Advanced Pultrusion Techniques as Alternatives in Aerospace Composite Manufacturing: A Review

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Abstract. Pultruded FRP composites' production and use in aerospace applications have grown over time as a result of its superior strength-to-weight ratio, enhanced durability, reduced labour costs, high productivity, corrosion resistance, and nonconductive qualities. In this regard, the pultrusion process has undergone several improvements enhancing its adaptability in producing composite products used in a variety of sectors. This review examines prospective uses for advanced pultruded FRP composites in the aviation and aerospace sectors as well as technological improvements in pultrusion.

1 Introduction

When it comes to commercial aerospace structural materials, the common materials used are steels, aluminum alloys, titanium alloys, and composites. Among these materials, composites are gaining significant attention from aviation and aerospace industries due to their high strength-to-weight ratio and superior physical properties. Generally, composites applied for aerospace structural applications aremade up of relatively strong and stiff fibres (carbon, Kevlar, glass) embedded in a tough resin matrix.

There are various manufacturing techniques in developing composites. Among the recent compositeprocessing techniques are categorized as open moulding, closed molding, cast polymer molding and additive manufacturing [1]. The selection of processing techniques depends on various aspects such as the resin type, reinforcement type and the positioning of fibre in the composites [2]. Theoretically, composites with better strength are produced through a process that utilises high volume of fiber reinforcement. Pultrusion is one of the most popular closed moulding processing techniques to create

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FRP profiles with high fiber volume and exceptional strength among the many types of manufacturing processes. Pultrusion is used to fabricate composite profiles of uniform cross sections which can be applied in aerospace industry.

Pultrusion process is time saving, and therefore economic way of fabricating composites. Besides that, parameters such as processing temperatures, processing speed and resin content can be accurately controlled, hence ensuring a good quality in the pultruded profiles. Table 1 lists some of the major advantages of pultruded FRPs over other conventional aerospace materials.

Table 1: Material properties comparison [3]

Properties	**Pultruded FRP composites**	**Steel**	**Aluminum**
Strength	High	High	High
Weight	Low	High	Low
Conductivity	Low	High	High
Corrosion resistance	High	Low	Medium
Impact resistance	High	Medium	Low
Dimensional stability	High	Low	Low
Finishing	Easy	Difficult	Difficult
Maintenance	Low	Medium	Medium

Typically, materials with lower weight are preferable in aircraft applications due to the lower fuel consumption during flight. Therefore, due to the low density of fiberglass composites, pultruded FRP profiles offer better strength-weight ratio as alternatives to heavier metallic structures in aerospace applications [4]. Pultruded composites are also far superior with excellent physical properties such as high corrosion resistance, and low magnetic and electrical conductivity when compared to traditional materials. Besides that, pultrusion process is also cost effective than compression molding and injection molding. Overall, with the numerous advantages pultruded FRP composite can offer, it has been steadily emerging in many development areas and is still open to market challenges. Moreover, pultruded profiles are recognized as high quality products applicable to wide range of structural element requirements in the aerospace sector.

2 Advancements in pultrusion manufacturing technology

Utilizing reinforcing fibers, resin, catalyst, fillers, and pigments, pultrusion is commercially practical for making polymer composite structures with a consistent cross-section in the form of flat bars, beams, channels, rods, solid, and hollow sections [5]. The main advantage of the continuous fiber laminating process is its capability of producing high fiber volume profiles with endless length making it an ideal process for structural applications with improved strength to weight ratio [6-8]. Additionally, the pultrusion method is not just restricted to the fabrication of open-section geometries; it may also be used to create single- or multi-celled closed-sections [9,10]. It is emerging in the composites industry due to continuous production and low labor cost [2]. Synthetic fibers such as glass and carbon fibres are the commonly used reinforcement materials in pultrusion. Pultrusion frequently uses resins notably polyester, polyurethane, vinyl ester, phenolic, and epoxy. The reinforcing materials usually used in pultruded FRP composites are continuous strand mats, continuous roving and chopped stand mats. The composite surface appearance, chemical resistance, and weather resistance are all enhanced by the employment of surfacing veil. The fiber arrangement and stacking sequence are varied according to theapplication of the pultruded composite [11].

Traditional pultrusion process starts with the fibre creel to easily pull the fibres without a knot. The fibers are then directed into the resin bath. The resin impregnated fibres will be pulled through a preformer into a heated die where the curing process takes place. Conventionally, the heating zones varies along the die depending on several factors, such as the resin type, the pulling speed, and the lengthof the die. The cross-sectional shape of the product is determined by the configuration of the die. A pulling device is installed to the system which pulls the fibres and cured profiles at desired processing speed. At the final stage, a sawing system is installed to cut the cured profiles according to the desired length. Generally, there are several processing control parameters that are important in producing pultruded composites such as the pull speed, resin viscosity, fibre volume fraction, and processing temperature [12,13]. The viscosity changes of the matrix determine the pulling speed to obtain a completely cured composite at the end of the process. In recent years, researchers and industrialists havebeen working on innovations of pultrusion process and its technology to expand its range of applicationsand productivity. The following sub-sections aim to provide an overview of the advancements made available in pultrusion technology which can be a potential alternative serving the aerospace industry.

2.1 Pultruded composite parts with variable thickness.

The traditional pultrusion process is restricted to the production of pultruded FRP profiles with constant cross-section with respect to the longitudinal pull direction. However, modified pultrusion techniques allows production of pultruded parts with variable cross-section and thickness. For instance, flanges, off-sets, bosses, and similar secondary structural products manufacturing is made possible via pultrusion[14]. During the process, the resin impregnated fibers are partially cured to a specific point which allowsdimensional stability. The uncured portion of the profile is then reshaped to desired variable cross-section and cured.

Technically, factors such as curing temperature in pultrusion die and pulling speed are controlled during the process to achieve a partially cured profile, hence reshaping the uncured portion from the die, and completely curing the profiles at the end of the process. Optionally, materials such as resin, fiber, molding compounds and metallic inserts can be added during the reshaping procedure. The modified pultrusion technique also can be used in developing functionally graded profiles for various application requirements.

2.2 Curved sections pultrusion

Although commercial pultrusion process has been known for its limitation to production of linear profiles, efforts and research has been also carried out to develop curved articles using pultrusion [15-17].

Fig. 1. Curved pultrusion by Shape Corp [15].

As shown in figure 1, Shape Corp's utilises curved pultrusion for the development of automotive bumper beams

Thomas Technik & Innovation (Bremervörde, Germany) developed Radius-Pultrusion technology where the fibre reinforced profiles cure in a heated movable die. The technique is different from traditional pultrusion where in traditional process, the die is stationary while radius pultrusion utilises a die that moves in a circular path over the resin impregnated fibers. Figure 2 shows a pipe coil prototypeand curved channel developed by the company using Radis-Pultrusion

Fig. 2. Curved pultruded products by Thomas Technik & Innovation [16].

PUL-AERO is introduced to produce curved and partially cured stringers aerospace applications. Technically, PUL-AERO project comprises two-stages. In the first stage, linear heated die partially cures the profiles for dimensional integrity. The partially cured profiles are then processed to the secondstage where curvature is introduced to the profiles and cured by a post-forming die Generally,advancements in curved pultrusion technology offers flexibility in designing FRP profiles and widens up new applications for composites in aerospace industry hence eliminating the limitation of pultrusionto linear profiles.

2.3 Prepreg systems

Traditional pultrusion typically uses dry fibers in manufacturing FRP profiles. However, an approach using aerospace-approved prepreg systems are used to develop pultruded FRPs to decrease the cost of pultrusion manufacturing One advantage of employing prepreg systems in pultrusion is the ability to maintain fiber angles within a tolerance of 1°. When compared to conventional pultrusion, which only allows for a tolerance of 4°, this is comparably efficient. Prepreg pultrusion also increases the fiber volume ratio to 65 % hence, providing more mechanical strength to the profiles. Besides that, the thickness is material is reduced compared to traditional pultrusion hence the amount of raw material usage is reduced while improving the fiber to matrix ratio inconsistency. Usage of prepreg system also eliminates the limitation of using high-viscosity resin system which is not suitable for traditional pultrusion. Additionally, pultruded parts fabricated using prepregs reduces void contents to less than 1 percent compared to conventional process which may result in up to 3 percent. Hence, prepregs in pultrusion can be an alternative option for producing primary aircraft and spacecraft structures with lower cost and higher performance.

2.4 Thermoplastic pultrusion

Commercially, thermoset resins such as epoxy, polyester, polyurethane, phenolic and vinyl ester are used in the pultrusion process. Among the thermosets, polyester is the most popular resin used in pultruded products, as it represents 75% of the total resins used in pultrusion. However, although numerous benefits offered by thermoplastic composites compared to thermosets, the application and market segment of thermoplastic pultrusion is comparatively lower than thermoset profiles [10]. Thermoplastic composites offer various advantages compared to thermoset composites such as unlimited shelf life, faster production, higher impact toughness, higher temperature resistance, environmentally friendly and recyclable. Besides that, thermoplastic pultrusion are also flexible for limited geometry reshaping after primary molding which can be also used in developing curved parts and parts with varying thickness [14].Studies and findings are proposed by researchers and validated the capability of thermoplastic pultrusion as alternatives to thermoset ones. Luisier et al. classified thermoplastic pultrusion into two categories which are reactive and non-reactive pultrusion. Reactive thermoplastic pultrusion involves chemical reactions between the resin and catalyst to polymerise the resin during the process while polymerized thermoplastic or towpregs are used in non-reactive process. A few examples of thermoplastic such as polyvinyl alcohol, polyamide, polyester, polylactide, polyethylene, polyurethanes, and polycarbonates provide a wide scope of applications in pultruded composite manufacturing Pultruded thermoplastic products can be a potential alternative to traditional aerospace materials by combining the superior properties of the material with the benefits ofpultrusion in the manufacturing industry.

2.5 Pultruded bio composites

Currently, pultruded structures and profiles with applications in many industries are produced using synthetic fibres, particularly glass fibres. Due to the usage of petrochemicals and the reliance on non- renewable energy sources, the excessive use of synthetic materials in composites has had certain detrimental effects on the environment. In addition, using synthetic fibre excessively is unhealthy and takes a very long time to disintegrate. Therefore, natural fibres are suggested to be preferable alternativesto synthetic materials in generating green composites for structural purposes in current period where green technology is rapidly rising. Natural fibres are preferred because of their superior strength-to- weight ratio, lighter weight, lower cost, and capacity to address sustainability challenges. Studies and research have been done by using natural fibres into the development of pultruded FRP composites Natural fibres such as kenaf, jute, hemp and flex are extensively studied by developing pure natural fibre reinforced pultruded composites and hybrid natural/glass fibre reinforced pultruded composites Overall, natural fibres can be employed to produce high performance structural elements for aerospace applications because of the improved qualities that pultruded composites could offer. Implementing natural fibres in pultruded FRP profiles can be a viable substitute for conventional fibreglass profiles in increasing awareness of the need to produce environmentally friendly and high- performance materials for constructions and infrastructure facilities

3 Pultrusion in Aerospace

`With the rising innovations in material science and engineering we are currently experiencing, advanced pultrusion is expected to witness significant gains in the global market due to the improved manufacturing flexibility according to the product's design criteria. Due to the superior properties pultruded FRP's could offer, efforts were taken by industrialists and researchers to develop innovative technologies for the applications that range from aerospace, construction, energy, and automotive sectors. Such innovations have led pultrusion technology to advance at a rapid rate and driving the growth for the global market. Aerospace industry have been leading the growth of composite materials market for the past decade due to the highly specific performance requirements of spacecraft and aircraft. An analysis was carried out on aerospace composites market has predicted the market growth of the materials to \$42.97 billion by 2022 with a CAGR of 9.85% between 2017 and 2022 Moreover, with the increased activity on space exploration and passenger traffic advanced pultrusion is expected to gain significant focus in developing aerospace materials with specific performance requirements where the pultrusion market is expected to reach production around 874,100 units by 2027.

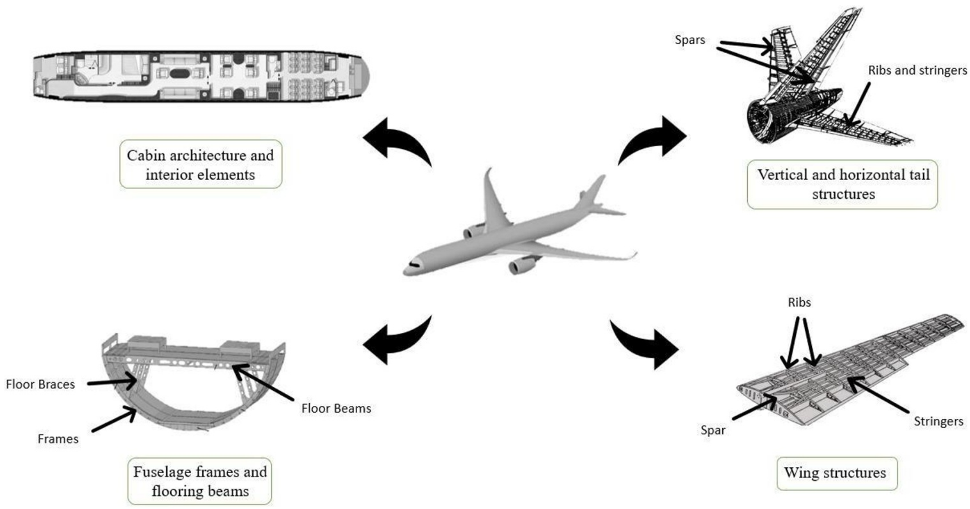

Fig. 3. Applications of pultruded profiles in aircraft components

For aerospace applications, traditional and advanced pultruded composites can be used to manufacture solid or hollow structural parts with various cross-sectional shapes (H, I, L, T, Z). The application is wide since pultrusion technology can solve any structural related requirements at any desired length and shapes. Besides that, the innovations in radius pultrusion have now unlocked the limitation of traditional method to manufacture linear pultruded profiles, hence can be applied to produce curved parts for various aerospace structural requirements. According to Minchenkov et al., thermoplastic pultruded composites have significant effects on the weight properties compared to traditional aluminum counterparts in aircraft structures [10].

As demonstrated in figure 3, some examples of the application in aircraft structure include vertical and horizontal tails, wings, flaps, curved and linear reinforcement parts (beams, frames, spars, stringers, stiffeners, etc.), upper deck floor beam and various interior elements. The applications can be also expanded into spacecraft structures such as in satellites, probes, rockets, shuttles, and space stations. Overall, having the biggest and fast-growing market in pultrusion, Asia Pacific could increase their market size in aerospace sectors by utilizing advanced pultrusion in developing FRP composites.

4 Conclusion

With the renewed push toward innovation in pultrusion technology, it's assured that pultruded FRP composites will continue to drive innovation in aviation and aerospace industry. The current advancements in pultrusion technology are believed to further uplift the market segment of these composites in aerospace applications. An overview of advanced pultrusion technologies such as pultrusion with varying thickness, radius pultrusion, prepreg pultrusion, thermoplastic pultrusion and bio composite pultrusion are discussed and its potential applications in aerospace are underlined in this review. Hence, besides providing solutions to overcome the limitations of traditional pultrusion, these advancements could serve as great alternatives to traditional materials by producing materials with superior performance and cost-effective properties.

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