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Development of a Pultruded FRP Sunroom System

by

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Abstract

An industry-first FRP sunroom system has been developed. This system, principally consisting of pultruded lineals combined with molded plastic components leverages multiple strengths of composites. The stiffness, strength, complex shapes, thermal efficiency, and finish options available in pultruded composites combine to make a beautiful home enhancement that performs to higher wind loads than competitive aluminum/vinyl hybrid systems. The article contrasts the composite solution with the current state of the art in traditional materials. The development of the product, from design to testing to final installation is described. Some description of material structure and processing methods are included.

Introduction

Pultruded fiberglass window framing materials were developed in the late 1980's as a response to a growing need for maintenance-free, high performing fenestration products. The DOE has identified that up to 50% of energy consumed by buildings is for heating, and has mandated that by the year 2025 all newly constructed commercial buildings must be energy neutral. Some of this efficiency will come from alternative power generation, such as solar, geothermal, or wind energy; however, much of these gains must come from improved efficiency. Fenestration technology is therefore of significant importance for energy savings.

Aluminum has been the framing material of choice for commercial window applications because of its high yield strength (35,000 psi) and modulus ($1.1X10^7$ psi). However, with a thermal conductivity (k) value of 140 Btu/hr-ft-^{0}F, it suffers significantly as compared to wood (0.70 to 0.85 Btu/hr-ft-^{0}F) or vinyl (0.110 Btu/hr-ft-^{0}F).

Vinyl has captured significant share of the residential window market, but has limited commercial application because of its inferior mechanical properties and inability to meet commercial building code requirements. With a modulus of only $4.1X10^5$ psi, and tensile yield stress of $8.0X10^3$ psi it is vastly inferior to aluminum, or even wood. Poor mechanical properties can lead to excessive deflection and/or total failure of the assembly under high wind loads (positive or negative), creating a significant safety concern. But the low modulus of vinyl also degrades the insulating performance of the window system at moderate pressures, since significant air infiltration can occur with even modest deflection under load. Furthermore, the high rate of thermal expansion and contraction can compromise the window seal at both the perimeter and glazing interface. In addition, finish options are very limited in vinyl, such that most vinyl windows are sold and installed with the 'as-produced' glossy white or almond color, with evident surface imperfections that are inherent in the extrusion process. There is very little that can be done to apply custom finishes in the field, and the unfinished surface yellows rapidly due to UV exposure.

Pultruded composite window framing, typically consisting of a thermoset resin matrix with E-glass reinforcement ranging from 45-70% by weight, addresses these deficiencies. The thermal conductivity of fiberglass is similar to that of vinyl, but because of the lower thermal coefficient of expansion ($4.4X10^{-6}$ in./in.^{0}F) thermal expansion and contraction is 85% lower than vinyl and 64% lower than aluminum (based on vinyl $29X10^{-6}$ and aluminum $12.3X10^{-6}$). This leads to better sealing of operating sashes and lower stress on glazing seals.

While the framing material represents only a fraction of the total mass of a window, it has a disproportionate impact on the thermal performance of the assembled unit, both because of losses through the frame, and because of the impact on edge-of-glass temperature. For example, the typical U-value for an aluminum casement window with low-E double glazing is 0.55, while the same window framed in fiberglass has a U-value of only 0.29—a 47% improvement in thermal performance!

With achievable modulus (dependent upon fiber fraction) of up to 6.5 $X10^6$ psi, fiberglass framing material can meet the stringent performance requirements of high-rise installations. Also, because pultruded FRP offers stability, resistance to corrosion, and methods of producing thin, hollow, and complex geometries with many finish options, it is also an ideal framing material for residential windows.

Composite windows therefore offer the strength of aluminum, along with the maintenance-free characteristics of vinyl with superior thermal performance and finish options. Because of the thermal properties combined with structural properties it is envisioned that pultruded

FRP could be ideal for integrated structural/fenestration systems such as curtain wall used in many commercial applications. Recently, fiberglass pultrusions have been developed to address just such a combined structural/fenestration market need within the *residential* envelope: a framing system for patio enclosures, usually referred to as sunrooms.

The purpose of a sunroom is to admit lots of natural light, but maintain a comfortable indoor environment. Excessive heat gain in the summer and heat loss in the winter could make the room unbearable, and climate control impractical. Sunrooms therefore present significant thermal performance demands. Additionally, a sunroom presents significant structural requirements to handle snow loads and wind loads. In some regions, particularly coastal, these wind loads can be severe, especially because the sunroom creates a projection from the main dwelling. One option for constructing a sunroom is stick-building, but this is costly and time consuming. Additionally, the openings for windows are limited by the stud spacing and header requirements in many code jurisdictions.

Producers have responded to this market need with aluminum-framed rooms, allowing larger and more numerous openings for glass. Such aluminum rooms are often clad with vinyl for aesthetic improvement, but this does little to address the thermal deficiencies. Additionally, unless the aluminum extrusions are relatively heavy (and costly) the wind-load performance is generally poor as compared to a stick-built room. Although it has been our experience that building codes are not uniformly applied across different jurisdictions, we believe that the string of natural disasters in recent years that have lead to significant property loss will lead to a tightening of code requirements. These demands will therefore become more stringent, and more uniformly applied in future. This is especially true in coastal (i.e. hurricane) regions, where design loads are based on 110 to 150 mph gusts.

The pultruded framing system that is the topic of this paper was developed and tested to meet stringent structural requirements in severe wind regions. The geometry was designed to be multi-functional and reduce the number of components as compared to competitive systems. In addition to the thermal benefits detailed earlier, the FRP room has better acoustical dampening properties, more effectively blocking nuisance noise from the outside, and the finished product looks superior to competitive systems. Despite these benefits, the installed cost is only a modest 10-15% premium over competitive vinyl/aluminum systems.

Structure

The basic structure of the room is demonstrated in Figure 1. The post is joined to the floor starter (the same profile is also used as the header) with an internal key that is screwed through the tabs to the starter. The same basic connection is used at all junctions, such as sills to posts, or headers to corner posts (shown in Figure 2). Internal channels in the post and starter accommodate wiring. The fiberglass components replace multiple components in typical competitive systems: an aluminum tube, a vinyl sleeve, and exterior applied electrical race. The whole structure can be delivered to the site as pre-finished components and assembled erector-set fashion. Figure 3 demonstrates the assembly of a typical wall section. Recently, a 10’ X 20’ cathedral room (figure 4) was completely assembled in 1 day excluding site prep. The finished product was aesthetically superior to either stick-built or typical aluminum/vinyl hybrid structures.

Performance, design, and testing

Performance requirements

PE calculations of required modulus (for deflections not exceeding L/240 at 70% of maximum pressure) and ultimate load (at a factor of safety of 2.5) to meet general building code requirements are shown for the vertical structural post in Tables 1 and 2, and for the header in Tables 3 and 4. Figures 5 and 6 demonstrate typical loading conditions on a studio-style room. As shown in tables 1 through 4, load requirements vary with the height of the room, and the spacing between vertical posts. Higher post spacing is desirable to minimize sight lines and maximize light transmission.

Design

In order to maintain high production speeds and optimum cost, the pultruded profiles were limited to a maximum 0.210” thickness. Beyond this, thermal problems become more complex in pultrusions, since the materials need to be heated upon entry to the die, and excessive heat build up in thicker parts can cause cracking upon exit of the die. The depth of the profile was limited by the window systems to 3.5”, and the width, in order to minimize the site lines of the structural members, was limited to 4.75”.

With the above limitations it was determined that the application demanded a local modulus of over $6X10^6$ PSI to meet performance targets. A rule-of-mixtures micromechanics model shown in the equation below was employed to determine the required reinforcement content.

$$E_1 = \phi_f E_f + (1-\phi_f)E_m$$

Where:

E_1 = Axial Modulus,

E_f = Fiber Material Modulus,

E_m= Matrix Material Modulus, and

ϕ_f = Fiber Volume Fraction

It was concluded that an average 70% by weight glass content would be required to meet the performance requirements. While this is not high for pultruded rods of all-roving construction, it is considerably higher than typical for complex hollow profiles with combined mat and roving.

Since in this application the profiles would see significant shear and transverse stresses, surface mats would be required. Also, in cosmetic applications typically mats with very fine fibers are placed on the surface, combined with a low-profile resin system. These are typically only available in A-glass mats, though in principal could also be produced with E-glass.

Since micromechanics models are linear, they can generally be applied with only a few percent error (predicted vs. tested deflection). We were therefore confident in meeting deflection requirements with the chosen design. However, we were concerned about meeting the ultimate load requirements. Finite element analysis using ABAQUS was therefore employed to determine the stresses in the part. Figure 7 shows the stress map on a vertical post member when simulated in 3-point bending. The stresses where the inner wall meets the outer flanges were predicted to exceed the strength of the random mats. Changing the loading condition to distribute the load uniformly significantly reduced these stresses. Such distributed load would also more realistically represent loads transferred to the structural members due to wind pressure on the assembly.

Even so, stress predictions exceeded the strength of the random mats for the highest load applications (for maximum room size and/or maximum wind speeds). Therefore, it was decided to employ off-axis (weft) rovings stitched to a mat carrier. By using small fibers (1800 yield) turned to the inside of the laminate it was felt that the print-through of the weft fiber could be minimized to the point that the applied cosmetic finishes would hide the remaining surface profile. More will be said about finishes below.

Testing

The challenge remained to apply a distributed load in a single-component deflection test. For this, a fixture was designed to pivot in 6 places and apply the load at 8 points along a 12 foot beam. The deflection test fixture at National Composites Center, originally designed to test composite bridge beams, was used to apply the load. A test in progress is shown in Figure 8.

Referring back to Tables 1 through 4, the superimposed ellipses show the range of height, spacing, and wind speed allowable within code requirements for the FRP structure as compared to a competitive “vinyl” room constructed with 3” X 3” X 0.095” aluminum tube structural members. It should be noted that code compliance for the aluminum structure is based on a safety factor of only 1.67, since the published design guide for aluminum mandates this. In contrast, the performance envelope for the FRP room is based on a safety factor of 2.5, which is mandated by the general building code in all cases where no published design standard exists. On an equivalent basis, the contrast between the composite and aluminum performance envelopes would be greater. Nevertheless, the net result was a much larger design envelope for the composite room, allowing installation in 150 mph wind regions with 8’ high wall posts spaced 72” apart. The highest load condition allowed for the competitive aluminum/vinyl room is 120 mph at only 7’ height and 54” spacing. This creates a significant competitive advantage for the composite room in coastal regions where sunrooms are very popular. It could be argued that an aluminum structural system can be produced to meet the same performance as the FRP room, but the material would have to be extruded much thicker than the typical 0.095” wall. This would erase the competitive price advantage of the vinyl/aluminum room and would do nothing to address the thermal or cosmetic deficiencies.

Surface Finish

FRP manufactured with styrenated resins typically exhibits poor UV performance. While higher performing alkyds can be selected, the styrene crosslink is prone to yellowing, and alternative crosslink agents are impractical for cost and environmental reasons. Therefore, most FRP fenestration products are painted in a secondary operation. This is costly and in-efficient, and the resulting finish is prone to scratching in assembly and installation operations.

To address these deficiencies it was decided to apply an extruded acrylic finish over the fiberglass. These thermoplastic acrylics have zero unsaturation and are therefore highly resistant to yellowing. They are also very tuff and therefore scratch resistant. Similar acrylic finishes are used on the surface of FRP spa tubs, and also extruded over PVC siding. Figure 9 shows QUV A weathering comparison of acrylic to PVC of the same color. Over a period of 9000 hours the acrylic color shift ΔE was in the range of 0.5 units, while the PVC color shift was 4.5 units.

Applying the acrylic finish requires an extruder to force the molten acrylic through a die at high pressure. It is important to achieve balanced flow in the die so that material is applied uniformly around the cosmetic surfaces of the part. This requires careful tuning of the die with consideration of the flow channels and clearances. Figure 10 shows the part exiting the extrusion die immediately upon start of the acrylic flow, showing the contrast between the light-colored FRP surface and the beige acrylic.

Production

Considering the significant design loads and stresses at wall intersections we did not want to risk any gaps in the transverse reinforcements. The goal was therefore to wrap a single piece of mat around the exterior perimeter of each part and another single piece around the interior. For the corner post, which is the largest part, the widest mat would therefore be 22". The mat had to be formed progressively to wrap around the part and into the contours of the corners and the electrical race.

To meet the reinforcement targets, over 600 ends of 113-yield roving were required in each part. This did not meet the EPA definition of 1000 ends for a "large part" that would exempt the die from control requirements, but on the other hand presented a significant challenge for control. With average lineal weight of almost 3 lbs per foot, and average neat resin content of over 0.5 lb/ft we could not afford to run the parts in an uncontrolled fashion (i.e., open bath), because of the impact on our average emission reduction. An enclosure would have been impractical to operate, and less efficient at emission reduction than pre-form injection. Therefore, pre-form injection was the only practical solution. To meet this challenge required multiple injection points prior to the die. In addition reaching desired production rates required circumferential heat around the die. Figure 11 shows the line in production.

Conclusion

Fiberglass pultrusions have been used to develop a sunroom framing system that is more attractive and structurally higher performing than a competitive aluminum and vinyl hybrid system, meeting code requirements at higher wind loads and therefore permitting installation in more regions. The fiberglass room is thermally more efficient than competitive products, and the extruded acrylic finish is highly resistant to fade and yellowing due to UV exposure, as well as being tough and resistant to scratches and chips. This high-performing product is sold at a modest premium to current competitive products.

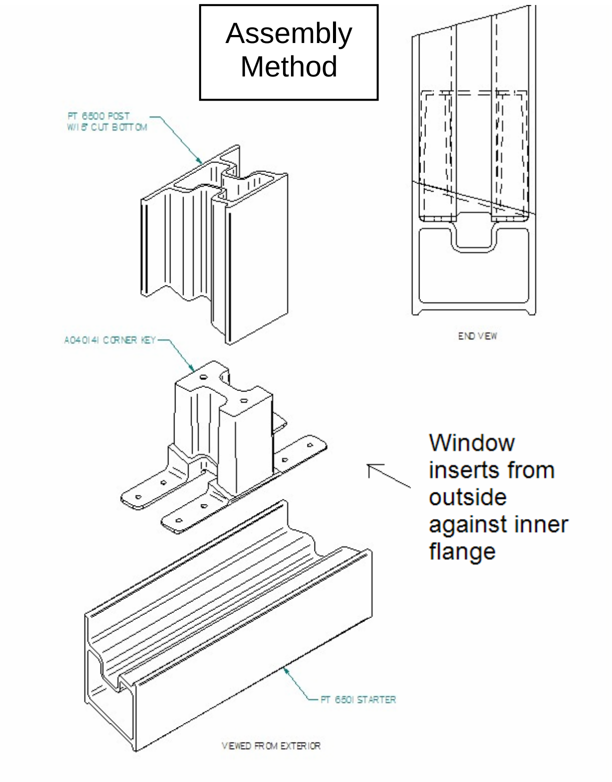


Figure – 1

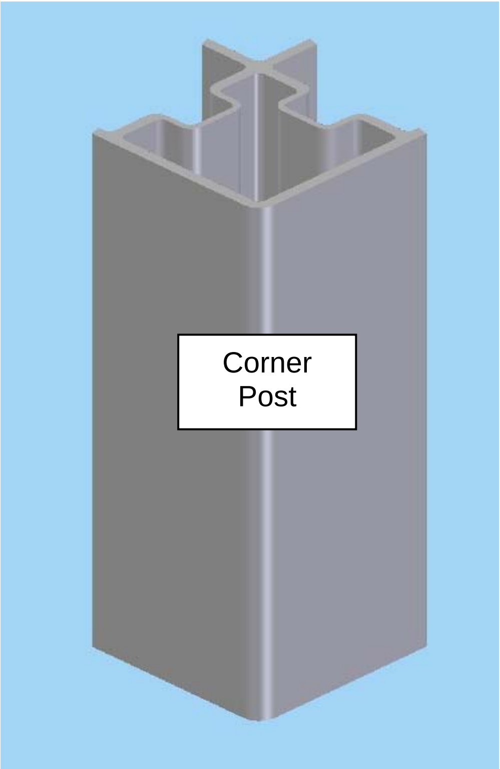


Figure-2

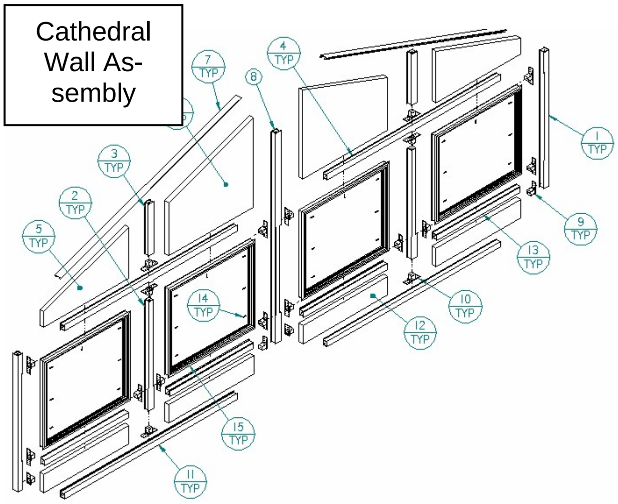
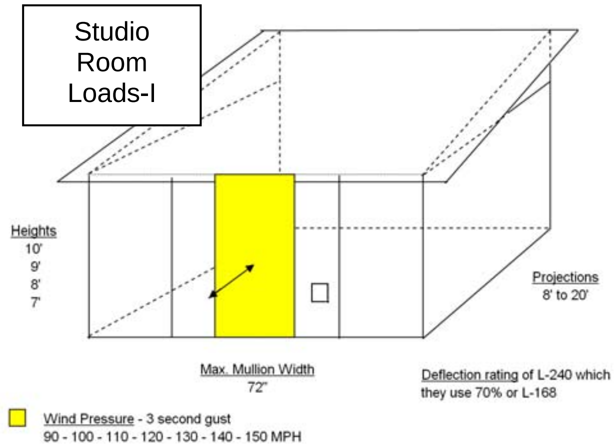


Figure-3

Figure-4



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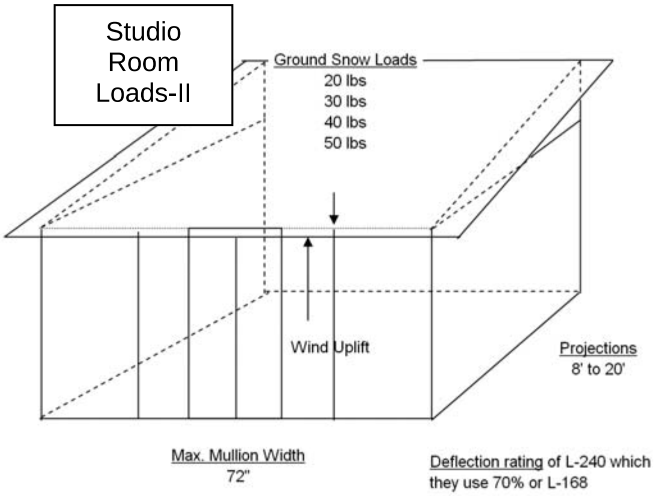

Figure-6

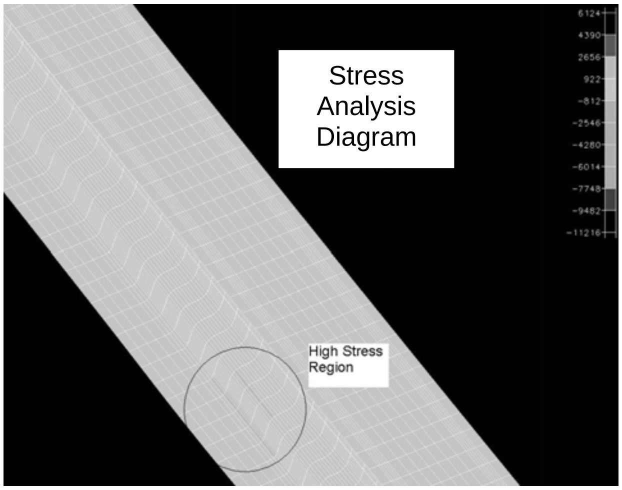

Figure-7

Figure-8

Table 1

Section Modulus, Vertical Posts (PSI, Millions)

	Wall Height	7 ft	8 ft	10 ft
Post Spacing	90 mph Wind			
	54 in spacing	8.9	13.3	25.9
	72 in spacing	11.9	17.7	34.6
	120 mph Wind			
	54 in spacing	15.8	23.6	46.1
	72 in spacing	21.1	31.4	61.4
	150 mph Wind			
	54 in spacing	24.7	36.9	72.2
	72 in spacing	33	49.3	96.2

Vinyl/Aluminum Room *FRP Room*

Performance Envelopes

Table 2

Ultimate Load, Vertical Posts (lbs, at 2.5 S.F.)

	Wall Height	7 ft	8 ft	10 ft
Post Spacing	90 mph Wind			
	54 in spacing	1441	1647	2058
	72 in spacing	1921	2196	2745
	120 mph Wind			
	54 in spacing	2559	2925	3656
	72 in spacing	3412	3900	4875
	150 mph Wind			
	54 in spacing	4016	4590	5737
	72 in spacing	5355	6120	7650

Vinyl/Aluminum Room *FRP Room*

Performance Envelopes

Table 3

Header, Negative Load (lbs, at 2.5 S.F.)

	Projection	10 ft	15 ft	20 ft
Post Spacing	90 mph Wind			
	54 in spacing	1545	2028	2512
	72 in spacing	2059	2704	3349
	120 mph Wind			
	54 in spacing	2317	3599	4457
	72 in spacing	3655	4799	5943
	150 mph Wind			
	54 in spacing	4290	5631	6973
	72 in spacing	5719	7508	9297

Vinyl/Aluminum Room *FRP Room*

Performance Envelopes

Table 4

Header, Positive Load

	Uniform Snow Loads (psf)			
	30 psf		50 psf	
Post Spacing	Load* (lbs	EI (psi, millions)	Load* (lbs	EI (psi, millions)
54”	3375	15.8	4500	24.8
72”	5625	37.4	7500	58.8

*At 2.5 S.F.

Vinyl/Aluminum Room *FRP Room*

Performance Envelopes

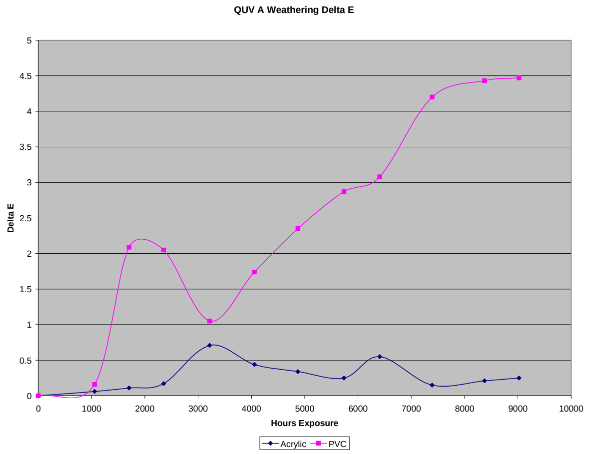

Figure-9

Figure-10

Figure-11

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