THE PULTRUSION OF WOOD-BASED COMPOSITES

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ABSTRACT

The manufacturing process of pultrusion has been utilized by the polymer industry to produce composites with high mechanical properties. The end product can be produced in a wide variety of cross-sectional profiles with no limit on the length of the member. Pultrusion utilizes pulling action on the composite to convey the material through a forming die. The pultrusion of wood composites has the potential to be a viable processing option for the wood industry. The production of wood composites through pultrusion is based on the ability of the material to flow through a stationary die and for the applied pulling load not to exceed the tensile strength of the composite. Based upon the consolidation and the frictional or flow behavior and of the composite, a model can be developed to predict the applied pulling load. This model can determine the feasibility of producing the desired composite design. The advantage with pultrusion enables the final product to be engineered in both the sectional profile and through the material lay-up.

Keywords: wood composites, pultrusion, consolidation, and friction

INTRODUCTION

In the last two decades, the processing of wood composites has gone through some dramatic changes. Traditionally, wood composites have dominated the panel markets with plywood, particleboard, medium density fiberboard (MDF), and oriented strand board (OSB). Methods to produce these composites generally include some form of flat-pressing, where the loose mat is compressed to its final thickness in a batch or continuous process. Similar methods have been utilized to produce structural wood composites such as laminated veneer lumber (LVL) and oriented strand lumber (OSL). With the onset of wood plastic composites (WPC's), processing technologies from the polymer industry have been utilized, changing, not only the shape of the final products, but also the mechanics of manufacturing.

Two of the most common methods of manufacturing WPC's are through extrusion and injection molding, with the first being used most frequently. In extrusion and injection molding, the wood and plastic particulates are pushed or extruded through a stationary die to form the profile of the composite. With these methods, the flow of the material through the die is a crucial processing parameter. The WPC's provide the wood composites industry with a product that has improved exterior performance and a variety of profile designs.

The polymer processing technique of pultrusion provides another processing alternative for the manufacture of wood-based composites. In pultrusion, the composite is formed by pulling the material through a stationary die (Fig. 1). The die is machined to the final design of the product and heated to cure or melt the resin matrix. A pulling apparatus grabs onto the outputted product to provide a means of conveyance.

Within the context of this paper, a wood composite pultrusion process is described and the important processing variables identified. With a solid-based pultrusion system, the material flow and the accumulation of pulling load are crucial variables to be evaluated. By modeling the pulling load, the feasibility of producing the desired composite design can be determined.

Traditional Pultrusion

In traditional polymer pultrusion, the final product is comprised of continuous fibers encased in a resin matrix. The pultrusion line consists of an initial fiber creel system, preformer, resin impregnation bath, forming die, and a continuous puller. At the beginning of the operation, a creel system feeds the continuous fiber tows (glass, carbon, ara-

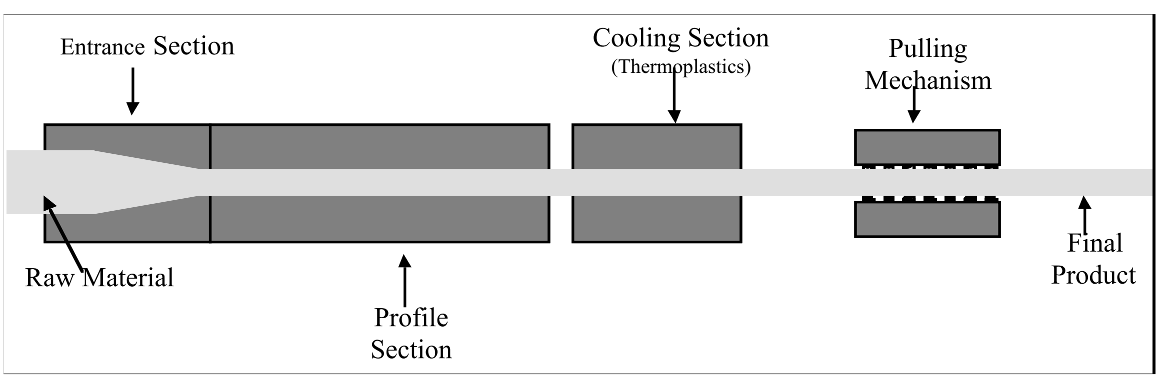

Figure 1.—Simplified pultrusion die setup with a cooling section for thermoplastic composites.

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mid, etc...) into a preformer section, which begins to align the fibers. Fiber mats and weaves can also be utilized in place of or in conjunction with the synthetic tows. The fibers are then drawn through a resin bath prior to entering the forming die, to impregnate the fibers with resin. The fibers then enter the tapered section of the forming die, where the material is consolidated into the final profile. The composite is held in its final form through the profiled section as the resins are heated. The pultruded product is then cut to length after passing through the pulling apparatus.

In the past, thermoset resins have been the most common matrix adhesive, however, thermoplastics resins can be found in limited applications. With the onset of thermoplastic resins, alterations in the pultrusion die are required. When utilizing thermoset resins, the entrance section of the die is quite short and has a dramatic taper. However, the higher viscosity thermoplastic resins require a longer more gradually taper to provide improved impregnation of the resin into the fibers (Astrom et al. 1991). Thermoplastic resin pultrusion also requires a cooling section at the outfeed of the die to harden the material prior to the pulling mechanism.

Pultrusion is utilized in the polymer industry to manufacture continuous composites with high mechanical properties and a variety of design profiles. Since the process is continuous, the final product can be of any desired length. The high amount of aligned, tensioned fibers makes pultruded composites very strong and stiff, especially in the longitudinal direction. Also, the flexibility in design profile enables the manufacture to produce many different profiles based upon the consumers needs.

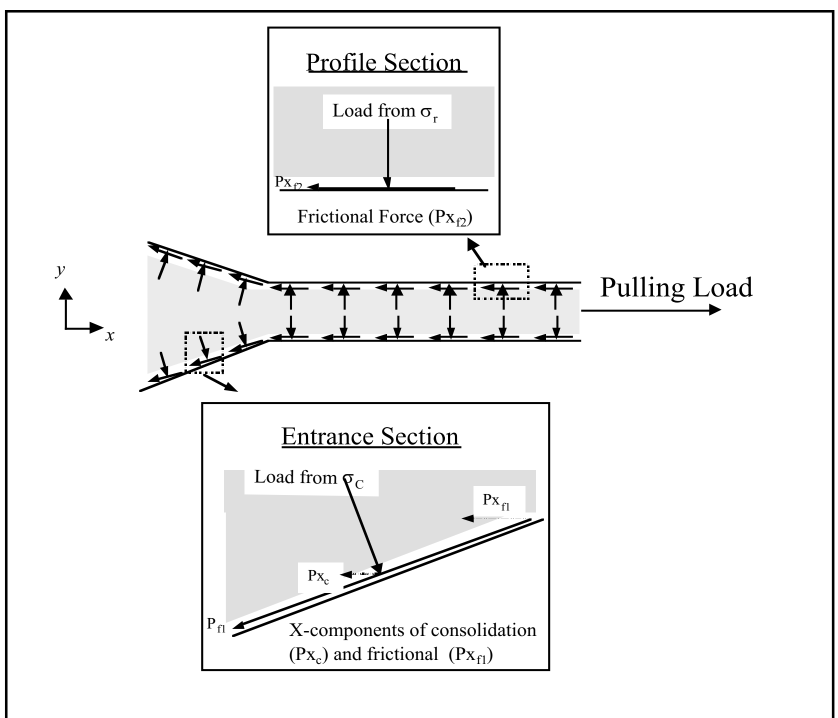
Wood Composite Pultrusion

Pulling Load Model

In a wood composite pultrusion system, the behavior of the material is based upon a solid mechanics, rather than fluid flow as seen with traditional pultrusion. The feasibility of pultruding wood composites rely on the ability to convey the raw material, and for the product to withstand the accumulated pulling load. The mat at the infeed of the die must have integrity or be conveyed through mechanical means. Modeling the acquired load is necessary to prevent failure from exceeding the tensile strength of the composite.

In order to estimate the pulling load for a wood composite system, a description of the consolidation stresses and the frictional behavior is necessary. As the wood mat enters the die, the wood elements are compressed into the final section profile. During this stage, compressive stresses are developed, which are influenced by elemental geometry, moisture content, die temperature, and strain rate. The frictional response of the wood composite also contributes to the pulling load, and can be influenced by the normal load, temperature, and exposure time (Englund 2001). In Figure 2, a schematic of a simplified pultrusion die is shown with the forces developed from consolidation and friction. The pultruded profile is a solid rectangular cross-section.

The forces in the entrance section develop from the consolidation (Px_c), Eq.1, and friction (Px_{f1}), Eq. 2, that result from the compressive stress (σ_c) developed as the composite is pulled through the tapered section. The total resistance (P_e) in the entrance section will be a summation



$$\sum Forces_x = Total\ Pulling\ Load = 2(Px_c + Px_{f1} + Px_{f2})$$

Figure 2.—Schematic of forces in a pultrusion die design.

of the two components (Eq. 3). The load is doubled based on the contact between the top and bottom surfaces and *x* is the direction in which the composite is pulled. An assumption for this model is that the edges of the composite along the die surface results in a minimal load accumulation and are neglected within the

$$Px_c = w\int_0^{L_e} \sigma_c \tan\theta \, dx \qquad \text{Eq. 1}$$

$$Px_{f1} = w\int_0^{L_e} \sigma_c \, \mu_k dx \qquad \text{Eq. 2}$$

where:

w – width of the composite

μ_k – dynamic coefficient of friction

θ – entrance angle

L_e – entrance length

$$P_e = 2(Px_c + Px_{f1}) \qquad \text{Eq. 3}$$

As the composite enters the profile section, the normal force will begin to decay as the compressive stress begins to relax (σ_r) at a constant strain. The total force for this section is due to friction along the die surface (Eq. 4). The total resistance to the applied load (P_t) then becomes a summation of the forces developed in the entrance and constant geometry sections (Eq. 5).

$$P_p = 2P_{f2} = w\int_0^{L_p} \sigma_r \mu_k dx \qquad \text{Eq. 4}$$

$$P_t = P_e + P_p \qquad \text{Eq. 5}$$

where:

L_p – length of the profile section

To determine the consolidation and frictional forces, a description of the compression response of the wood material is required. During consolidation, the wood mat exhibits a stress-strain behavior as the composite is compressed to a final thickness. A relaxation of stress ensues as the composite is held at a final profile, where a stress-time response is present.

The stress-strain and stress-time behavior of the wood mat is dependent upon the type of wood material utilized. Much research has been dedicated to the stress-strain modeling of wood (Easterling et al. 1982; Gibson and Ashby 1982; Maiti et al. 1984) and wood strand composites (Wolcott et al. 1994; Dai and Steiner 1993; Lang and Wolcott 1996; Lenth and Kamke 1996). Recent work by Englund (2001) modeled the stress-strain response of wood fiber mats. Little research in wood composites has addressed the relaxation behavior during processing, however, the field of polymer science has utilized mechanical analogies to create a numerical description of the relaxation process (Ferry 1980). These analogies were found to fit well with wood fiber composites (Englund 2001).

Existing Wood-Based Pultrusion

The wood composites industry has had little exposure to pultrusion processing methods. Trus Joist MacMillan utilizes a modified pultrusion method to produce Parallam®, while Frank Beall (1991) developed a patent to pultrude non-woven cellulosic fiber mats with synthetic fiber reinforcement. Parallam® technology incorporates long wood strands coated with resin into a continuous press. The primary means of conveyance is through pulling mechanisms at the outfeed of the press, however, a belt on the top and bottom of the product helps reduce the frictional component of the process as the solid rectangular billet is produced. The patent developed by Beall, is more similar to traditional pultrusion, where the cellulosic fiber mat act as a filler and a high amount of resin and synthetic fiber reinforcement are utilized. TJM currently has three plants producing Parallam, while no known commercial use of Beall's patent is in use.

Recent work with pultruding low resin wood-based composites has been ongoing at the Wood Materials and Engineering Lab in Pullman, WA. Their work has included the pultrusion of a rectangular profile of laminated veneers and non-woven wood fiber mats. With the laminated veneers, phenol-formaldehyde (PF) resin was applied to the wood surface at spread rates similar to LVL manufacturing. Pulling loads for the laminated veneers were below the tensile strength of the composite, therefor no reinforcement was required. Non-woven wood fiber mats were also pultruded, however, the pulling loads exceeded the tensile strength and carbon fiber was utilized to reinforce the composite.

Potential Markets

The potential markets for pultruded wood-based composites lie in utilizing the advantages of the process. Pultrusion provides the manufacturer with a product that can be processed into a variety of design profiles and allows for the opportunity of incorporating continuous reinforcement to increase mechanical properties. Engineering the composite profile, either through sectional design or by lay-up, can minimize the material utilized and decrease weight, while maintaining the mechanical and physical property requirements of the product.

The ability to reinforce the wood composite and form the profile into a variety of sectional designs make pultruded wood composites an attractive option for structural members. Beams, headers, and columns for light frame construction are possible interior products, along with window and door applications. Incorporating thermoplastics into a non-woven mat also opens the possibility of exterior structural composites. Deck joists, columns, and pilings for residential and commercial usage could also be achieved with the proper composite lay-up.

CONCLUSION

The concept of pultruding wood-based composites has proven to be a feasible production method. One of the most important parameters for pultruding wood composites is the product being able to withstand the applied pulling load. By modeling the pulling loads, the composite type, density, profile design and processing parameters can be determined for their feasibility. The flexibility in profile design and the ability to add synthetic reinforcement, make wood composite pultrusion an attractive product for light frame construction and exterior structural use.

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