Spring-in experimental evaluation of L-shaped pultruded profiles

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Abstract. Currently pultruded profiles are widely applied as structural elements in different areas due to their high strength, low weight, improved corrosion and fatigue resistance properties. Nevertheless, production of pultruded elements presents challenging aspects related to the peculiarities of pultrusion manufacturing process. Indeed, produced profiles exhibit shape deformations immediately after curing such as spring-in and warpage. These manufacturing induced shape distortions evidence time evolution behavior. This paper presents a seven months long experimental investigation of time-dependent distortion evolution of pultruded L-shaped profiles.

1. Introduction

In last decades, the remarkable improvements in manufacturing of advanced fiber reinforcement polymers (FRP) lead to a massive use of composite materials in several different industrial applications [1–10]. Their success is due to the high strength to weight ratio as well as the possibility to customize physical and mechanical properties of final products choosing different constitutive components [11,12].

Due to its automatable continuous nature, pultrusion process combines the aforementioned advantages and extremely high productivity with respect to other polymeric composite manufacturing techniques [13]. Moreover, the pultruded FRPs exhibit mechanical performance averagely higher than the ones produced by other techniques, due to the elevated fiber content achievable and the fiber architecture [11]. Nevertheless, the produced profiles are extremely sensitive to the process parameters. Indeed, the most of the cure reaction occurs in the curing-forming die, and the thermal cycle imposed to the resin depends on the temperature of the heating plates and on the pulling speed [14].

The numerous loads, acting on the profile during pultrusion, (such as pulling force, the viscous-adhesive interaction with the die, thermal expansion under constrains, chemical shrinkage [15]) provoke in the profile process related internal tensions [16]. The residual stresses generate distortions in the produced FRPs, which can lead the final shape out of geometric tolerances [17]. In that case problems during the assembly process arise and provoke expensive and time-consuming extra shimming operations [18]. Residual stresses produced both during the manufacturing and assembly steps decrease mechanical performance of desired structure [19], [20]. Therefore, prediction and control of such effects is crucial for the achievement of effective design.

Up to authors knowledge researches regarding shape deformations of composite profiles have been done so far [21–28], however there is no study considering time dependent behavior of elements.
produced by pultrusion process. This paper presents an analysis of the shape deformations evolution in time of L-shaped pultruded FRPs profiles. The deformations were experimentally measured for 200 days after the manufacturing process, in order to define the spring-in and the warpage behavior of the elements.

2. Materials and methods

The FRP L-shaped profiles were pultruded with three different pulling speeds, namely 200, 400 and 600 mm/min\(^{-1}\) (figure 1(a)). The geometry of the cross-section is reported in detail in figure 1(b). The pultruded elements were made of an ethylene-vinyl acetate resin system (EscoureneTM Ultra FL 00309M) reinforced with 104 E-glass rovings (T30 PS1200) and 2 layers of E-glass fabric (LT 0600 / S 300/06 H 01/125 GUS) disposed on external (top and bottom) surfaces of the profile. The cure-forming process occurs in a 600 mm long die, heated by electrical controlled thermal plates fixed on the last 350 mm in pulling direction. The temperatures of plates were monitored using thermocouples embedded in the die. Their temperature set point was 140°C. After the production step all the profiles were not thermally post treated.

The spring-in and the warpage of the L-shape profiles were evaluated using a calibrated angular tool which has an accuracy of ± 0.09°. Warpage phenomenon has been observed and, therefore, measured only for the profile produced at the highest speed of 600 mm/min\(^{-1}\). All the data collected are referred to the cross sections of the profile located 20 cm one from each other. In order to investigate the evolution of the mentioned shape distortions measurements were done every 2/3 days in the period of first 90 days, while in the following 110 days measurements were repeated once per week. In particular, the difference between the pultruded profile and the calibrated tool was measured, as shown in figure 1(c),(d). The gap \(t_w\) (figure 1(d)) at the center of the profile wing is a measure of the warpage, while the gap \(t_s\) (figure 1(c)) at the extreme of the profile was used to compute the spring-in angle \(\alpha_s\) accounting for the wing length \(L_w = 62\) mm, as described in equation (1):

\[
\alpha_s = \arctan\left(\frac{t_s}{L_w}\right)
\]  

Figure 1. (a) Pultrusion of L-shaped profiles; (b) Cross-section of pultruded L-shape; (c) Measurement technique of spring-in; (d) Measurement technique of warpage
3. Results and discussions

Figure 2(a) represents the evolution of absolute spring-in angle as a function of the time measured in days starting from the day of manufacturing process. The first measurement has been done at the same day immediately after pultrusion. It can be seen that the initial spring-in angle exists and not equal to zero. This effect is mainly due to the differences in coefficients of thermal expansion of reinforcement and matrix material as well as chemical shrinkage of the resin. The following 60 days exhibit growth of the absolute spring-in angle for all the specimens. After this the overall trend tends to the plateau. Besides, it is clear that the value of spring-in depends on the pulling speed of the manufacturing process: higher the speed higher is the angle. Speaking about relative growth of the spring-in, it is worth to be mentioned that the highest value is related to the production speed of 200 mmmin\(^{-1}\) and is equal to 15.4%. These numbers are the 10.1% and 10.8% for the pulling speed of 400 and 600 mmmin\(^{-1}\) respectively. Warpage phenomena displays the similar behavior in terms of time evolution (Figure 2(b)). However, relative growth of the warpage is higher and is equal to 81%.

![Figure 2](image.png)

**Figure 2.** (a) Evolution of absolute spring-in angle in time for the production rates of 200, 400 and 600 mmmin\(^{-1}\); (b) Evolution of absolute spring-in angle and warpage in time for the production rate of 600 mmmin\(^{-1}\)

4. Conclusions

This paper presents results and analysis of 200 days experimental investigation of shape distortions related to the L-shaped pultruded profiles produced with the different pulling speed. Depending on the process parameters, different levels of shape distortions were registered. In particular in the case of slow curing process the resulting shape distortions exhibit lower value. It was observed that the spring-in and warpage take place immediately after manufacturing process and then start growing reaching the plateau after 60 days. Results of the experiment prove that pultruded profiles exhibit time dependent shape distortions.

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