INFLUENCE OF FIBER ORIENTATION ON MECHANICAL PERFORMANCE FOR THERMOFORMED COMPOSITES

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Abstract

The combination of woven fabric based composites and thermoforming has shown a potential to produce fast parts from raw material with reduced manufacturing costs. However, the behavior of the composite structure is strongly related with the fiber orientation of the woven reinforcement inside the product. Small deviations on fiber orientation can produce a significant reduction in structural performance. In this paper, composite hemispheres were fabricated and tested for three loading directions (0°, 90° and ±45°). For this component, three different fiber orientations were used: orthotropic, manufacturing simulated and experimental ones. Thus the influence of these orientations was assessed using finite element calculations and compared against test data.

1 Introduction

Nowadays, the success of an aerospace design is evaluated in terms of affordability. This concept is measured in terms of weight, fuel consumption, environmental impact, and above all acquisition and operational costs. The introduction of advanced reinforced plastic composite materials in aerospace systems has provided designers with great flexibility to improve these metrics. The first impression is that composites are the material of choice for many applications but their cost is very high compared to that of steel and aluminum. This situation has restricted their extensive use in the industry. In addition, composite products can only be competitive with aluminum, with respect to both performance and price, when both the design concept and the manufacturing process are efficient.

Actually, around 70% of the plastic reinforced composite applications in the market are based on thermosets [1]. However, thermoplastic composites (TPCs) are becoming popular in aircraft structures as replacement of sheet metal components, and they are moving quickly from secondary to primary structural applications [See Fig. 1]. This relatively new material provides several processing and design advantages over thermoset composites. TPCs can be processed in a few minutes while thermoset composites need a time-consuming cure cycle. In addition, other benefits of thermoplastics are their toughness, chemical resistance, high temperature performance, indefinite shelf live without refrigeration, low manufacturing costs, weldability, reshaping and reforming flexibility, better reparability potential and recyclability.

The TPCs are nicely formed into their final product shape by thermoforming processes, such as rubber forming or diaphragm forming, producing fast components from raw material with reduced manufacturing costs. Most of these processes were derived from classical metal forming technologies and show, in general, the same principles [2]. Thermoforming consists of laminates in flat-sheet form, which are assembled from individual plies to the desired thickness and reinforcement orientation, and then consolidated with heat and pressure over a certain geometry or mold.

Among the most important thermoforming deformation mechanisms, intraply shear and interply slip are responsible for the formability of the desired part. In particular, the intraply shear is affected by part geometry, type of reinforcement, and selected manufacturing process. In addition, multiple layers suffer from laminate/tools thermo-mechanical contact interactions producing thickness distribution and fiber orientations different from those proposed by the structural engineer on the product. This situation can be clearly observed in Fig. 2.

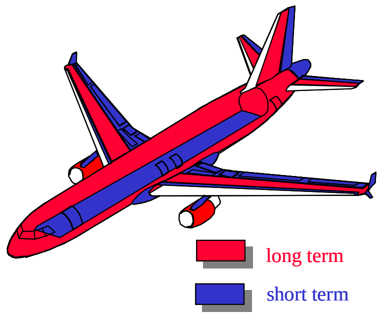


Fig.1. With the advent of composite wings and fuselage structures, the opportunities for thermoplastics will expand into these areas on the long term [3].

The prediction and assessment of the real fiber orientations (RFO) on the final part is still an issue. However, material properties such as modulus, strength and thermal expansion are greatly dependent on this fiber orientation state and thickness distribution in the composite. It is clear that manufacturing has a strong influence on the success of any design and must be considered early to ensure that it is both feasible and viable [4].

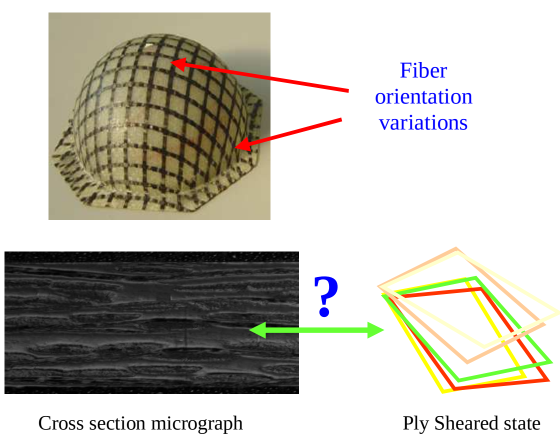


Fig. 2. Thermoformed woven product with fiber orientations on the surface and through the thickness.

In this paper, an experimental method to obtain the fiber orientation on internal woven plies was applied on thermoformed products. Then, the specimens were tested on three different load directions: 0°, 90° and +45° with the aim to detect change in performance. Finally, structural Finite Element (FE) simulations based on the RFO and other simulated fiber orientations were computed and validated against the mechanical tests.

2 The Experimental Technique

One efficient way to estimate the complex formed fiber orientation relies on the use of the intraply shear deformation. In this case, a grid or a pattern is attached somehow to the ply (plies) of interest prior to manufacturing. Once the pattern distorts, the deformation can be measured using image processing techniques. The introduction of Heat Emitting Layers (HELs) into the composite allows the identification of the RFO *through-the-thickness*.

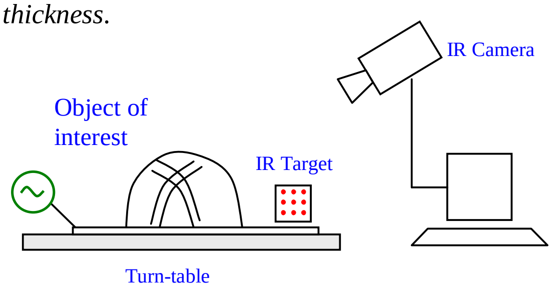


Fig. 3. Sketch of the IRSGA set-up.

2.1 Infrared Square Grid Analysis

The square grid analysis technique is a well-known method used for strain analysis in metal forming processes [5,6], and it has been adapted and used for thermoformed composites [7,8]. However, with the aim to visualize the RFO through-the-thickness on formed composites, a modified technique called Infra Red Square Grid Analysis (IRSGA) has been developed [9,10]. IRSGA utilizes HELs that are incorporated into the specimen lay-up prior to deformation. In this paper, HELs are based on glass fabrics with orthogonal interwoven metallic fibers.

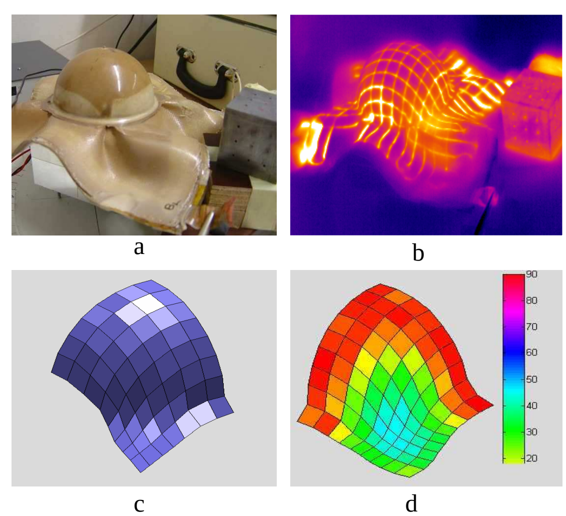


Fig. 4. The IRSGA process: a) Visual product image, b) Infrared picture of internal ply, c) 3D reconstruction of the ply, and d) Ply fiber orientation distribution.

Once the composite has been formed, the product is placed on a set-up as it is depicted in Fig. 3, where an infrared target is placed near to the composite. Then, the HELs are thermally activated and the user takes a series of thermal pictures of the product from different perspective views. From the Infrared (IR) photos, the deformed array position per layer is localized and with two or more images, the global 3D coordinates are computed using perspective projection geometry. Thus, the global coordinates are used to compute the fiber orientation for each deformed square per HEL on the composite part. In this study, the photographs were acquired with a FLIR ThermaCAM SC2000 infrared camera and a typical IRSGA result can be observed in Fig. 4.

3 Manufacturing and Testing

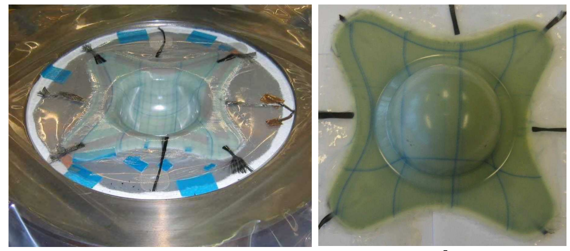
3.1. Composite Manufacturing

3.1.1 The HEL

In general, the HEL is a hybrid textile based on the same fiber reinforcement used in the composite but with a small fiber volume fraction of another kind of thermal conductive fiber. In this investigation, the HEL layer was made by hand weaving 316 type stainless steel fibers with 70µm diameter into a glass 8H satin fabric from Ten Cate Advanced Composites. This fabric has blue glass-fiber tracers stitched each three fabric unit cells apart, i.e. 10mm, and it allowed straight lines of metal fiber at equal distances to be stitched. The stainless steel was chosen due to its excellent corrosion resistance and deformation (forming) properties. The thermal activation of the HEL was achieved using electrical heating based on the Joule effect. Hence, copper mesh was used as busbar material due to its high electrical conductivity.

3.1.2 The Composites Hemispheres

Hemispheres of 50mm radius were manufactured using HELs and glass-fabric/epoxy (bisphenol A-based) prepreg from Ten Cate Advanced Composites. The laminate lay-up was 0°/90° and three HELs were placed in the 2nd, 4th and 7th ply positions respectively. The plies were held between two Capran 988 Nylon films of 100 µm from Aerovac Systems. The build-up of the diaphragm/laminate stack was placed on top of an aluminum mould with a hemispherical cavity. The system was pressurized at 6 bar; then, the hemisphere was formed between 60-80°C by lowering the pressure in the molds cavity at 2 bar/min, while maintaining 6 bar of pressure above the laminate/diaphragms stack. Afterwards, the formed part was heated to 140°C and kept there for 15 min of curing. Finally, it was cooled down until the temperature was below 80°C. A typical diaphragm formed hemisphere is depicted in Fig. 5.



a b

Fig. 5. Diaphragm forming. a) Formed product inside the autoclave, and b) Released product.

3.1.3 The Coupons

In order to perform structural finite element simulations, the composite lamina material properties were investigated in accordance to ASTM D3039. Thus, the required samples were manufactured via autoclave and consisted of 9 plies of the same glass-fabric/epoxy prepreg used to fabricate the hemispheres as it is shown in Fig. 6.

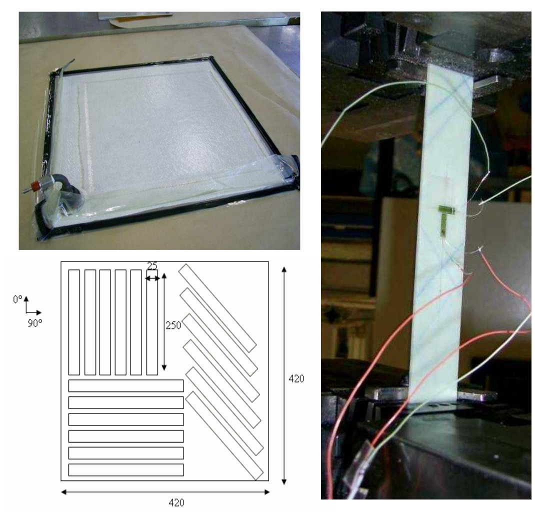


Fig. 6. Glass fabric/Epoxy coupon manufacturing, cutting lay-out and testing.

3.2. Testing

3.2.1 The Composite Hemispheres

Before testing the hemispheres, they were placed in the IRSGA set-up described in section 2.1. Then, the embedded HELs were activated and their thermal images were taken. The following procedure is explained in section 4.2.3.

In Fig. 5b can be observed that the parts were not symmetric. Therefore, the hemispheres were trimmed in order to test the 3 loading directions (0°, 90° and +45°). The resulting shapes are depicted in Fig.7. A Zwick 250kN Static testing machine was used to apply a tension load on the hemispheres. The resulting force-displacement curves for each load case are depicted in Fig. 8.

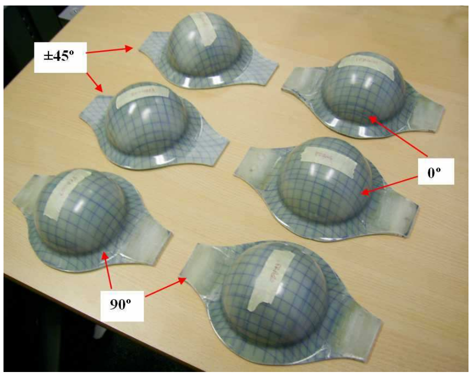


Fig. 7. Trimmed hemispheres for tensile test.

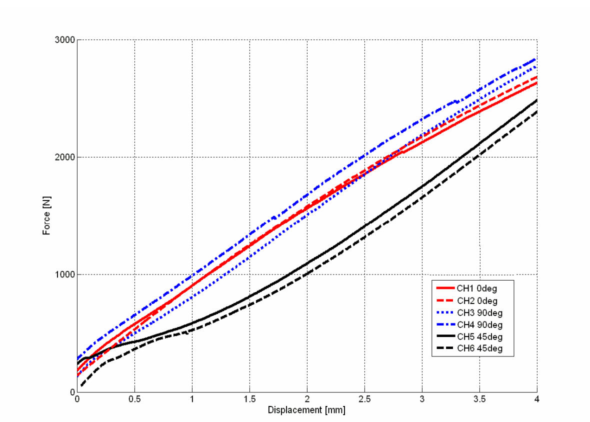


Fig. 8. Force/Displacement curves for diaphragm formed hemispheres.

3.2.2 The Coupons

The composite lamina material properties such as Young's modulus E_1 and E_2 and the in-plane shear modulus G_{12} were characterized in accordance with ASTM D3039. The results are presented in Table 1.

Table 1. Glass fabric/Epoxy material properties.

Property	Value
E_1	24.058 GPa
E_2	21.978 GPa
G_{12}	2543 MPa
ν_{12}	0.1
Ply thickness	0.24mm

4 Structural Assessment

4.1 The HEL effect

Based on the current HEL configuration, where the metal fibers were placed 10mm apart in both directions, the metal fiber volume fraction was 0.27% per HEL. Now, the effect of embedding 3 HELs on the 8-ply glass/epoxy composite properties was computed using the rule of mixtures and the data of Table 1. As it is indicated in Table 2, the change in E_1 and E_2 is too small so, the presence of metal fibers in the HEL was neglected on this investigation. However, if the size of the HEL's squares decreases; then, the effect of the metal fibers will become important.

Table 2. Glass fabric/Epoxy material properties.

Property	Value	% change
E_1	24.23 GPa	+ 0.70
E_2	22.15 GPa	+ 0.78

4.2 Structural Analysis

The influence of the fiber orientation on the mechanical performance of the hemisphere composite part was assessed using Abaqus, commercial FE software. The process started defining the trimmed hemisphere geometry, and then a surface discretization was performed. Here, for each load case, three types of fiber orientations were used for the FE analysis: orthotropic, manufactured simulated and the RFO. A description of this process can be observed in Fig. 9. Then, a load of 1000N was applied to one side of the specimen in order to compare the simulations with the experimental tests in the linear range.

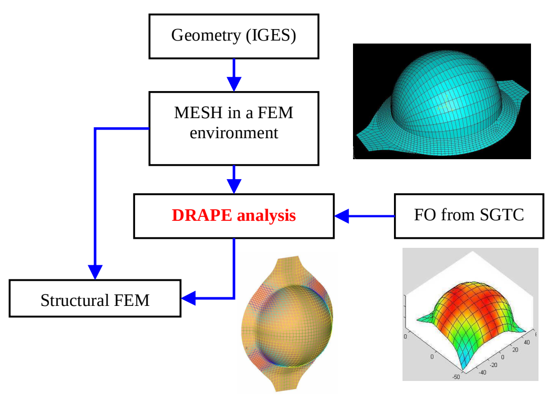


Fig. 9. Fiber orientation scheme process used for the FE analysis of thermoformed hemisphere composites.

4.2.1 Classical Analysis

In this case, the model uses a classical FE analysis based on an orthotropic lamina material description (Table 2) for the 8-ply glass/epoxy hemisphere. In this case, *classical* means that all elements used the same orthotropic material properties. So, there was not including any manufacturing fiber orientation effects.

4.2.2 Drape Analysis

A kinematic drapability analysis was used to simulate the manufacturing process and to provide the fiber orientation distribution after forming. Drapability is simply a measure of how easy it is to drape a fabric over a particular shape without wrinkles. This ability is governed by fiber properties, fabric style and geometry of the product to be fabricated. Then, the drapability behavior can be simulated by an in-house code called Drape. This tool takes into account the influence of the number of layers on intraply shear and the change in thickness due to this new shearing state. However, manufacturing variables and contact mechanics effects are not modeled by Drape and there is not any gradient information. Nevertheless, this software allows the designer to get insight into the manufacturing problems in early design stages.

Once the classical Abaqus model has been created, Drape imported it as an *input format file*. Then, the different plies were placed on the product. At the end of the manufacturing analysis, Drape split each woven composite ply into four UD materials. The shearing effect was then introduced by stacking the UD materials under the right angles. The total thickness for each discrete element and the coupling matrix ABD (extensional, coupling and flexural stiffness matrices respectively) were computed according to the Classical Laminate Theory. This approach is further described by [11]. Finally, the predicted material properties were translated back to Abaqus via a new input file.

4.2.3 The IRSGA Analysis

In order to reconstruct each three-dimensional formed HEL, at least eight pictures from different perspective view were required by the IRSGA. In Fig. 10, the thermal images of a quarter of a hemisphere can be observed showing the three embedded HELs.

Thanks to the flexibility of Drape to interact with Abaqus, it has been used as a platform to deal with the acquired RFO information. The 3D reconstructed data was imported as a new formed ply. Then, it was rotated, translated and projected automatically onto the product surface. This step requires the selection of at least two reference points on both surfaces (CAD and the reconstructed ones) in order to perform the right matching process as it is shown in Fig. 11.

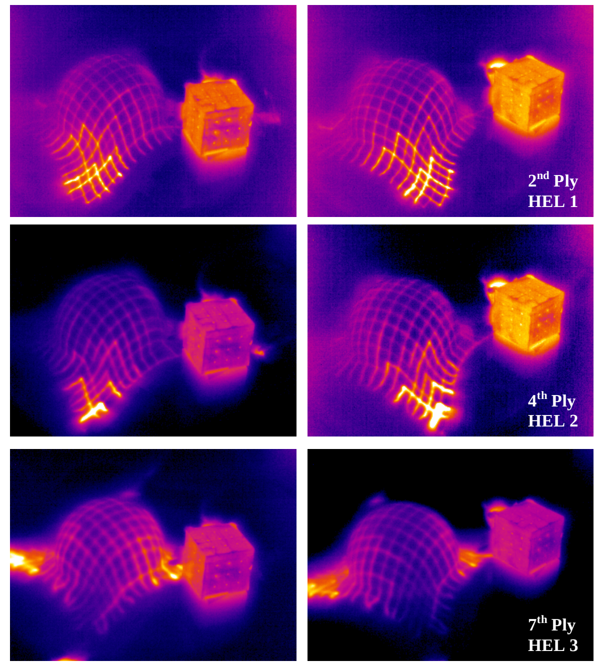


Fig. 10. Thermal images for the acquisition of internal fiber orientations using the IRSGA.

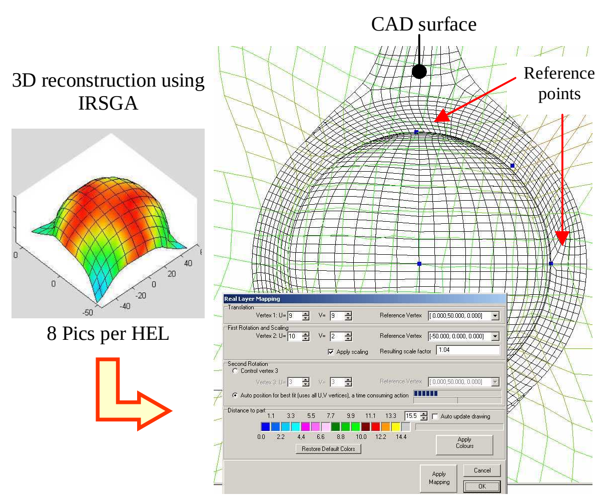


Fig. 11. Mapping process between IRSGA and Drape.

The hemisphere laminate was assembled as follows: Plies 1 and 2 had the same RFO from HEL 1; Plies 3, 4, and 5 used the RFO from the HEL 2 and Plies 6, 7, and 8 were assembled with properties from HEL 3. Once the real orientations were mapped, material properties were assigned to each ply and then exported to Abaqus in the same way as it was explained before in the Drape case.

4.3 Results

A shear-stress field obtained with the classical approach can be observed in Fig. 12a showing that the hemisphere did not present high stresses at the top of the shape. The highest shear stresses were found at the flange section of the hemisphere. This situation was expected due to the nature of the loading case and the geometry of the part. In addition, the tested composite hemispheres failed under shear at the four mentioned regions as it is depicted in Fig. 12b. A detailed inspection of the fracture surface of the composite specimen was performed with a Jeol JSM-840 scanning electron microscope (SEM). It was found that the fibers were well impregnated by polymer resin, thus the manufacturing process was appropriate as it can be observed in Fig. 12c.

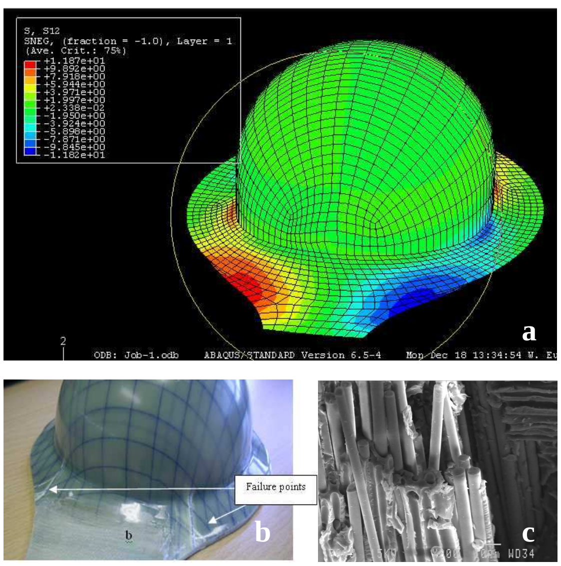


Fig. 12. a) FE shear-stress field for classical analysis, b) Sample failure for the 0^o load case at 4519N, and c) SEM micrograph of the failure zone.

A summary of the Abaqus results and the average experimental displacements are presented in Table 3 and visualized in Fig. 13. The simulations showed that the classical FE approach over estimated the displacements by 45% for 0° and 90° load directions. In the case of the Drape fiber orientations, the error was 21% for 0° and 16% for 90° load directions. However, the use of RFO in the calculations reduced this error to 10% in 0° and 11% in 90^0 load cases

Table 3. Displacement at 1000N for FE fed with different fiber orientations.

Direction	Experimental	Classical/FEA	Drape/FEA	SGATC/FEA
0^o	1.15 mm	1.670 mm	1.393 mm	1.269 mm
90^o	1.14 mm	1.673 mm	1.324 mm	1.261 mm
45^o	1.92 mm	1.724 mm	1.405 mm	1.678 mm

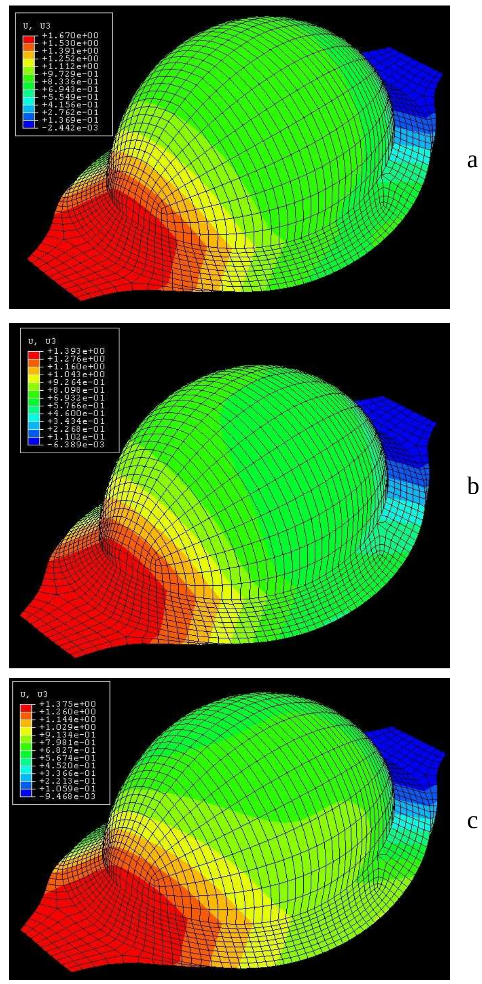


Fig. 13. FE displacement field results. a) Classical analysis, b) Drape analysis, and c) IRSGA analysis.

In the 45^o load direction, the composite behavior was different. The hemispheres showed the larger deformation of all three cases. This situation was expected because the in-plane fabric sheared state created a complex load path on the composite part. However, the classical approach underestimates this behavior only by 10% in comparison with Drape (26%), and RFO (12%). It can be observed that for the classical FE, the difference between the displacement values for 45^0 and 0^0 was 3%. In the other hand, the experimental displacement difference for the same loads was 33%. Therefore, the apparent precision of the classical FE was just coincidence.

It is important to recall that the RFO were computed using a coarser mesh (10mm) than those used for Drape (3.8mm) and the classical FE (3mm). Thus, a finer mesh pattern will improve considerably the description of the RFO field and the accuracy of the structural analysis. Nevertheless, a larger presence of metal fibers will influence the results. In addition, the RFO calculations were based on the use of the only 3 HELs to describe the whole fiber orientation field on the composite part. It is expected that the replacement of all plies by HELs will enhance the mechanical description of the composite part. However, the complexity controlling the thermal activation on each layer will increase and maybe short circuit problems will arise.

5 Conclusions

The use of multiple heat emitting layers can produce an internal mapping of the real fiber orientation in the manufactured composite. Using the IRSGA, it is possible to reconstruct the specimen geometry and transfer these orientations into a finite element code to perform a more realistic structural analysis of the part.

It is clear that the classical FE does not provide an accurate description of the system. However, drapability methods and measured real fiber orientations can offer reasonable values, especially, if a smooth, gently and isothermal manufacturing process such as diaphragm forming is used.

The selection of the manufacturing process and its conditions will strongly affect the way in which fabrics will accommodate to the mould geometry. Then, the approach used on this paper can be extended to any manufacturing process that uses woven composites such as rubber forming, RTM or vacuum infusion, among others.

Finally, the results of the combination of real fiber orientations with finite element analysis are promissory. It is expected that this approach will provide a fresh feedback into the available manufacturing simulation codes, and then improve their fiber orientation predictions.

Acknowledgment

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