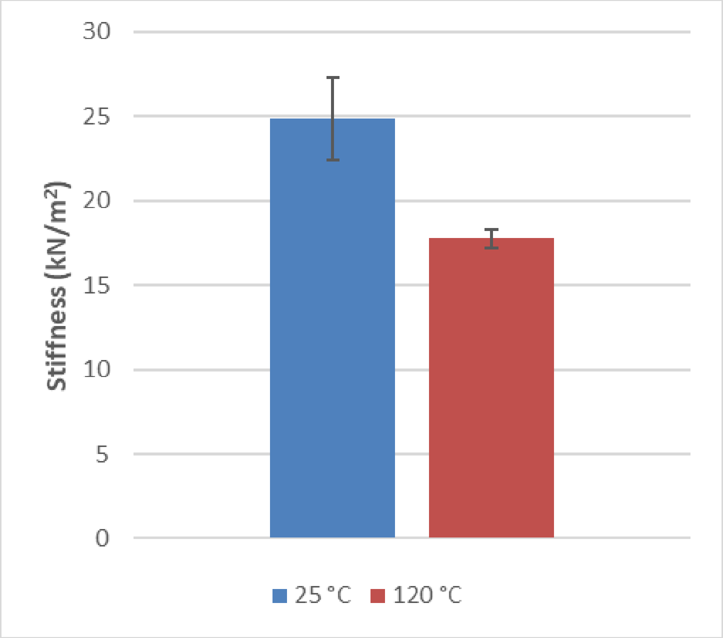
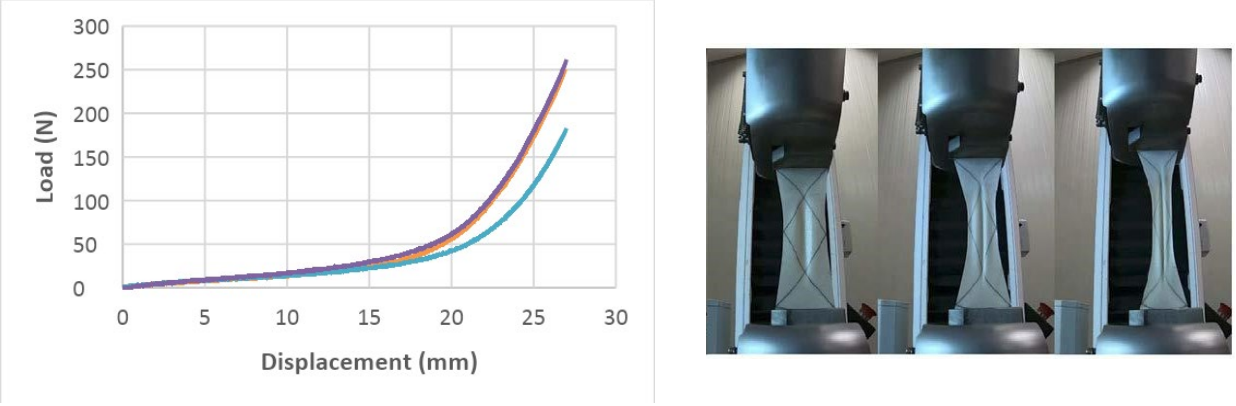


Fig. 8. Prepreg stiffness derived from cantilever test.

Bias extension test.

The results from the bias extension test are shown in Fig. 9. The load-displacement curves showed an exponential trend, with a significant increase in load after a displacement of approximately 15 mm. These curves were normalized with respect to the size of the specimen, then the average curve was extrapolated and used as input into the PAM-FORM calculation code.



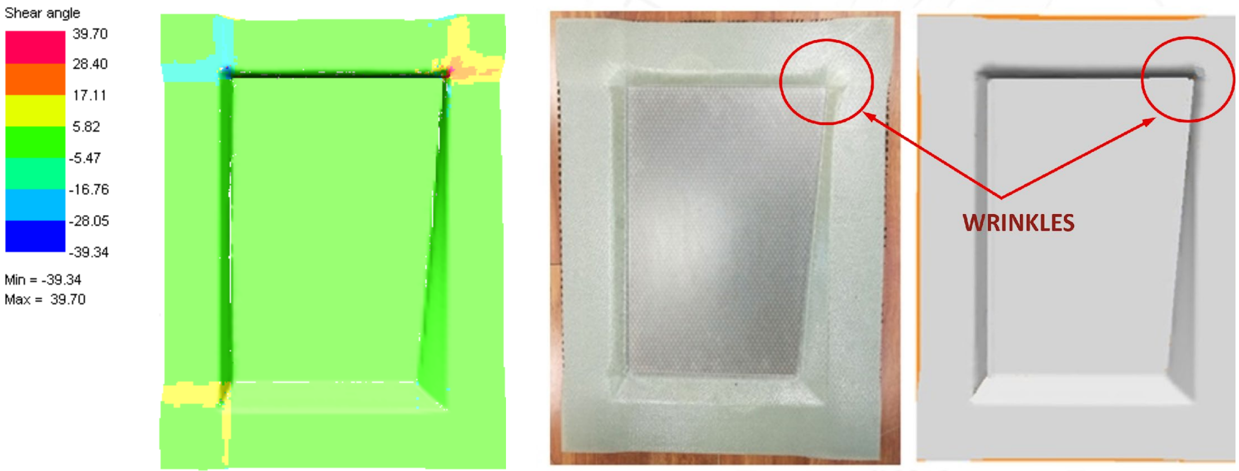
a) b)

Fig. 9. Results from bias extension test on the EP121-68-40 prepreg: a) load vs displacement curves; b) images of the prepreg specimens during the test.

CCF process: comparison between experimental and numerical outcomes.

Measurement of temperature by using thermocouples during the forming process and the ultrasonic control on the formed part confirmed soundness of the manufactured sandwiches, confirmed by the good adhesion between core and skins after the forming.

From visual analysis it can be observed that the variation of orientation of the fabric is located near the vertices of the cavity, or where there is a greater variation of the normal of the piece surface (Fig. 10). By analyzing the simulated panel, it is possible to assess that the software was able to predict with good accuracy the formability and directional variation of the reinforcement of the skin with the presence of wrinkles near the vertices of the pocket.



a) b)

Fig. 10. Sandwich panel manufactured by CCF process: a) numerical shear angle; b) comparison between experimental and numerical results.

Summary

In the present work, an innovative approach to produce structural sandwich structures, known Crush Core Forming (CCF), has been investigated. This process allowed to form simultaneously the core and the skin in a single forming step to produce structural sandwich panels with complex shapes, reducing time and manufacturing costs. First, the mechanical behavior of the core and the skins has been obtained through compression tests, bias extension tests and cantilever tests. Subsequently, the results of the tests conducted on the prepreg cure temperature of 120°C were added as input in the PAM-FORM simulation environment. A case study has been realized through CCF process, showing the reliability of the proposed approach, while the outcomes proved the model's capability to predict the plastic deformation of the core and relative angular variation of the skin sheets with the formation of wrinkles near the vertices of the cavity.

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