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FOUNDATION ELEMENTS FOR NAVAL LOW-RISE BUILDINGS

FINAL REPORT

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Foundation Elements for Naval Low-Rise Buildings

Processing of Engineering Polymer Wood Plastic Composites: Thermoplastic Epoxy Resin (TPER) and Nylon 12

Material Improvements Group

Task M1 – Implement crosslinked polyolefin reactions during manufacture

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Project End Report

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Abstract

Natural fiber composites are commonly used in residential decking, siding, and fencing applications, but their use in high-load structural applications has been limited by their low strength performance. However, wood-plastic composites (WPCs) consisting of nylon 12 and thermoplastic epoxy resin (TPER) exhibit excellent mechanical performance. This study evaluated the extrusion parameters for each composite including: barrel/die temperature profile, lubricant compatibility, wood flour (WF) content, and WF moisture content (MC). Increases in strength and modulus of both composites indicated significant adhesion between polymer and wood components. These composites show promise for use in structural applications currently lacking WPC presence.

Introduction

Over the past two decades, wood-plastic composites (WPCs) have become widely accepted as a viable substitution for wood members in non-structural or low-load applications (Smith and Wolcott, 2006; Clemons, 2002). WPCs are commonly used in residential decking, siding, and fencing, which are applications sensitive to decay and moisture damage. The limited strength of existing WPCs has limited their impact on structural materials requiring higher-strength properties, although other applications such as industrial decking and transportation materials could benefit from WPCs natural durability and processing capabilities. However, this would require superior strength performance to traditional WPC systems. Commercial WPCs currently utilize polypropylene (PP), polyvinylchloride (PVC), and polyethylene (PE) as the base polymer. Previous research has identified two engineering polymers, poly(hydroxyaminoethers) (e.g. thermoplastic epoxy resin, TPER) and nylon 12 (Figure 1), as having significant potential in high strength WPCs (White et al., 2000; Lu et. al., 2007).

TPER is commercially used in automotive frames and packaging applications (White et al., 2000; Constantin et al., 2004; Chmielewski, 2008). Analogous to their thermosetting cousins, thermoplastic epoxy resins exhibit vastly improved mechanical characteristics compared to commodity thermoplastics. In addition, intermolecular hydrogen bonding afforded by the TPER structure promotes excellent adhesion gas barrier properties. White et al. (2000) found that compression-molded TPER WPCs increased tension capacity from 43 MPa to 75 MPa with the addition of 30 % wood flour. Unlike many polyolefin WPCs, this was attributed to the adhesion potential of TPER.

Previous research has also identified nylon 12 as having significant potential in WPCs due to its high strength properties, low melt temperature and water sorption rate relative to other nylons. Like TPER, nylon 12 is widely used in many commercial applications such as food processing, packaging, marine products, clothing, tubing, and piping (Lu et. al., 2007). The challenge for commercial use of nylon 12 in WPCs is its relatively high melt temperature (ca. 178ºC), which requires processing temperatures over 200ºC.

The development of nylon 6 WPCs (T_m: 215ºC) has been widely studied, especially for injection and compression molding processes with both wood and high purity cellulose (Klason et al., 1984; Sears et al., 2001). However, few studies have been conducted on the use of nylon extrusion processes in WPCs because processing wood flour at temperatures over 200ºC leads to the production of volatiles from decomposition. In this process, entrapped gases and degraded wood polymers reduce the mechanical properties of the wood flour and polymer systems (Saheb and Jog, 1999).

To avoid the high processing temperature requirements of nylon 6, Lu et al. (2007) characterized several formulations of nylon 12 WPCs processed with various wood flour loadings. In this research, material was processed at or below 200ºC using a torque rheometer to melt blend the formulation followed by compression molding to form a plaque. It was found that increasing the wood content significantly improved the modulus of elasticity (MOE) and modulus of rupture (MOR) in nylon 12 wood composites. Lu et al. (2007) hypothesized that strong interfacial adhesion between wood and nylon 12 improved the mechanical properties.

However, little research has been conducted on the extrusion processing of TPER and nylon 12 WPCs. The goals of this research are to explore formulation and process parameters towards development of extruded TPER and nylon 12 wood flour (WF) composites. In some experiments, injection molding was used to facilitate a larger range of wood flour content. The primary objectives of this study are to:

1. Define a suitable temperature profile for the extrusion process,
2. Determine a compatible lubricant system for an extruded composite,
3. Evaluate the influence of wood fiber moisture content on mechanical and physical properties of the final extruded composites, and
4. Experimentally relate wood fiber loading to mechanical performance for each composite.

Materials and Methods

Material

The WPC formulations evaluated were composed of wood flour, lubricant, and one of two engineering polymers: a commercial TPER polymer (L-TE05-10, MFI: 10, Tg: 81ºC), provided by L&L Products (Romeo, MI), or nylon 12 (Grilamid L 20 G, T_m: 178ºC, MFI: 20, density: 1.01g/cm^3), supplied by EMS-Chemie (Sumter, SC). The wood flour component used was 60-mesh pine (*Pinus spp*) flour (American Wood Fibers, Schofield, WI) with a moisture content (as received) of 9-10%. Commercial lubricants evaluated were: OPE629A oxidized polyethylene homopolymers (Honeywell, Morristown, NJ), Glycolube® WP2200 (Lonza Inc., Allendale, NJ), and a 2:1 blend of zinc stearate (Lubrazinc® WDG) and EBS wax (Kemamide® EBS) (Chemtura, Middlebury, CT).

Prior to extrusion, the wood flour was dried to a moisture content of < 2% by total mass (oven dry weight) using a steam tube dryer. Wood flour, polymer, and lubricants were then mixed in a low intensity blender for 5-10 minutes to form a dry blend, which was fed into the appropriate processing equipment.

Torque Rheometry

Torque rheometry data was collected on a Haake Rheomix 600 with a 69 ml net chamber capacity. Testing was performed on a 50 gram sample at a screw speed of 50 rpms for 10 minutes. Torque data was used to evaluate potential barrel zone temperatures for extrusion and potential compatible lubricants for TPER and nylon 12 WF composites.

Extrusion

Extrusion trials were performed on a conical counter-rotating twin-screw extruder (Cincinnati Milicron CM 35). The extruder has a downstream diameter of 35-mm, tapered from the feeding throat to the die, with a length to diameter ratio of 22. Test materials were extruded through a rectangular cross-sectioned slit die (3.7 X 0.95-cm) at a screw speed of 10 rpm (TPER/WF) and 20 rpm (nylon 12/WF), and spray-cooled with water upon exiting. Extrusion temperatures were independently controlled in three barrel zones and two die zones (Table 2). Melt pressure was monitored immediately before the material entered the first die zone.

Injection Molding

Flexure samples (12 X 3 X 127 mm) were injection molded with a Sumitomo SE 50D machine. Temperature zones of the molding machine were independently controlled for TPER/WF formulations at 70°C, 180°C, 180°C, and 180°C, from feed zone to nozzle, respectively. For nylon 12/WF formulations, the molding temperature profile was increased to 170°C, 220°C, 220°C, and 220°C, from feed zone to nozzle. Mold temperature was maintained at 70°C with a cooling time of 40 seconds for TPER/WF, and reduced to 55ºC and 30 seconds for nylon 12 formulations. The mold temperature and cooling time for TPER/WF formulations were increased to facilitate flow of the highly viscous composite melt in the mold cavity. Although not optimized, average cycle times of 90 and 60 seconds were recorded for all TPER/WF and nylon 12/WF samples respectively. Filling pressure was set at 1600-kgf/cm^2, while the 1st and 2nd stage packing pressure was set at 500-kgf/cm^2 for TPER/WF formulations. In nylon 12/WF formulations, filling pressure was reduced to 1200-kgf/cm^2, while the 1st and 2nd stage packing pressures were increased to 900-kgf/cm^2 and 750-kgf/cm^2, respectively.

Prior to injection-molding the formulation, pellets were prepared using a co-rotating twin screw extruder (Leistritz ZSE-18) with a screw diameter of 17.8-mm and L/D ratio of 40. The 8 independently controlled barrel zones were set to 150°C, 160°C, 170°C, 180°C, 180°C, 180°C, 180°C, and 180°C from the feeding throat to the die adapter in TPER/WF formulations and set to 190°C, 205°C, 210°C, 210°C, 215°C, 215°C, 215°C, and 215°C in nylon 12/WF formulations. Screw speed was maintained at approximately 60 and 80 rpm for TPER/WF and nylon 12/WF blends, respectively, throughout the compounding of the composite material.

Mechanical Testing

Both extruded and injection molded samples were tested in flexure according to ASTM D790 standards. Each sample was planed on the two wide faces to eliminate any irregularities in the surface of the material, and then conditioned for 48 hours prior to testing. Length, width, thickness, and mass were measured for each specimen after conditioning and used to compute density. Mechanical testing was performed on a screw driven Instron 4466 Standard with 10 kN electronic load cell. The support span for testing was 16 times the depth. A crosshead speed of 1.7 mm/min, for injection molded, and 3.8 mm/min, for extruded, were maintained throughout testing.

Results and Discussion

Processing Temperature

In developing the processing regime necessary for a WPC, proper barrel and die temperatures must be determined to facilitate good flow and melt strength of the extrudate. Extrusion temperatures below 200ºC are typically used to minimize wood degradation and volatile formation (Saheb and Jog, 1999). Additional information regarding the thermal degradation of nylon 12 WPCs is available in Appendix A. Prior to attempting extrusion, torque rheometry was utilized to observe the change in melt properties with temperatures varying between 180ºC to 200ºC for TPER/WF formulations. An initial temperature of 180ºC was selected based on previous research where metering and die temperatures ranged between 180ºC and 220ºC (White et al., 2000). Due to the relatively high melt temperature (T_m = 178ºC) for nylon 12, torque rheometry temperatures were selected between 190ºC to 225ºC. As shown in Figure 2, at all temperatures and formulations, the torque decreases rapidly and reaches a relatively stable value within one-minute. Nylon torque curves never plateau at a constant torque, but continue to decrease well after one minute, indicating sensitivity to shear heating of the composite at these temperatures. For each composite, both the rate of change and the minimum torque decreased with increasing temperatures. However, based on experience with TPER/WF, all processing temperatures appear to be adequate for an extrusion process. Nylon 12/WF, on the other hand, appears to require a higher processing temperature to decrease the amount of torque required on the system, indicating better melt flow of the composite.

The time required to reach a stable minimum torque remains constant, with little variability for the various processing temperatures investigated. This value can be associated with the residence time required to achieve a uniform melt blend during extrusion. Based on our work, barrel residence times in WPC profile extrusion range from 3 to 8 minutes. Considering the minimum time of three minutes, a processing temperature of 180ºC and 225ºC is more than adequate to reach a uniform melt for TPER/WF and nylon 12/WF formulations, respectively. Therefore, barrel zone temperatures were then selected for extrusion with center barrel zones 2 and 3, both maintained at 180ºC or 225ºC based on polymer type. However, during nylon 12/WF extrusion, heating coil capacity in the 3rd and final barrel zone was limited to 205ºC. Consequently, the first barrel zone was set at 225ºC to ensure proper melt. Cooling of the extruded composite is very important in nylon 12 WPCs to mitigate the effects of prolonged exposure to these higher temperatures (Appendix B). For TPER/WF formulations, a maximum temperature of 150ºC was controlled for the feed zone to ensure that premature melting of the material did not impede feeding of the dry blend.

Additional consideration must be given for the die temperatures to facilitate flow and achieve a well consolidated composite with good melt strength. Mechanical properties are listed in Table 1 for TPER/WF and nylon 12/WF WPCs extruded with different die temperatures. Interpretation of this data for both polymer systems indicates that reducing the die temperature from 180ºC to 120ºC (TPER/WF) or 205ºC to 190ºC (nylon 12/WF) increased composite density (1.17 g/cm^3 to1.25 g/cm^3 and 1.098 g/cm^3 to 1.154 g/cm^3, respectively) (Figure 3). Likewise, the modulus of rupture (MOR) for TPER WPCs was lowest for a die temperature of 180ºC and remained relatively constant below 160ºC (Figure 3). The dramatic decrease in MOR at a high die temperature may be associated with the decreased density of the composite. Low die temperature was found to raise melt pressures at the extruder exit, which in turn affected density by promoting the penetration of the polymer matrix into the wood fiber voids. Melt pressure for TPER and nylon 12 WPCs are shown in Table 1 and indicate that at 180ºC and 120ºC the melt pressures for TPER WPCs are 287 and 938 psi, respectively. Analysis of nylon 12/WF composites yields a similar correlation between melt pressure, density, and MOR for die temperatures of 205ºC to 190ºC (Figure 3). Based on optimum mechanical properties, all further extrusion trials were conducted using the extrusion profiles detailed in Table 2, with die zone temperatures of 140ºC and 190ºC for TPER and nylon 12 WPCs, respectively.

Effect of Lubricant

It is important to select a proper lubricant for processing a wood fiber composite in order to lower the melt viscosity of the heavily filled WPC formulation and ensure a uniform flow through the die. However, in some cases, any added lubricant can impede the adhesion of the wood and polymer interface (Gupta et al, 2007). For both polymer systems, the oxidized polyethylene lubricant, OPE629A, showed excellent potential in preliminary torque rheometry tests by reducing the melt viscosity considerably (Figure 4). However, the WP2200 in TPER WPCs and the Zinc Stearate/EBS wax blend in nylon 12 WPCs showed only moderate to low potential in lowering viscosity.

To further evaluate lubricant performance in extrusion, composites containing 3%, 2%, 1% OPE629A, 3% WP2200 (TPER), and 3%(2:1) zinc stearate/EBS wax (nylon 12) were produced (Table 1), and mechanical properties were characterized. TPER WPCs produced with both 3% WP2200 and 1% OPE629A exhibited poor external lubrication, which resulted in severe surface tearing of the composites (Figure 5). Melt pressures observed for both 1% OPE629A and 3% WP2200 were unstable and greater than 1000 psi, suggesting high flow resistance or poor melt strength in the die. Nylon 12 WPCs containing 3% zinc stearate/EBS wax and < 3 % OPE629A yielded similar tearing behavior and an increasing melt pressure trend. However, TPER composites produced with 2% or 3% OPE629A and nylon 12 composites produced with 3% OPE629A could be extruded without visible defects. Additionally, the homogenous cross sections in both composites suggested a uniform density and flow. The MOR of the TPER composite was 86.0 to 93.4 MPa at 3% and 2% OPE629A loading, respectively. MOE, density, and strain at failure all exhibited similar behavior, indicating that lubricant content significantly impedes TPER/WF interaction (Table 1). Therefore, based on the apparent influence of lubricant content on mechanical and physical properties of the composites, 2% OPE629A for TPER and 3% OPE629A for nylon 12 composites were selected as the lubricant loading for all remaining work.

Influence of Wood Fiber Moisture Content

Prior to extrusion, wood flour is typically dried to a moisture content (MC) of less than 2% to eliminate a majority of water vapor from the extrusion process. Excess water vapor can become trapped in the composite melt, leading to a reduction in density, bubbles that form stress concentrations, and surface defects. In the third heating zone of the extruder, a vacuum was utilized to remove gases and vapor that form as byproducts during extrusion. To understand the effect of MC on the final composite, blends were extruded with MCs of 1.2-1.8% (dry), 3.0% (partially dried), and 9.3% as received (Table 3) following the extrusion profile in Table 2.

Mechanical testing of nylon 12 samples at 9.3% MC showed little statistical variation, while the MOR of TPER samples was reduced (Table 4). Of particular interest is that at MCs of less than 2% and 9.3 % respectively, densities obtained for nylon 12 (1.153 and 1.160 g/cm^3) and TPER (1.228 and 1.237 g/cm^3) did not differ significantly. This indicates that water vapor created during extrusion was either easily evacuated from both composites or does not act as a foaming mechanism.

Mechanical Performance of Engineering Polymer Composites at Different Wood Loadings

Both injection-molded and extruded samples of varying wood flour contents were evaluated to determine mechanical properties. Samples were formulated at wood contents from 40 to 70-wt% extruded (Table 4), and 0 to 60-wt% injection-molded (Table 5) for both nylon 12 and TPER WPCs. Injection molding of TPER WPCs beyond 50% was limited, due to the difficulty of maintaining optimum melt flow into the mold, which is consistent with other composites developed using injection molding techniques (Singh and Mohanty, 2007). Thermal properties for injection molded TPER and nylon 12 WPCs are presented in Appendices C and D (Hatch, 2008). As expected, MOE increases with wood content for both polymer systems (Figure 6), and strain to failure is reduced (Figure 7). Of significant interest is the impact of increasing wood fiber content on MOR (Figure 8). For injection molded TPER samples, MOR increases consistently from 82.4 MPa to 125.9 MPa (53 % increase in strength) at 50 % wood fiber (Table 5). A similar increase in MOR was observed for nylon 12 samples, resulting in a 96% (60% wood flour-injection) and 75% (50% wood flour- extruded) increase over injection molded pure nylon 12 (MOR = 48.43 MPa) (Table 4-5). The apparent increase in MOR of injection molded samples vs. extruded samples seems to be linked to the higher strains to failure sustained by injection molded samples (Figure 7). Representative stress strain curves for nylon 12, TPER, and HDPE (Gacitua, 2008) injection molded composites with 40% wood flour are presented in Figure 9.

Stiffness and density of TPER WPC's correlated very well between processing methods, indicating the stiffness of TPER WPC's is independent of the type of processing method employed (Figure 6, 10). Anderson (2007) found similar results, with little difference in stiffness of PE wood fiber composites using the methods discussed. The correlation between increased densities of injection-molded composites with increased wood loadings aligns with previous research using high wood loadings of 50-57% (Anderson, 2007; Stark, 2004).

Conclusions

Mechanical performance of TPER/WF and nylon 12/WF composites is governed by many processing variables. A reverse extruder temperature profile was selected, which provided adequate melt pressures to facilitate the consolidation of both TPER and nylon 12 WPCs in the die and form a composite with high melt strength and density as it exited the die. Lubricant selection significantly affected processing of these composites, and OPE629A was ultimately selected for both systems. OPE629A was found to promote melt flow and not significantly inhibit adhesion of either TPER or nylon 12 to the wood fiber matrix. Wood fiber moisture content (MC) was found to have a negligible affect on nylon 12 composite mechanical performance, while TPER composites at 9.3% MC exhibited a reduction in strength.

A comparison of wood flour loadings using injection molded and extruded samples of TPER and nylon 12 WPCs demonstrated that increasing the wood content of the composite results in a corresponding increase in stiffness and a reduction in strain to failure. The modulus of rupture for TPER WPCs was increased by 53% in injected samples of 0 to 50% wood flour, while extruded material exhibited a peak wood flour loading of 40%. More promising results were observed for nylon 12 WPCs, in which MOR increased by 96% and 75% for injection molded and extruded specimens, respectively. Processing method, as expected, significantly influenced the mechanical properties of both WPCs.

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Tables

Table 1. Mechanical properties, density, and processing melt pressures of extruded TPER/WF and nylon 12/WF composite formulations at various die temperatures and lubricant contents.

% Wood	% TPER	% OPE	Die Temp. [ºC]	Modulus of Rupture [MPa]	Modulus of Elasticity [GPa]	Strain @ Failure [%]	Density [g/cm^3]	Melt Pressure [psi]
60	37	3	**120**	81.43 (6.71)	6.040 (0.109)	1.21 (0.12)	1.246 (0.016)	938
60	37	3	**140**	86.03 (8.45)	6.130 (0.172)	1.26 (0.10)	1.245 (0.011)	530
60	37	3	**160**	85.33 (5.32)	6.079 (0.143)	1.26 (0.09)	1.217 (0.013)	375
60	37	3	**180**	70.14 (8.00)	5.421 (0.422)	1.16 (0.15)	1.168 (0.026)	287
60	38	2	**140**	93.42 (8.99)	6.416 (0.224)	1.33 (0.10)	1.233 (0.019)	847
	NYLON 12							
60	37	3	**190**	76.05 (7.42)	4.207 (0.228)	1.81 (0.21)	1.154 (0.008)	200
60	37	3	**200**	55.23 (7.33)	3.750 (0.122)	1.49 (0.24)	1.089 (0.013)	150

Table 2. Extrusion temperature profile for TPER/WF and nylon 12/WF composites.

	TPER [°C]	Nylon 12 [°C]
Barrel Zone 1 (Feed)	150	225
Barrel Zone 2	180	225
Barrel Zone 3	180	205
Die Zone 1 & 2	140	190
Screw	155	199

Table 3. Mechanical properties, density, and processing melt pressures of TPER/WF and nylon 12/WF composites at various initial wood fiber moisture contents (MC).

% Wood	% TPER	% OPE	Wood Fiber MC [%]	Modulus of Rupture [MPa]	Modulus of Elasticity [GPa]	Strain @ Failure [%]	Density [g/cm^3]	Melt Pressure [psi]
60	37	3	**1.8**	91.96 (7.04)	6.37 (0.120)	1.31 (0.13)	1.228 (0.010)	530
60	37	3	**3.0**	93.40 (5.44)	7.183 (0.189)	1.15 (0.07)	1.264 (0.011)	793
60	37	3	**9.3**	84.55 (5.49)	6.815 (0.247)	1.09 (0.11)	1.237 (0.013)	625
	NYLON 12							
60	37	3	**1.2**	78.92 (8.98)	4.649 (0.162)	1.77 (0.34)	1.153 (0.014)	150
60	37	3	**3.0**	77.63 (5.70)	4.434 (0.229)	1.81 (0.24)	1.141 (0.019)	180
60	37	3	**9.3**	78.89 (5.68)	4.312 (0.178)	1.94 (0.30)	1.160 (0.016)	220

Table 4. Mechanical properties, density, and processing melt pressures of extruded TPER/WF and nylon 12/WF composites at various wood fiber loadings.

% Wood	% TPER	% OPE	Modulus of Rupture [MPa]	Modulus of Elasticity [GPa]	Strain @ Failure [%]	Density [g/cm^3]	Melt Pressure [psi]
40	58	2	103.32 (3.81)	5.78 (0.131)	1.72 (0.12)	1.243 (0.005)	287
50	48	2	97.93 (6.70)	6.28 (0.115)	1.43 (0.12)	1.243 (0.005)	375
60	38	2	91.96 (7.04)	6.37 (0.120)	1.31 (0.13)	1.228 (0.010)	530
70	28	2	77.58 (7.42)	6.97 (0.143)	0.95 (0.11)	1.241 (0.011)	938
	NYLON 12						
40	57	3	43.61 (4.63)	1.728 (0.098)	3.69 (0.61)	0.927 (0.011)	130
50	47	3	84.90 (3.66)	3.973 (0.082)	2.47 (0.23)	1.144 (0.008)	150
60	37	3	77.80 (5.53)	4.258 (0.112)	1.89 (0.23)	1.160 (0.10)	200
70	27	3	47.18 (10.05)]	3.870 (0.323)	1.18 (0.21)	1.128 (0.029)	400

Table 5. Mechanical properties and density of injection-molded TPER/WF and nylon 12/WF composites at various wood fiber loadings.

% Wood	% TPER	% OPE	Modulus of Rupture [MPa]	Modulus of Elasticity [GPa]	Strain @ Failure [%]	Density [g/cm^3]
0	100	0	84.43 (0.61)	2.762 (0.007)	4.16 (0.06)	1.173 (0.003)
0	97	2	82.81 (1.22)	2.639 (0.040)	3.60 (0.15)	1.160 (0.006)
20	78	2	105.22 (1.13)	4.204 (0.065)	3.29 (0.06)	1.202 (0.007)
30	68	2	115.59 (1.96)	5.091 (0.138)	2.64 (0.10)	1.226 (0.007)
40	58	2	122.17 (0.68)	5.702 (0.077)	2.37 (0.04)	1.253 (0.002)
50	48	2	125.94 (2.06)	6.386 (0.179)	1.90 (0.12)	1.270 (0.004)
	NYLON 12					
0	100	0	48.43 (0.71)	1.182 (0.013)	4.86 (0.12)	0.994 (0.001)
0	97	3	43.89 (0.29)	1.056 (0.022)	4.80 (0.07)	0.976 (0.002)
20	77	3	63.50 (0.90)	1.888 (0.034)	4.57 (0.07)	1.027 (0.004)
30	67	3	74.74 (0.51)	2.411 (0.030)	4.30 (0.08)	1.066 (0.003)
40	57	3	84.16 (0.66)	2.871 (0.054)	4.13 (0.14)	1.093 (0.003)
50	47	3	91.11 (0.60)	3.589 (0.043)	3.09 (0.09)	1.133 (0.003)
60	37	3	94.96 (1.07)	4.480 (0.131)	2.36 (0.08)	1.178 (0.006)

Figures

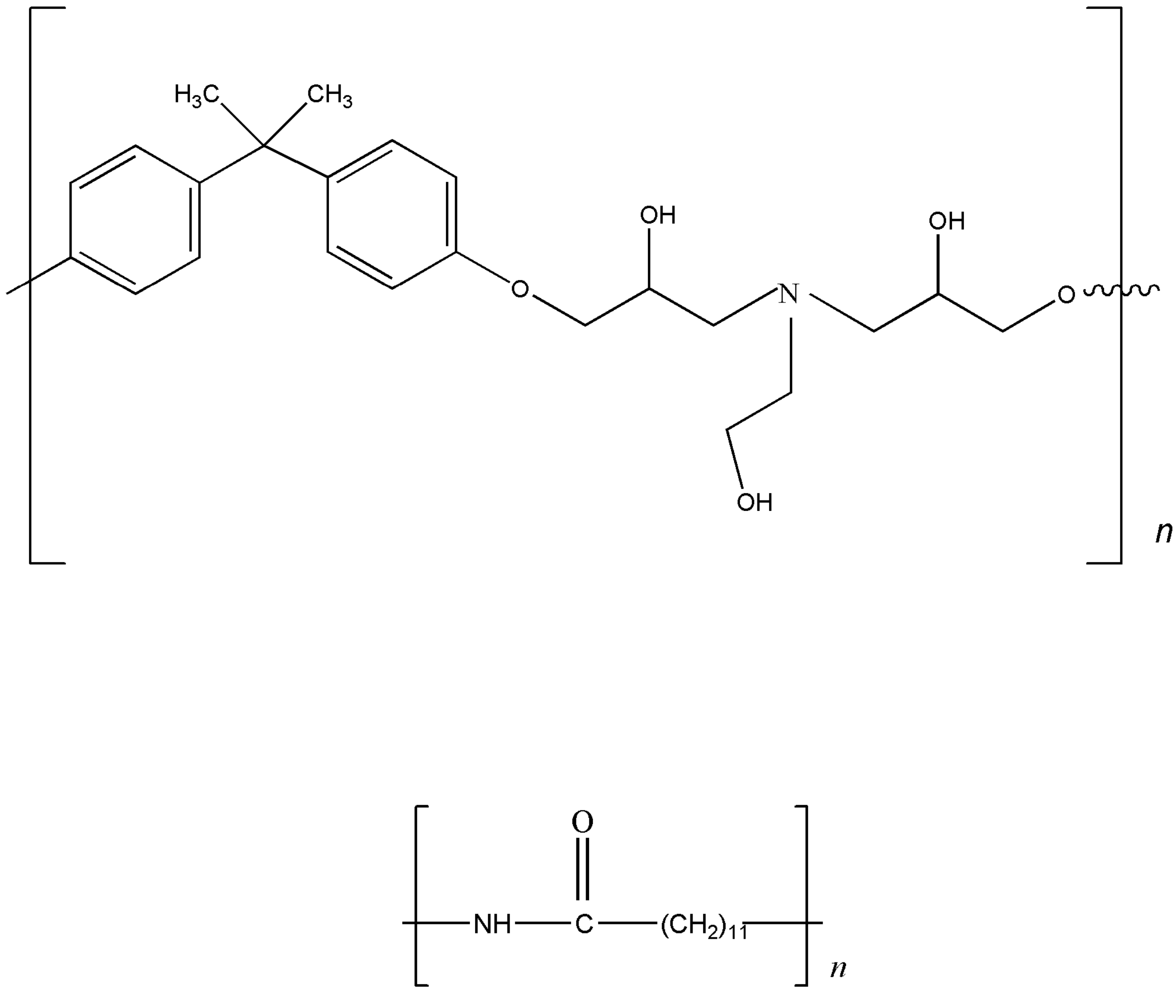

Figure 1. Primary chemical structure of TPER (Top) and nylon 12 (Bottom) polymers (TPER adapted from Constantin et al., 2004).

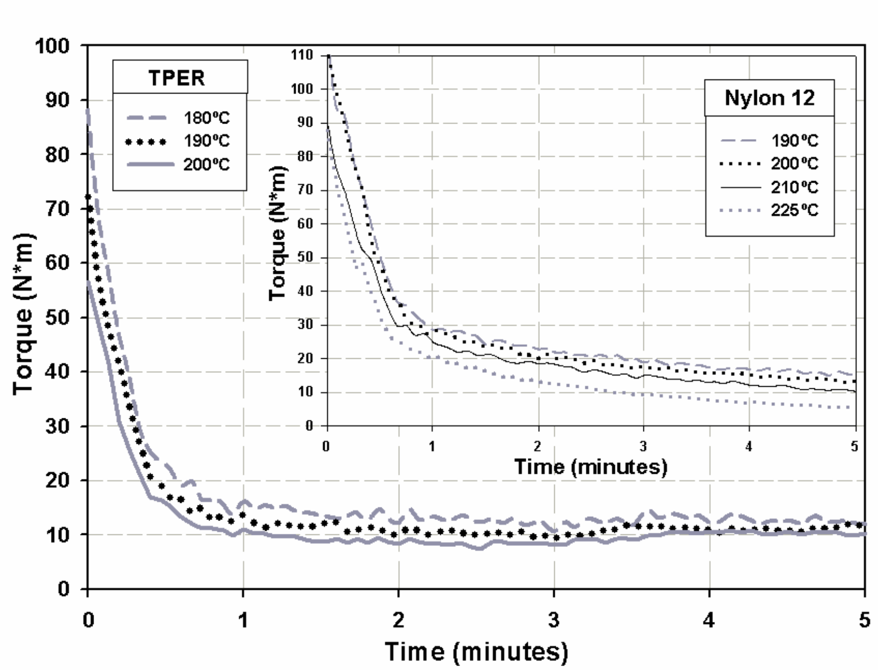

Figure 2. Variation of torque with respect to time of 40% TPER/ 60% WF and 40% nylon 12/ 60% WF composites (no lube) at various chamber temperatures.

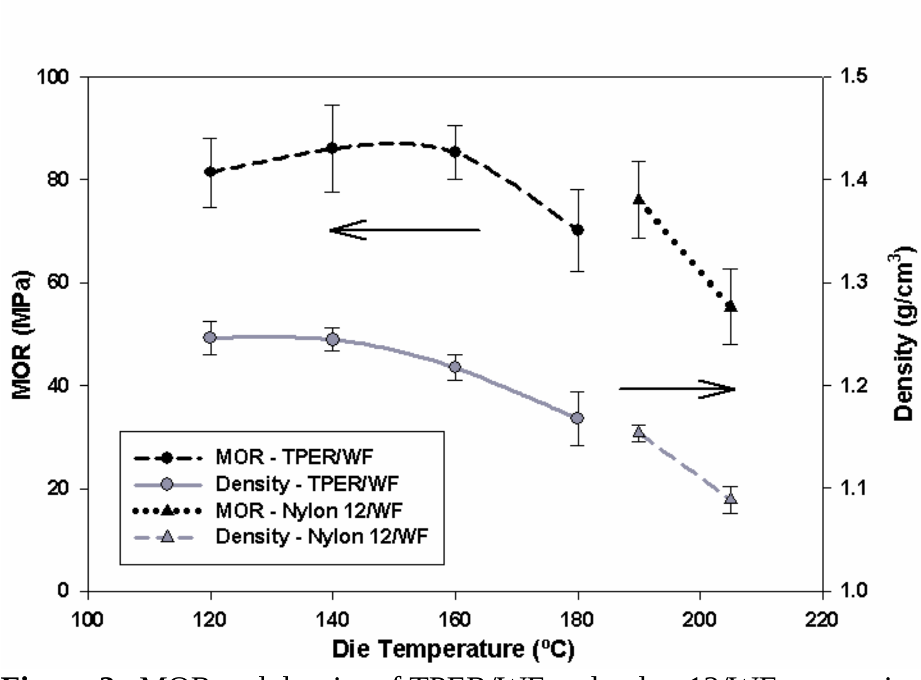

Figure 3. MOR and density of TPER/WF and nylon 12/WF composites at various extrusion die temperatures.

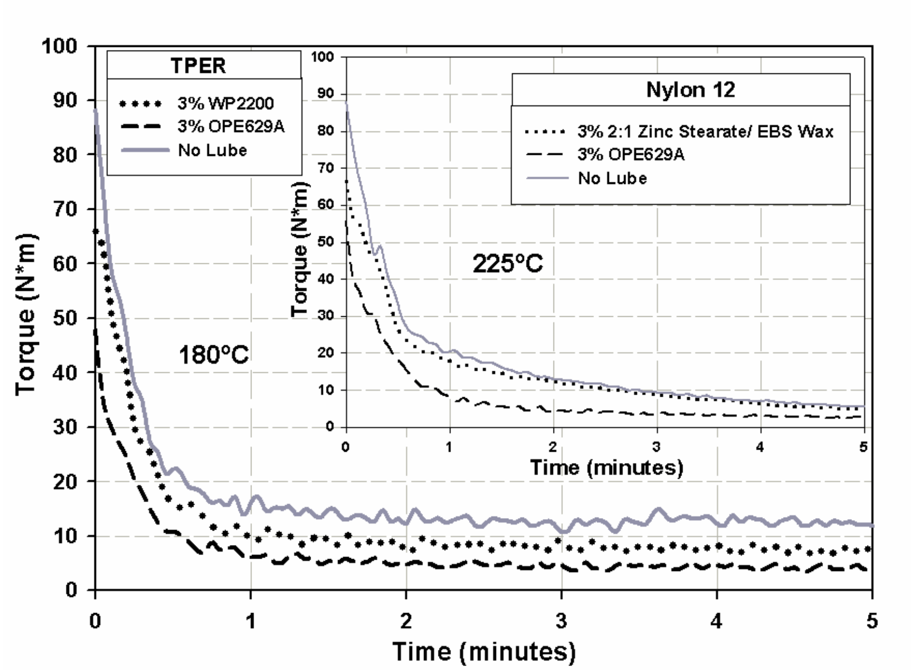

Figure 4. Variation of torque with respect to time of various formulations of 37-40% TPER/ 60% WF and 37-40% nylon 12/ 60% WF.

Figure 5. Extruded TPER/WF composites containing 2% OPE629A, 1% OPE629A, and 3% WP2200 from left to right, respectively.

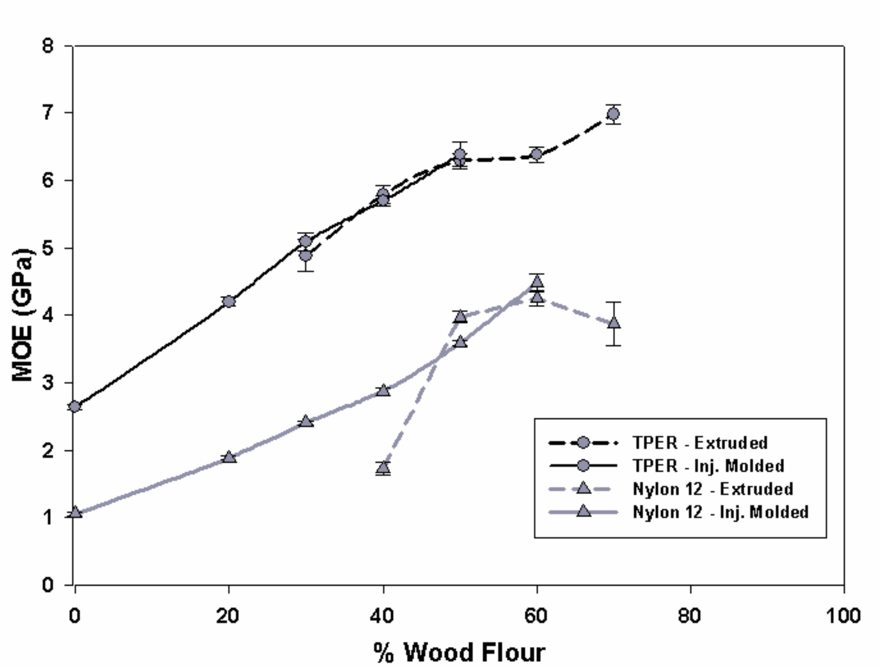

Figure 6. Flexural modulus of elasticity (MOE) of TPER/WF and nylon 12/WF composites with various wood flour contents.

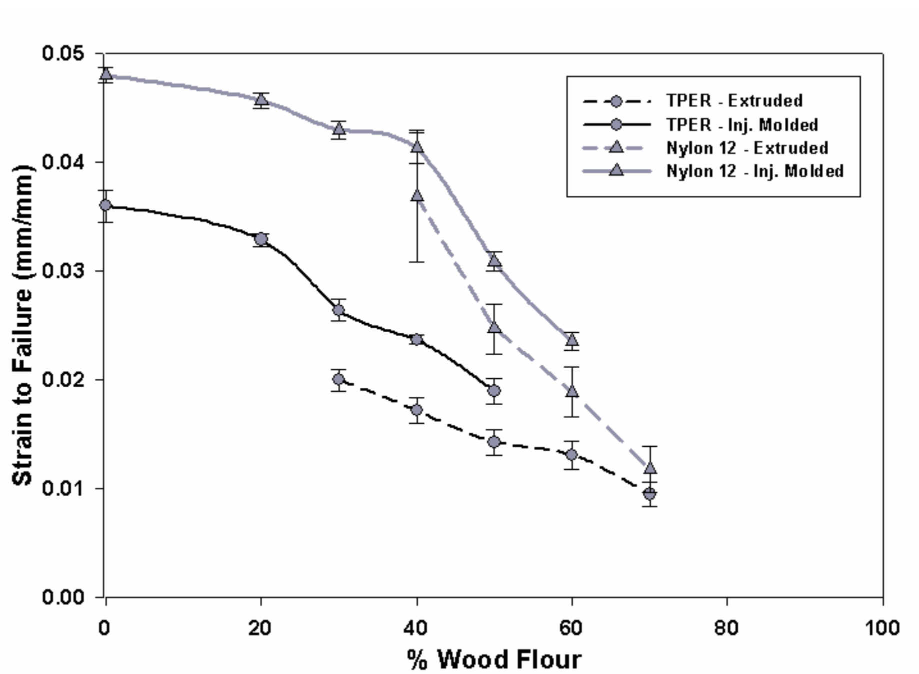

Figure 7. Strain to failure of TPER/WF of TPER/WF and nylon 12/WF composites with various wood flour contents.

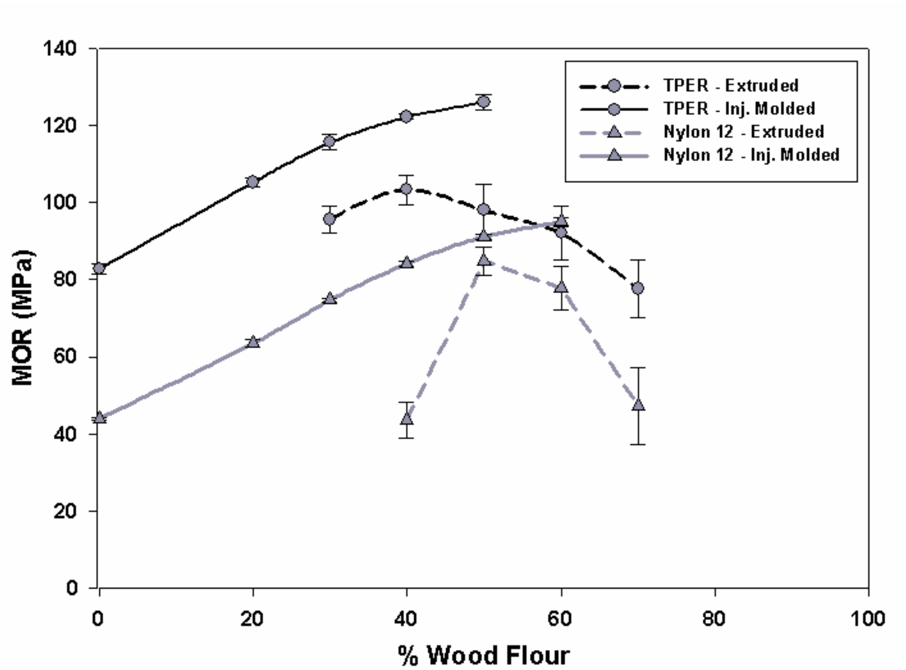

Figure 8. Flexural modulus of rupture (MOR) of TPER/WF and nylon 12/WF composites with various wood flour contents.

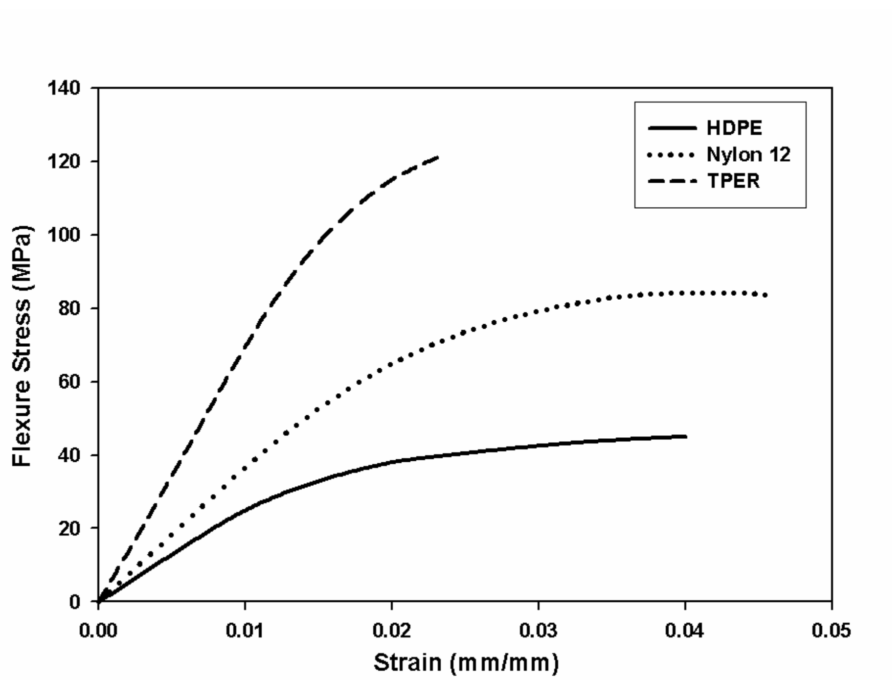

Figure 9. Stress-strain curves for injection molded TPER, nylon 12, and HDPE WF composites with 40% wood fiber. (HDPE curve adapted from Gacitua, 2008)

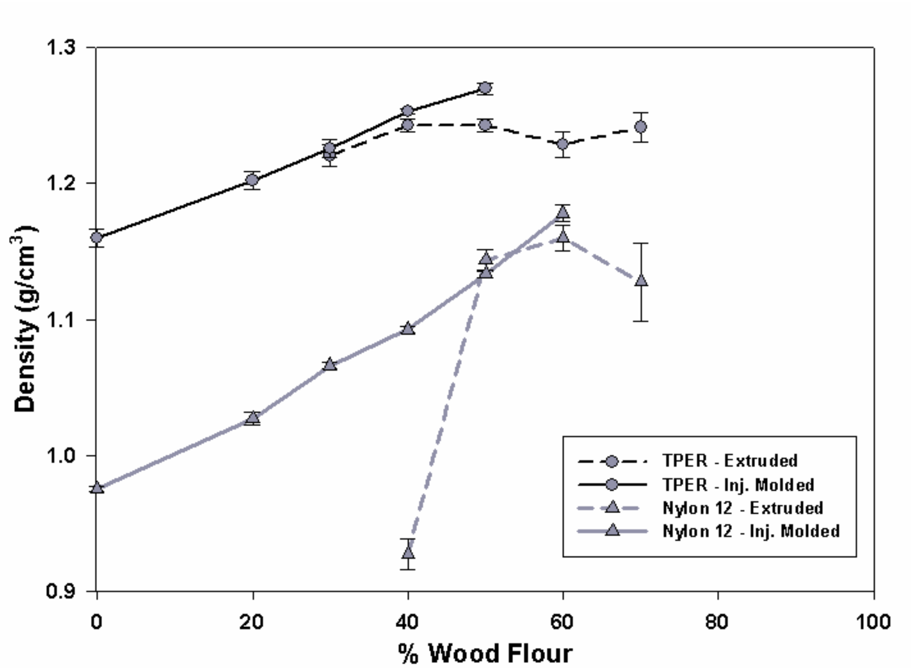

Figure 10. Density of TPER/WF and nylon 12/WF composites with various wood flour contents.

APPENDIX A – PROCESSING INFLUENCES ON THERMAL DEGRADATION OF EXTRUDED NYLON 12 COMPOSITES

A.1 Introduction

In previous research, nylon 12 was shown to have significant potential for use in wood-plastic composites (WPCs) due to its high strength properties (Hatch, 2008). However, processing temperatures above 200ºC can produce volatiles from wood degradation, which affects material properties during the extrusion process. Lu et al. (2007) observed through thermo-gravimetric analysis (TGA) that the combination of wood and nylon 12 altered degradation compared to other common thermoplastic WPCs consisting of either polypropylene (PP) or polyethylene (PE). Cozzani et al. (1995) found that rule of mixtures (ROM) modeling was effective for determining fractional components of refuse derived fuels made from polyethylene and wood based materials. However, Rennecker et al. (2004) noted that thermal degradation of WPCs is significantly affected by the proportion of polyolefins present, such as polypropylene and polyethylene.

This study's primary objective is to evaluate wood degradation as it relates to processing of nylon 12 WPCs. Three specific objectives were defined:

1. Evaluate processing and mechanical properties of nylon 12 WPCs utilizing pre-processed/extruded wood flour (PW).
2. Determine the influence of extruder screw speed on mechanical performance of nylon 12 WPCs.
3. Analyze thermal degradation (TGA) behavior of nylon 12 WPCs.

A.2 Materials and Methods

Nylon 12, OPE629A, and wood flour were sourced and blended according to previous studies (Hatch, 2008). Specific formulations are defined in Table A.1 for each extrusion variation. A Cincinatti Milicron CM 35 extruder consisting of two twin counter-rotating screws was used to produce extruded rectangular specimen (3.7 X 0.95-cm). Extrusion processing temperatures were controlled in 3 barrel zones, 2 die zones, and the screw at 225, 225, 205, 190, 190, and 199ºC from barrel to screw, respectively. Screw speeds were maintained at 20 revolutions per minute (rpm), unless specifically stated otherwise (i.e. Table A.1 - 10 rpm). Pre-extruded wood flour (PW) was also produced by extruding dried wood flour at processing temperatures described previously, with a screw speed of 30 rpms. Samples were planed on the two wide faces, conditioned, and then tested in flexure according to ASTM D790 standards. Mechanical testing was performed on a screw driven Instron 4466 Standard with 10 kN electronic load cell.

Thermogravimetric analysis (TGA) was performed to determine the influence of specific processing parameters on fiber and polymer thermal degradation. TGA (Rheometric Scientific STA) 9 to 11 mg samples were heated from 50ºC to 600ºC at 10ºC/min.

A.3 Results and Discussion

Pre-extruded wood flour (PW) produced a composite in which the wood flour had already been subjected to the elevated temperatures required for extrusion of nylon 12. Heat treatment of wood at temperatures above 200ºC has been proven to decrease equilibrium moisture content, add dimensional stability, improve decay resistance, and increase durability, but also makes the wood more brittle (Rapp et al., 2001). However, all mechanical properties, including strain to failure, of the final composite were apparently unaffected by this pre-processing step (Table A.1). Coloration of the composite with PW exhibited a very dark brown/black appearance as opposed to the dark brown appearance of the typical nylon 12/WF composite, signifying material degradation.

Mechanical performance of nylon 12 WPCs indicated a very strong association with extruder screw speed. A reduction in screw speed from 20 rpm to 10 rpm reduced the modulus of rupture (MOE) and strain to failure dramatically from 76.05 to 53.56 MPa and 1.81 to 1.15 %, respectively (Table A.1). No significant effect, however, was observed on modulus of elasticity (MOE) or density.

To gain understanding of nylon 12 WPC thermal degradation during processing conditions, TGA was performed on both individual components and the final nylon 12/ WF extruded composites. The following components were analyzed: pure nylon 12 (N12), wood flour (WF), pre-extruded wood flour (PW), and OPE629A (OPE) (Figure A.1). Several composites formulated with 3% OPE were observed, based on variations in processing characteristics, which included: a standard formulation with a screw speed of 20 rpm (60% WF, 37% N12) (Figures A.1-2), 10 rpm (60% WF, 37% N12), and PW at 20 rpm (60% PW, 37% N12) (Figure A.2).

A simple prediction model based on the ROM approach was performed to predict the standard composite degradation with 60% WF, 37% N12, and 3% OPE (Cozzani et al., 1995). This model uses a weighted sum of the individual components:

$$M_T = C_1 m_1 + C_2 m_2 + C_3 m_3 \quad \text{Eq. A.1}$$

Where M_T is the total residual mass at any given point in the TGA curve for a composite consisting of three components (1 = WF, 2 = N12, 3 = OPE). The coefficient C is the residual mass fraction of the respective component at a given temperature and m is the initial mass for each component. Two critical assumptions are made in this model: 1) no interaction occurs between components and 2) TGA heating rates for components are equal.

According to my prediction model in Figure A.1, the curves for the respective model and experimental data differ dramatically. A deviation from the critical assumption that no interaction is occurring between the WF and nylon 12 components is a primary factor. Some stability appears to be provided by the nylon 12, delaying the thermal decomposition of the wood fraction within the temperature range of 220 – 400 ºC (Figure A.1). Inversely the decomposition of the wood fraction appears to cause premature degradation of the nylon. Similar observations were made by Lu et al. (2007) in compression molded nylon 12/WF composites.

A.4 Conclusions

Evaluation of extrusion processing influences on nylon 12 WPC has yielded some insight into the processing requirements for these composites. Screw speed had significant influence on material strength and strain. In composites with pre-extruded wood flour, the effect on mechanical properties was negligible, while darker coloration appeared to indicate degradation. TGA analysis, however, provided no indication of thermal degradation of components at required processing temperatures for nylon 12 WPCs. From additional analysis, the thermal degradation of nylon 12 WPCs does not follow from a sum of the components, suggesting interactions between nylon 12 and the wood flour. Although no TGA evidence of thermal degradation at processing temperatures is apparent, additional analysis is suggested to determine possible heat-induced chemical reactions.

A.5 References

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Hatch, M. C., "Processing of Engineering Polymer Wood-Plastic Composites: Thermoplastic Epoxy Resin (TPER) and Nylon 12." Masters Thesis, Chapter 2, Washington State Univ., Pullman, WA, August 2008.

Lu, J.Z., Doyle, T.W., Li, K., "Preparation and Characterization of Wood-(Nylon 12) Composites." Journal of Applied Polymer Science, Vol. 103, 270-276, 2007.

Rapp, R.O., "Review on heat treatments of wood." The Federal Research Centre for Forestry and Forest Products, Hamburg, Germany, 2001.

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A.6 Tables

Table A.1. Mechanical properties, density, and processing melt pressures of extruded nylon 12/WF formulations at 10 rpms, 20 rpms, and with pre-processed wood flour.

% Wood	% Nylon 12	% OPE	*Sample ID:*	Modulus of Rupture [MPa]	Modulus of Elasticity [GPa]	Strain @ Failure [%]	Density [g/cm^3]	Melt Pressure [psi]
60	37	3	**20 RPM**	76.05 (7.42)	4.207 (0.228)	1.81 (0.21)	1.154 (0.008)	200
60	37	3	**10 RPM**	53.56 (6.97)	4.362 (0.307)	1.15 (0.15)	1.139 (0.029)	320
60	37	3	**Pre-Processed Wood**	74.38 (3.11)	4.361 (0.048)	1.69 (0.13)	1.176 (0.010)	360

A.7 Figures

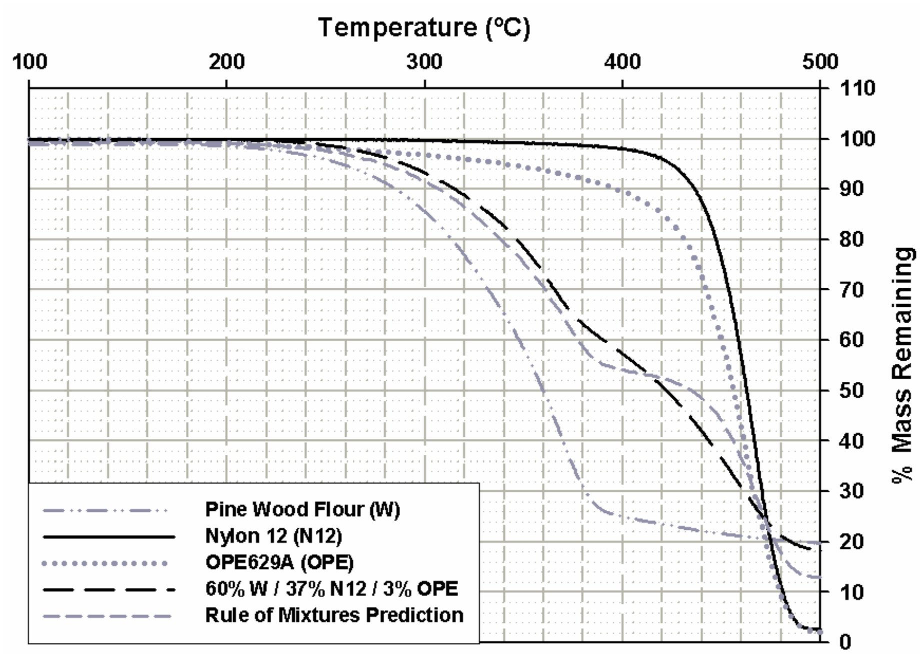

Figure A.1. Thermogravimetric curves for nylon 12/WF components, composite, and prediction curve based on rule of mixtures.

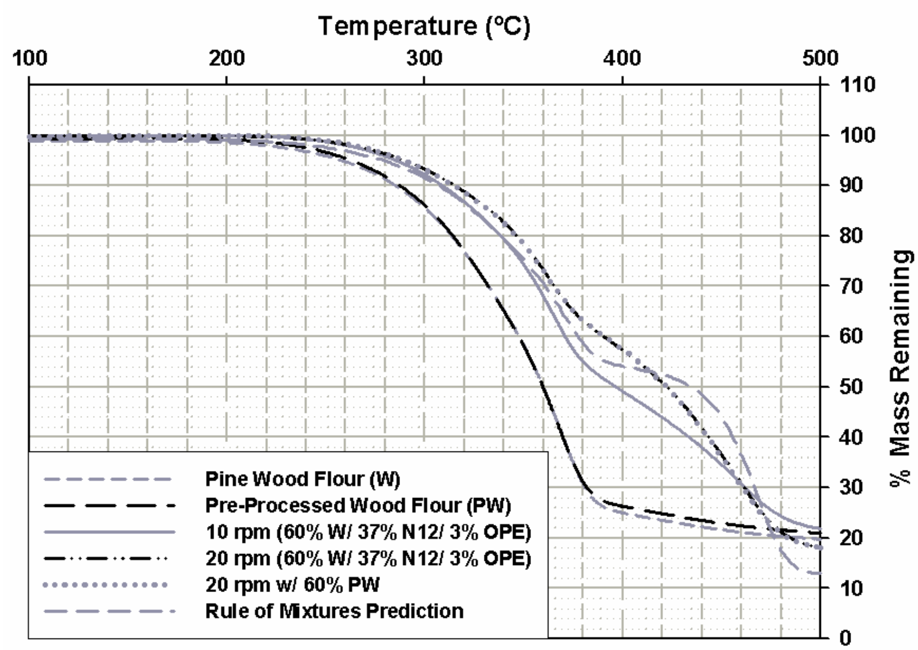

Figure A.2. Thermogravimetric curves for nylon 12/WF composites and prediction curve based on rule of mixtures.

APPENDIX B – POST EXTRUSION COOLING OF NYLON 12 COMPOSITES

B.1 Introduction

Processing of extruded wood-plastic composites (WPCs) often concludes with water spray cooling as material exits the extruder die. The importance of cooling rate is often neglected in many WPC studies in which processing temperatures are well below any initiation of wood degradation. However, in nylon 12 WPCs, processing temperatures (max 225ºC) are within the onset of wood degradation and volatile formation cited at around 200ºC (Hatch, 2008; Saheb and Jog, 1999). This study determines the overall importance of adequate post-extrusion cooling of the composite in regard to mechanical performance of nylon 12 WPCs.

B.2 Materials and Methods

The base formulation for this study consisted of 60% wood flour, 37% nylon 12, and 3% OPE629A, with each material sourced and blended as specified previously (Hatch, 2008). A Cincinatti Milicron CM 35 extruder consisting of two twin counter-rotating screws produced extruded rectangular specimens (3.7 X 0.95-cm). Extrusion processing temperatures were controlled in 3 barrel zones, 2 die zones, and the screw at 225, 225, 205, 190, 190, and 199ºC from barrel to screw, respectively. Screw speed was set to 20 revolutions per minute (rpms) and extrudate upon exit was spray cooled 360 degrees with water for 2.44 m. (8 ft.). Samples were planed on the two wide faces, conditioned, and tested in flexure according to ASTM D790 standards. Mechanical testing was performed on a screw driven Instron 4466 Standard with 10 kN electronic load cell.

B.3 Results and Discussion

Standard positioning of the cooling chamber for nylon 12 WPCs is ~0 cm (0 in.) from the extruder die, as observed for this study and others (Hatch, 2008). To evaluate cooling effects on material properties, the position of the cooling chamber from the die was increased from ~0 cm (0 in.) to 7.6 cm (3 in.), and 15.2 cm (6 in.) to obtain three different data sets. Flexure testing of the material showed in Figure C.1 that composite properties were significantly affected by cooling. As cooling was postponed from 0 cm to 15.2 cm, density, modulus of rupture (MOR), and modulus of elasticity (MOE) decreased (Table C.1, Figure C.1). Although this data clearly points to a dependency of composite mechanical properties to density, the cause of this density variation is not yet known. Two possible contributors to density reduction are wood degradation and swell as material exits the extruder die. Further, wood degradation can exacerbate the influence of swell by producing gaseous voids within the composite (Saheb and Jog, 1999).

B.4 Conclusions

Performance of nylon 12 WPCs was significantly influenced by the rate of cooling. Prolonging extrudate water quenching reduced MOR, MOE, and density, while no significant affect was reported for strain to failure. This study indicates the importance of immediate and efficient cooling of nylon 12 WPCs.

B.5 References

Hatch, M. C., "Processing of Engineering Polymer Wood-Plastic Composites: Thermoplastic Epoxy Resin (TPER) and Nylon 12." Masters Thesis, Chapter 2, Washington State Univ., Pullman, WA, August 2008.

Saheb, D. N., Jog, J. P., "Natural Fiber Polymer Composites: A Review". Advanced Polymer Technology, Vol.18 No. 4: 351-363, 1999.

B.6 Tables

Table B.1. Mechanical properties and density of extruded nylon 12/WF formulations at various distances from extruder die exit to cooling chamber.

% Wood	% Nylon 12	% OPE	Distance to Cooling Chamber [cm]/(in.)	Modulus of Rupture [MPa]	Modulus of Elasticity [GPa]	Strain @ Failure [%]	Density [g/cm^3]
60	37	3	**0 (0)**	65.84 (5.83)	3.905 (0.125)	1.71 (0.2)	1.159 (0.018)
60	37	3	**7.6 (3)**	57.68 (7.49)	3.493 (0.235)	1.68 (0.18)	1.125 (0.023)
60	37	3	**15.2 (6)**	50.40 (5.79)	3.200 (0.271)	1.62 (0.21)	1.100 (0.021)

B.7 Figures

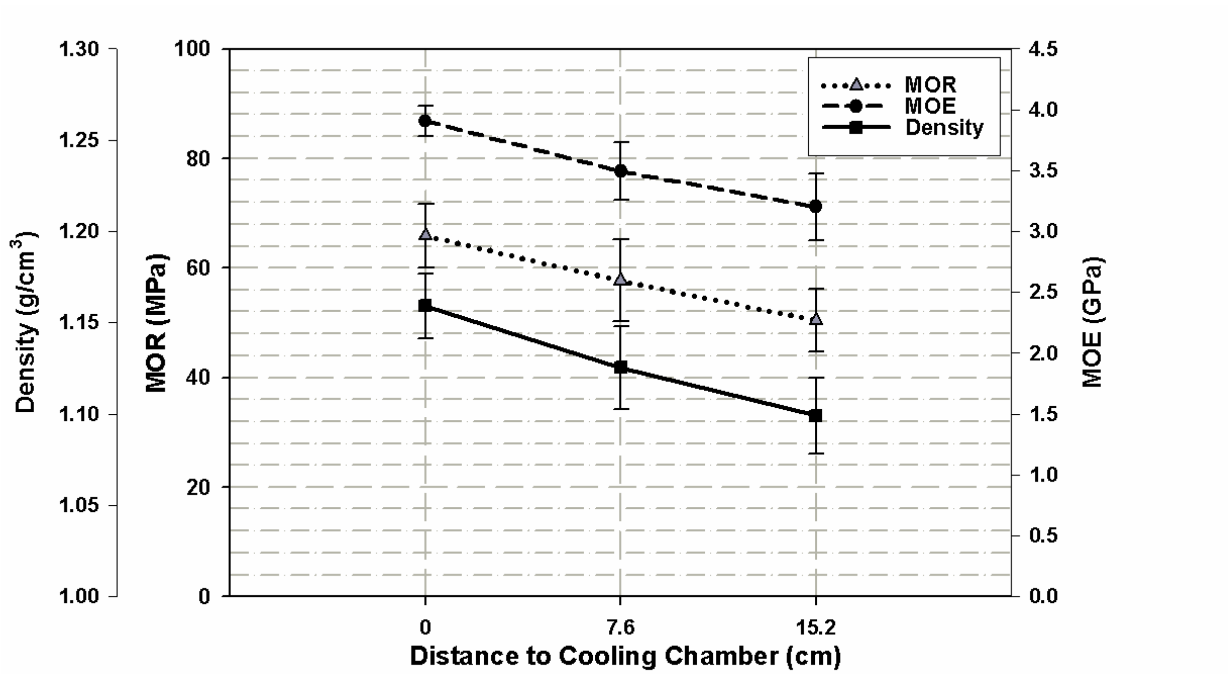

Figure B.1. Flexural modulus of rupture and elasticity, and density of nylon 12/WF composite with delayed cooling after die exit: 0, 7.6, and 15.2 cm.

Foundation Elements for Naval Low-Rise Buildings

Moisture and Temperature Influence on TPER and Nylon 12 Wood-Plastic Composites

Material Improvements Group

Task M1 – Implement crosslinked polyolefin reactions during manufacture

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Prepared for
Office of Naval Research
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Project End Report

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Abstract

Building materials are often subjected to many different climates and environments. Current WPCs have been proven to be mechanically sensitive to changes in temperature and moisture content. Although the incorporation of nylon 12 and thermoplastic epoxy resin (TPER) into WPCs instead of traditional high density polyethylene (HDPE) has shown promise, there was no data on environmental influences prior to this study. Four extruded wood flour composites were produced (one each using TPER and HDPE, and two using nylon 12). Flexure tests were performed at temperatures of -30, 0, 21.1, 40, 65.6ºC and samples soaked in a water bath from 0 to121 days. TPER exhibited the least mechanical sensitivity to temperature changes, followed by nylon 12 and HDPE WPCs. Rates of moisture absorption for nylon 12 and TPER WPCs indicate that they can sustain longer periods of saturation than HDPE WPCs. For nylon 12 and TPER composites at 15% moisture content, stiffness and strength were reduced by 60%.

Introduction

The use of thermoplastic polymers in natural fiber composites have recently grown in popularity, primarily as a means to promote recyclability and native resistance to decay. Previous research has shown that wood-plastic composites (WPCs) based on thermoplastic epoxy resin (TPER) and nylon 12 exhibit superior mechanical strength properties to current WPCs (Hatch, 2008). However, when used in engineered applications, influences of temperature and moisture must be considered in the structural design capacities (Marcovich et al., 1997; Huang et al., 2006; Stark, 2001; Schildmeyer, 2006; Anderson, 2007). Current commercial WPCs principally contain polyolefins, which are hydrophobic in nature. However, TPER contains similar affinity to water and hydroxyl functionality to hydrophilic wood polymers (White et al., 2000). Nylon 12 absorbs water less easily than the more commercially prevalent moisture sensitive nylon 6, but both nylons absorb more moisture than polyolefins.

The mechanical properties of WPCs based on HDPE and polypropylenes (PP) are strongly correlated to application temperature (Schildmeyer, 2006). In addition, the thermally stable wood component in WPCs can reduce the sensitivity of mechanical properties to these temperature changes. With PP, an increase from room temperature to 65ºC resulted in 30% and 50% reductions in tensile strength and modulus, respectively. Evaluation of moisture and temperature dependence of TPER and nylon 12 composites is necessary for their development of as viable structural composites.

Assessing temperature and moisture influences on performance of TPER WPCs and nylon 12 WPCs was the overall goal of this research. Specific objectives of the study were to:

1. Evaluate the sensitivity of flexural properties to various application temperatures,
2. Determine the influence of moisture content on flexural and physical properties and compare moisture absorption rates, and
3. Develop factors to adjust composite flexural capacities for temperatures and moisture effects.

Materials and Methods

Material

Four WPC formulations were examined utilizing three commercial polymers: TPER (L-TE05-10, MFI: 10, Tg: 81ºC), provided by L&L Products (Romeo, MI), nylon 12 (Grilamid® L 20 G, T_m: 178ºC, MFI: 20, density: 1.01g/cm^3), provided by EMS-Chemie (Sumter, SC), and HDPE (LB010000, MFI: 0.5, density: 0.953 g/cm^3) from Equistar (Houston, TX). A 60 mesh pine (*Pinus spp*) flour with a moisture content of 9-10% was acquired from American Wood Fibers (Schofield, WI). An oxidized polyethylene homopolymer (OPE629A, Honeywell, Morristown, NJ) was used as a lubricant for both TPER and nylon 12 formulations, and Glycolube® WP2200 (Lonza Inc., Allendale, NJ) was employed for HDPE blends. Specific formulations for each composite are outlined in Table 1.

A steam tube dryer was utilized to reduce the flour moisture content to < 2% by total mass (oven dry weight). Prior to extrusion, each composite formulation, consisting of wood flour, polymer, and lubricants, was dry-blended in a low intensity blender for 5 – 10 minutes.

Extrusion

The various WPCs were extruded into a rectangular section using a slit die (3.7 X 0.95-cm) and then spray cooled with water. Extrusion was performed on a conical counter-rotating twin-screw extruder (Milicron CM 35) with a downstream diameter of 35-mm and L/D ratio of 22. Extruder temperatures were independently controlled in 3 barrel zones, and 2 die zones with the temperature schedules presented in Table 2. An additional thermal conditioning heat treatment was applied to some of the wood flour pre-extruding it at the barrel and die schedule for nylon 12 at a screw speed of 30 rpms. The nylon 12 WPCs containing this "pre-extruded wood flour" (PWF) were produced using the same extrusion profile and formulation as nylon 12 WPCs.

Environmental Conditioning of Test Specimen

Initial conditioning for both temperature and moisture samples was performed for 48 hours according to ASTM D790. Before the flexural testing at elevated temperature was performed, each sample was placed in an environmental chamber at 65.6ºC for 12 hours to facilitate relaxation of residual stresses from processing (Anderson, 2007). Subsequently, each sample was conditioned at the respective testing temperature for 12 hours followed by the final mechanical testing at the assigned temperatures of -30, 0, 21.1, 40, 65.6ºC ($\pm$ 2ºC) in an environmental chamber. Water absorption was evaluated following submersion in de-ionized water from 0 to 121 days. At prescribed time intervals, specimens were removed and evaluated for physical dimensions (length, width, thickness) and mass. These measurements were subsequently used to compute percent moisture content, density, and volumetric strain. After physical measurements were complete, the samples were tested in flexure according the protocol given below.

Mechanical Testing

All flexure testing was performed according to ASTM D790 standards with the exception of specimen treatments used to produce the desired temperature and moisture conditions. Mechanical testing of moisture samples was performed on a screw driven Instron 4466 Standard with 10 kN electronic load cell. The universal test machine used for evaluating temperature samples consisted of 222-kN servo-hydraulic test frame (MTS Corp.) with an inline 2.2 kN load cell and environmental chamber. The support span for all testing was 16 times the nominal depth (12.7 cm) with a constant crosshead speed maintained at 3.8 mm/min. Strain to failure for each sample was defined as the resultant strain coincident with the maximum load.

Results and Discussion

Temperature Influences

All of the WPC formulations exhibited a decreasing trend of MOE and MOR with increasing temperatures from -30ºC to 65.6ºC (Figure 1). As with previous research (Schildmeyer, 2006), the strain to failure of the nylon 12 and HDPE WPCs increased over the same temperature range (Figure 2). However, a constant strain to failure was noted for the TPER composites with no significant deviation from 0.0125 mm/mm (1.25 %) over the temperature range examined. Although speculative, the constant failure strain of TPER WPCs may be associated with strong fiber-matrix interaction afforded by the hydroxyl-functionality of the TPER polymer.

To evaluate the overall affect of temperature among the different WPC polymer systems, relationships were produced to determine the temperature corrected composite strength ($\Gamma_{t,R}$) and modulus ($\Gamma_{t,E}$) given by:

$$\Gamma_{t_{(E,R)}} = C_{t_{(E,R)}} \cdot \Gamma_{i_{(E,R)}} \qquad \text{Eq. 1}$$

where:

$$C_{t_{(E,R)}} = 1 - \lambda_{(E,R)} \cdot (\Delta T) \qquad \text{Eq. 2}$$

where Γ_i is the composite strength or modulus at ambient temperature (21.1ºC), C_t is the temperature modification factor, ΔT is the change in composite temperature from ambient, λ is the slope of the normalized linear curve, and E and R denote the modulus of elasticity and rupture stress, respectively. These values were derived after normalizing the composite mechanical properties to 21.1ºC (ΔT = 0). A similar correction for temperature affects was proposed by Schildmeyer (2006) for the design of PP composites, which utilized a linear correction for MOR and a second order relationship for MOE. Contrary to his research, the composites studied here appear to follow a linear correction for both MOE and MOR (Figure 3). The relationships developed for MOR and MOE highlight how sensitive the current HDPE composites can be to temperature deviations. The TPER composites were affected less by temperature changes than any of the other composites evaluated. The nylon 12 materials display an intermediate behavior, positioned between TPER and HDPE.

Moisture Absorption

Moisture absorption and the resulting volumetric strain were observed following submersion in liquid water for times between 0 and 121 days. Water absorption of WPCs has been reported to be characterized by Fickian, non-steady state diffusion (Anderson, 2007, Chowdhury and Wolcott, 2007). To accurately analyze the Fickian diffusion coefficient, moisture content (MC) is plotted vs. the square root of time producing a linear region followed by a non-linear approach to the saturated moisture content, M_{sat}. The HDPE formulations exhibited this behavior, reaching saturation within 60-days (Figure 4). Although the TPER and nylon composites displayed similar behavior, they did not reach saturation within the test period, negating the ability to quantify the diffusion coefficient. The moisture absorption rate of TPER and nylon 12 composites was significantly less compared to the HDPE composite. Possible explanations for this behavior include the adhesion of wood to the polymer matrix, which could reduce water transport via intermolecular hydrogen bonding, the reduction in void space, which could eliminate direct flow pathways within the composite, and the hydroscopicity of the polymers, which could discourage water absorption. The latter is clearly not the case, since both nylon 12 and TPER polymers are hydrophilic, while HDPE is hydrophobic. For each composite evaluated except TPER, increased MC resulted in an equivalent increase in volumetric strain (Figure 5). Over-swelling of TPER composites is potentially systematic of the highly hydrophilic nature of this polymer system.

Comparison of both nylon 12 composites clearly shows the effect that heat treatment of wood fibers has on reducing water absorption. High temperature processing of wood increases stiffness and decreases hydroscopicity due to the reduction in hemicellulose content of the wood along with functional hydroxyl groups (Hillis, 1984; Saheb and Jog, 1999). Cross-linking of lignin networks and an increased proportion of crystalline cellulose may significantly influence heat treated wood properties (Boonstra and Tjeerdsma, 2006).

Moisture Content and Mechanical Properties

Similar relations to those derived for temperature sensitivity were developed for the influence of composite moisture content on mechanical properties. It was determined that MOR data correlated best to a linear function normalized to 0% MC, while MOE data followed a logarithmic function. MOE was normalized to 1% MC due to the tendency of a log function to approach infinity, MOE $\rightarrow \infty$, as MC approaches 0 %. MOR was observed to follow a decreasing linear trend with increasing moisture content for each composite. Further adjustment of Eq. 2 provides the moisture content strength reduction factor ($C_{m,R}$) given as:

$$C_{m_{(R)}} = 1 - \delta_{(R)} \cdot (MC) \qquad \text{Eq. 3}$$

where δ is the slope of the normalized linear curve. Consequently, regression of stiffness modulus data resulted in a logarithmic function of MC (log MC) which provided the best correlation. Data was then normalized to 1% MC, (log (0) → - ∞). Thus, the relation for the modulus reduction factor ($C_{m,E}$) can be expressed as:

$$C_{m_E} = 1 - \omega_E \cdot \log(MC)$$ Eq. 4

where ω is a constant. The moisture corrected modulus ($\Gamma_{m,E}$) and strength ($\Gamma_{m,R}$) are then obtained from substitution of Eq. 3 and 4 into the following:

$$\Gamma_{m_{(R,E)}} = C_{m_{(R,E)}} \cdot \Gamma_{o_{(R,E)}}$$ Eq. 5

where Γ_o is the strength and modulus at 0% and 1%, respectively. Reduction factors, C_m, for both stiffness and strength for each composite is shown in Figure 6. For nylon 12/PWF the reduction factor curve is only valid up to 8% MC, since moisture absorption of this composite was significantly inhibited. The average strength projected for 0 % MC for TPER, nylon 12, nylon 12/PWF, and HDPE was 98.9, 66.0, 71.5, and 21.4 MPa, respectively. At 1% MC the average stiffness modulus for TPER, nylon 12, nylon 12/PWF, and HDPE was 6.77, 3.90, 3.81, and 2.89 GPa, respectively.

Closer analysis of the curves shows moisture's influence on the strength and stiffness of engineering polymer WPCs, especially strength. The strength of the HDPE composite under investigation exhibited only a decrease of 40% at 20% MC where both nylon 12 and TPER composites showed a dramatic decrease of approximately 70% and 80%, respectively, at 18 % MC. However, the strength of nylon 12 and TPER composites at 0 % is roughly 300% to 460% higher than HDPE, which even with the strength loss projected for these composites at 70 and 80% still exceed the strength of dry HDPE.

Only minor variations in stiffness reduction factors (C_m) between composites were observed (Figure 5). Both nylon 12/WF and TPER composites followed the same trend for stiffness, while HDPE showed slightly less impact from moisture content. Improved stiffness performance of nylon 12 WPCs was observed with pre-extruded wood flour at 8% MC in which $C_{m,E}$ was reduced by approximately 12%.

Conclusions

WPCs are promoted for their resistance to environmental factors affecting traditional wood member performance and life cycle expectancy, but are susceptible to moisture due to their high wood content. Environmental sensitivity of thermoplastic polymers can significantly affect the moisture and temperature response of the composite. Results produced using nylon 12 and TPER WPCs were similar to those using traditional HDPE WPCs.

Testing for TPER and nylon 12 WPCs at various temperatures from -30ºC to 65.6ºC indicated that both MOR and MOE are sensitive to temperature changes. When MOR ($C_{t,R}$) and MOE ($C_{t,E}$) were normalized to ambient temperature (21.1ºC), clear comparisons could be made. TPER was the least sensitive to temperature, followed by nylon 12 and then HDPE. However, the overall strength of TPER and nylon 12 composites remained significantly higher than HDPE.

TPER composites more readily absorbed water than nylon 12 composites, while HDPE composites had a higher comparative absorption rate. Heat treatment of wood flour prior to extrusion with nylon 12 reduced moisture absorption and increased composite stiffness. For nylon 12 and TPER composites, reductions in both MOE and MOR were approximately 60% at

15% MC. Overall, the mechanical properties of both TPER and nylon 12 composites were more sensitive to moisture than traditional HDPE composites.

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Tables

Table 1. Formulation for each WPC polymer system.

	TPER	Nylon 12	HDPE
Wood Flour :	60 %	60 %	60 %
Polymer :	38 %	37 %	38 %
Lubricant :	2 %	3 %	2 %
Lubricant Type :	OPE629A	OPE629A	WP2200

Table 2. Extrusion profile for each WPC polymer system.

	TPER	Nylon 12	HDPE
Barrel Zone 1 (Feed) [ºC]	150	225	165
Barrel Zone 2 [ºC]	180	225	165
Barrel Zone 3 [ºC]	180	205	165
Die Zone 1 [ºC]	140	190	170
Die Zone 2 (Exit) [ºC]	140	190	170
Screw [ºC]	155	199	165
Screw Speed [rpm]	10	20	10

Figures

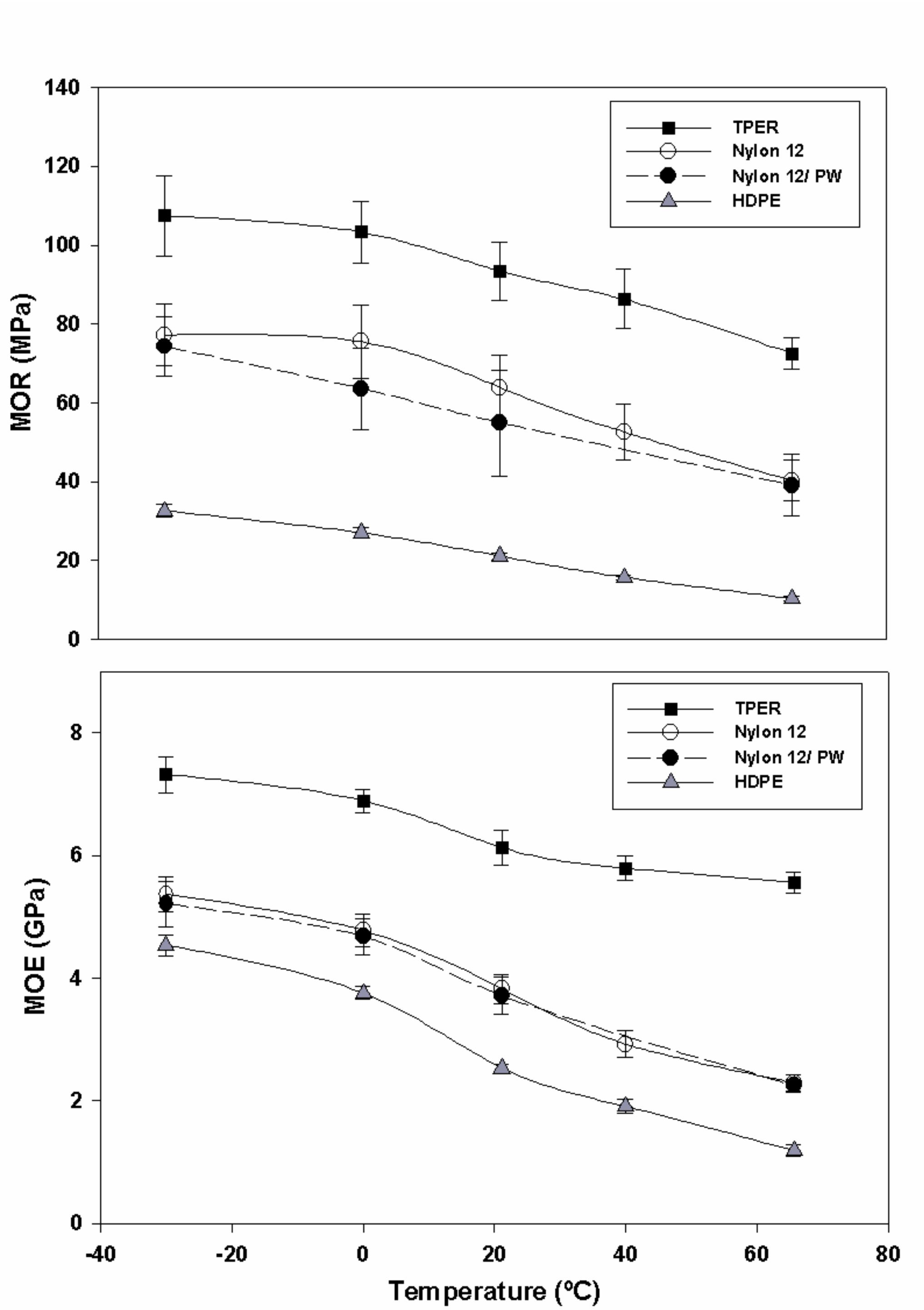

Figure 1. Modulus of rupture (MOR) and modulus of elasticity (MOE) of WPCs at various temperatures.

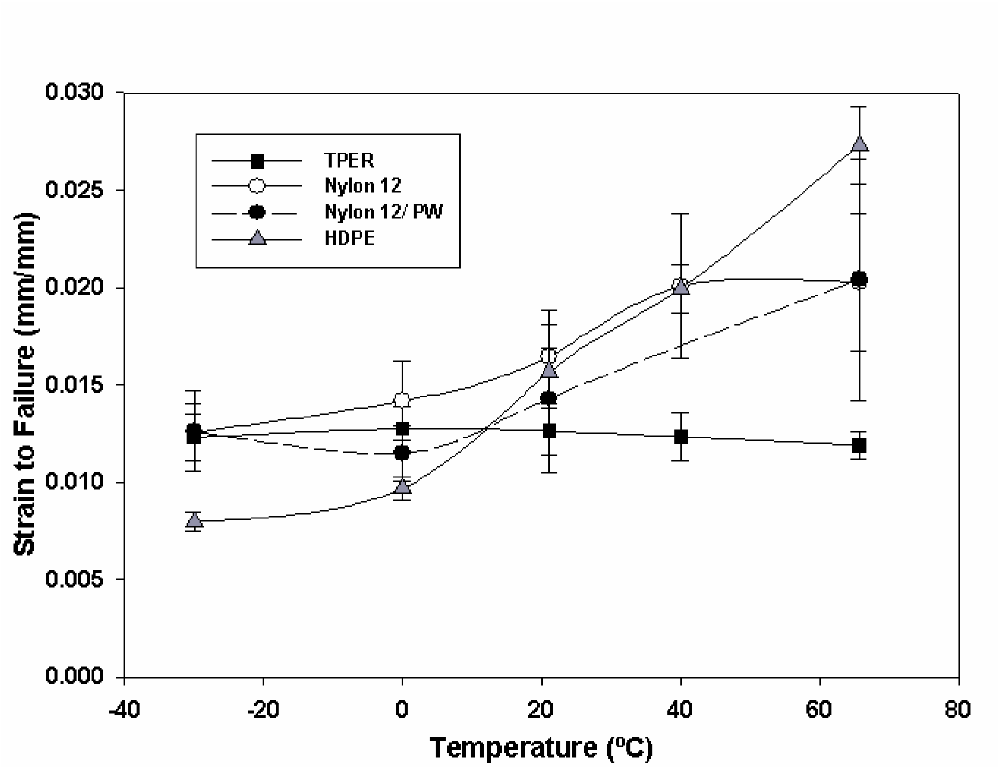

Figure 2. Strain to failure of WPCs at various temperatures.

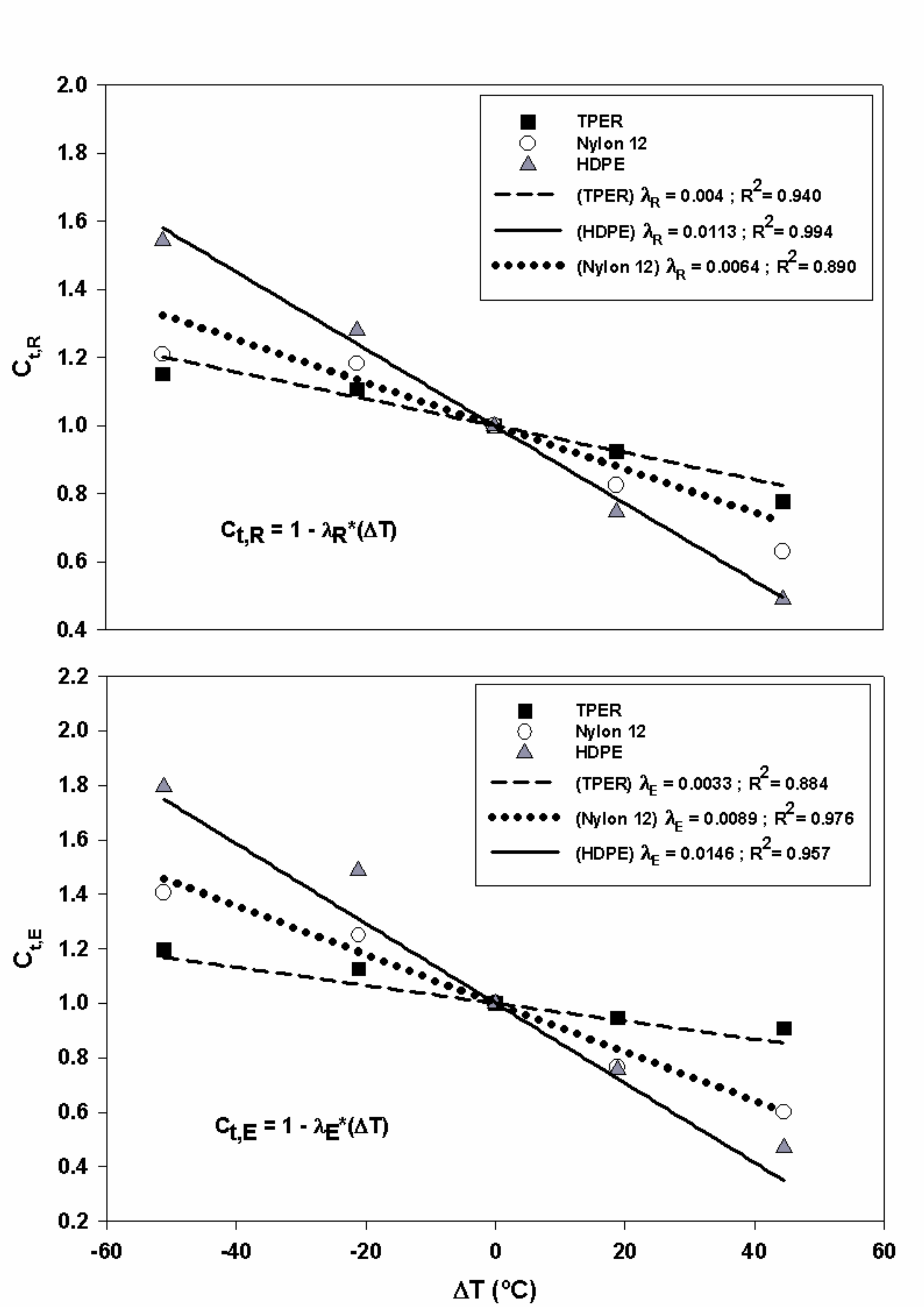

Figure 3. Temperature modification factor, C_t, from ambient (21.1ºC) for MOR ($C_{t,R}$) and MOE ($C_{t,E}$) of WPCs.

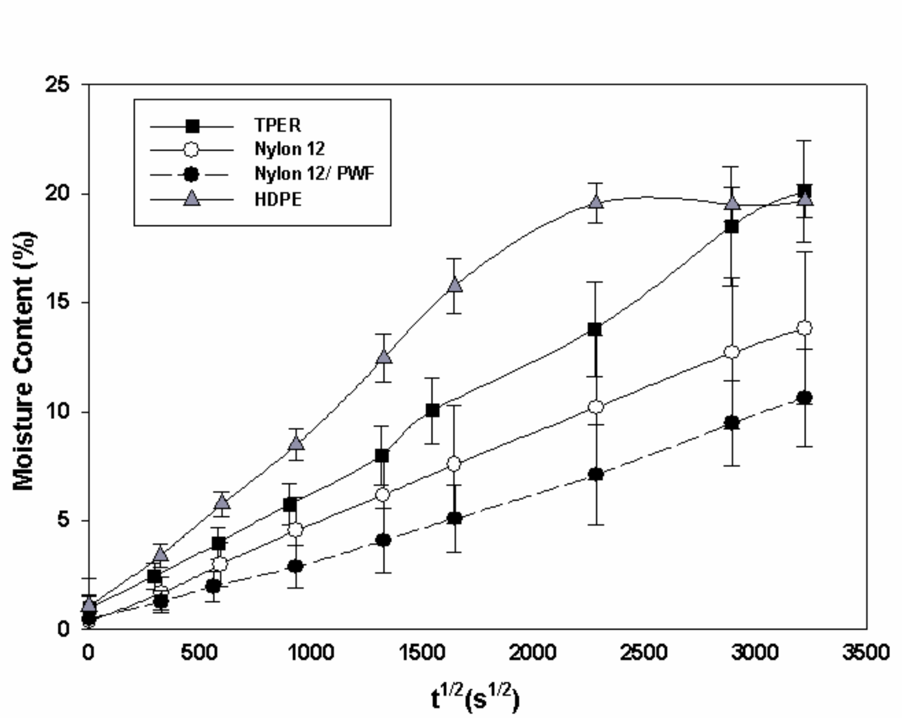

Figure 4. Moisture absorption of WPCs from 0 to 121 days of water soaking.

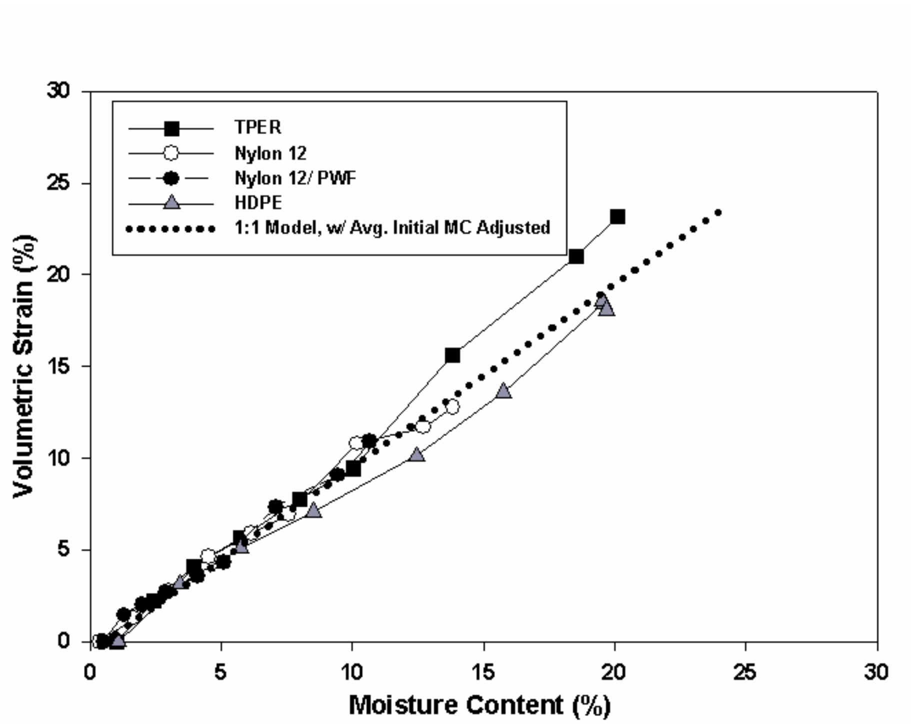

Figure 5. Moisture content vs. volumetric strain of WPCs.

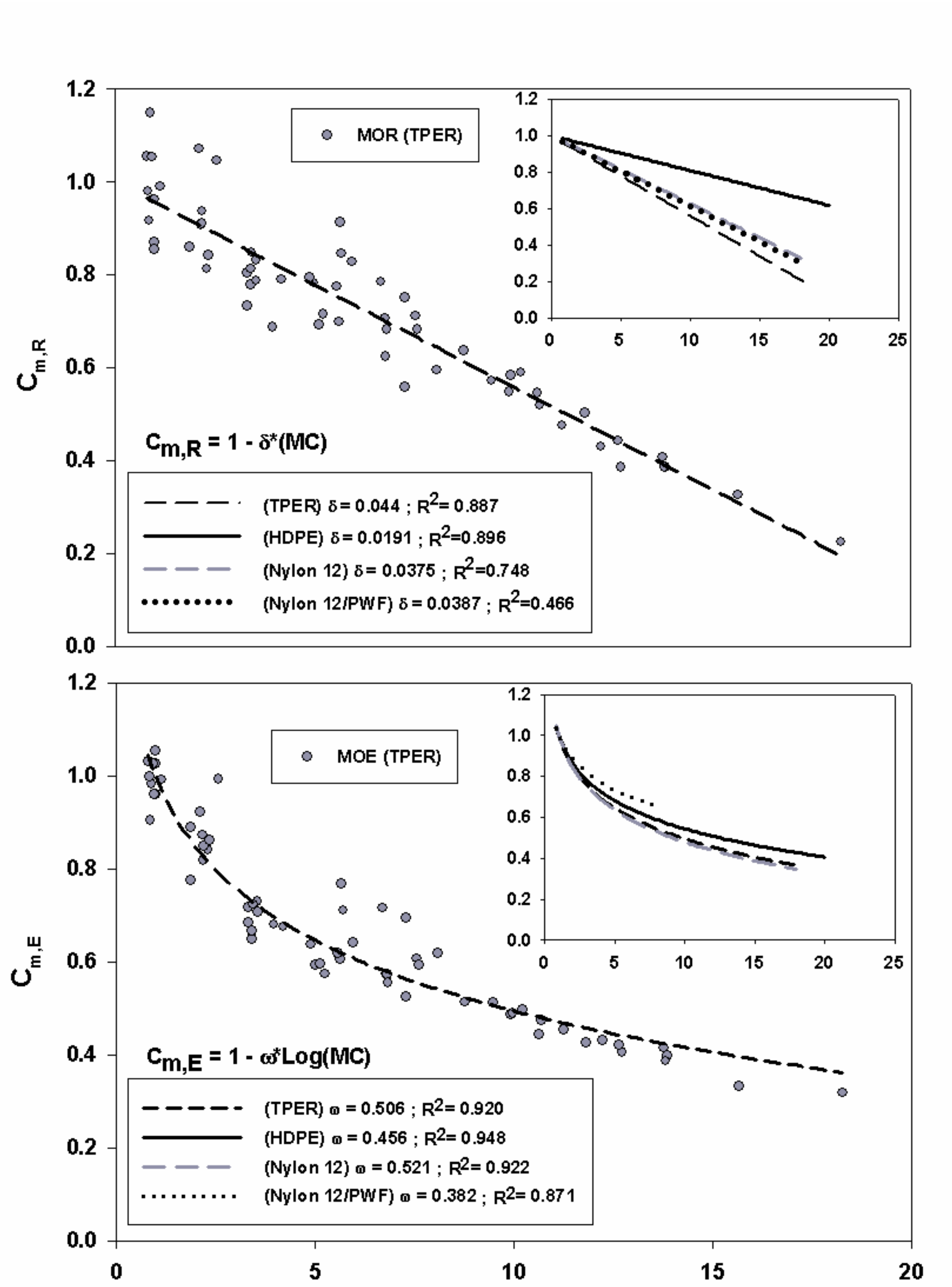

Figure 6. Moisture Content modification factor, C_m, for MOR ($C_{m,R}$) and MOE ($C_{m,E}$) of WPCs.

Foundation Elements for Naval Low-Rise Buildings

Improving Coupled Polypropylene WPC's for Commercial Production

Material Improvements Group

Task M2 – Implement member reinforcing

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Project End Report

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Abstract

The use of maleated coupling agents can greatly influence the mechanical and physical performance of WPCs. However, the addition of these materials into the formulation can often lead to poor processing performance where surface roughness and edge tearing occurs, especially at higher rates. To alleviate the surface roughness a two-step relieved die land was used in place of a typical constant profile land. The surface improved dramatically and provided the opportunity to perform extrusion rate analysis. The increase in screw rate had minimal influence on the WPC product performance, while an increase in temperature profile improved product properties.

Introduction

The efficacy of coupling agents on WPCs is well documented to enhance mechanical and physical performance. However, much of the literature does not address the sensitivity of these coupled systems to commercial production rates. In the previous M2 report, we identified an ideal formulation for maximum properties for polypropylene(PP)-based WPCs. The idealized formulation did not extrude well at commercial rates (above 750lb/hr). Poor surface characteristics were exhibited and the addition of more lubricant only decreased the mechanical performance. The surface roughness appeared to be an adhesion issue, where the coupled melt blend was attracted to the die surface and exhibited a tearing and rolling affect that degraded the surface quality. In an attempt to control and minimize this poor surface characteristic and to evaluate the processing parameters of screw rate and temperature on the mechanical and physical performance of a PP-based coupled WPC, the following objectives were employed:

- Utilize a die-land relief system to gradually release the extrudate by gapping the profile.
- Extrude the coupled PP-based WPCs at various screw rates and temperature profiles and determine their influence on the final product properties
- Compare the performance with high density polyethylene (HDPE) WPCs under the same processing conditions.

Materials and Methods

<u>Materials</u>

High density polyethylene (HDPE) from Equistar (LB-0100-00) and polypropylene (PP) from Inovene (Ineos H04F-00) were used as the polymer matrix, while a commercial wood 60-mesh pine (*Pinus sp.)* flour from American Wood Fibers ® was the reinforcing organic filler. Added to the mix was talc from Rio Tinto Minerals (Nicron 403), lubricants, and a maleic anhydride polypropylene coupling agent. When a coupling agent was not used the lubricant package consisted of zinc stearate and ethylene bis stearamide wax (EBS) at a 2:1 ratio, respectively. The coupling agent used with both the PP and HDPE composites was a MAPP from Honeywell ® (AC 950p), previous work has shown that MAPP can be used on both HDPE and PP WPC's(Chowdhury *In Press*). The weighted formulations for the PP and HDPE coupled and uncoupled composites can be seen in Table 1.

Table 1. Formulation design for the coupled and uncoupled extruded composites.

Component	Uncoupled Component Type	Formulation %	Component	Coupled Component Type	Formulation %
Wood	60-mesh pine	58	*Wood*	60-mesh pine	58
Polymer	PP or HDPE	32	*Polymer*	PP or HDPE	32
Talc	Nicron 403	7	*Talc*	Nicron 403	6
Lubricant 1	Zn St	2	*Lubricant*	OP 100	2
Lubricant 2	EBS	1	*Coupling Agent*	950p	2

Extrusion Methods

All of the materials were weighed and dry-blended in 350lb batches prior to profile extrusion. The wood flour was first dried with a steam tube dryer to a moisture content of approximately 2%. The measured components were dry-blended in a ribbon blender for 5 minutes before being fed into the 86mm counter-rotating intermeshing conical twin-screw extruder (Milacron®). The dry-blend was fed directly into the feed throat of the extruder with a crammer-feed mechanism to maintain a consistent flow of material. Two temperature profiles (Table 2) for each polymer system were utilized as the screw speeds were set at 8, 16, 24, and 32 rpm's. An outline of the trial extrusion runs can be seen in Table 3. Once the extrudate exited the profiled die, the composite deckboard was cooled with a 40°F water spray tank for 25 feet and cut to length for flexure and water soak testing.

Table 2. Temperature profiles for the extruder and die zones for the HDPE and PP formulations

	86mm Extruder Barrel, Screw and Die Temperatures (°F)			
	HDPE		PP	
	T1	T2 & CA	T1	T2 & CA
Barrel Zone 1	340	380	415	450
Barrel Zone 2	340	375	400	435
Barrel Zone 3	340	365	385	400
Barrel Zone 4	340	360	380	385
Screw	340	365	380	385
Die Zone 1	340	355	370	370
Die Zone 2	340	355	370	360
Die Zone 3	340	355	370	360

Table 3. Experimental run plan for the HDPE and PP WPC extrusions.

Designation	Polymer Type	Trial Runs Temperature Profile	Coupling	Screw RPM's
HDPE-T1	HDPE	T1	No	8, 16, 24, 32
HDPE-T2	HDPE	T2	No	8, 16, 24, 32
HDPE- CA	HDPE	T2	Yes	8, 16, 24, 32
PP-T1	PP	T1	No	8, 16, 24, 32
PP-T2	PP	T2	No	8, 16, 24, 32
PP-CA	PP	T2	Yes	8, 16, 24, 32

During extrusion, melt pressure and output rate was collected for each individual run. The melt pressure was taken at the screw tips in the beginning of the die and the output rate was taken from boards marked and measured at 30 second intervals.

Die Modifications

A traditional straight land die was replaced with a relief land to minimize the tearing and surface roughness of the composite. The initial 1" of the die land was machined to a 1x5.5" cross-section. The next 1" of the die land was opened approximately 15 mils throughout the entire cross-section followed by another 1" section having an opening of roughly 45 mils. Once the extrudate passed the last land, the composite entered directly into the water spray tank.

Testing Methods

The WPC composites were then prepared for flexure and water sorption tests according to the procedures outlined in ASTM D 6109 and D 1037, respectively (ASTM 1997; ASTM 1999). Flexure specimens were tested in a 3^{rd} point set-up utilizing a universal testing apparatus with a LVDT measuring the linear displacement at the center-point. Water sorption specimens were first knife-planed to a 0.25" thickness, taking material off the two surfaces and cutting them to a 4" square. The specimens were first conditioned, measured and placed in a distilled water bath. Subsequent measurements were then taken at specific times over the next 70 days.

Results and Discussion

Processing Parameters

The use of the relieved land allowed the extrudate to process at higher extrusion rates without the complication of poor surface characteristics. The gradually increase in the die's profile reduced the normal stress induced by the melt-blend, but still maintained a calibrating component to the die that contained the profile and smoothed the surface.

The output rate and melt pressures of the PP and HDPE WPC's were influenced by temperature and formulation, respectively. The HDPE composites showed similar output rates with temperature, but the coupled formulation exhibited a lower production rate as the screw speed increased (Figure 1). Coupling agents in HDPE WPC's have been shown to significantly influence the melt flow rheology (Li and Wolcott 2006). The change in viscosity could potentially alter the extrusion output rate. With the PP composites, the output rate was increased with a lower temperature profile (Figure 2). The lower temperature profile likely created a higher melt stiffness, thus increasing the output. Similar trends were also seen with the melt pressures of the extruded WPC's, where temperature and formulation played a role in the behavior of the melt blend (Figures 3 and 4).

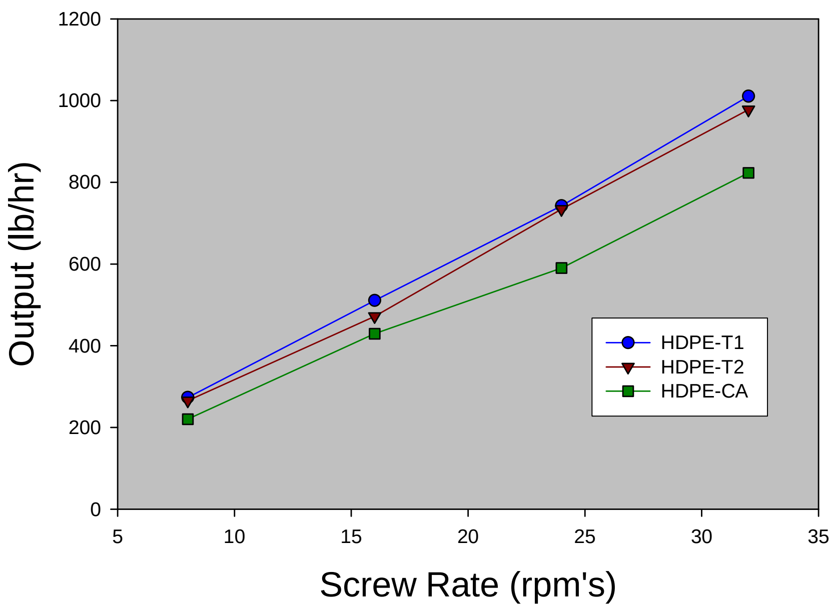

Figure 1. Output rate for the HDPE WPC at varying screw speeds and temperature profiles.

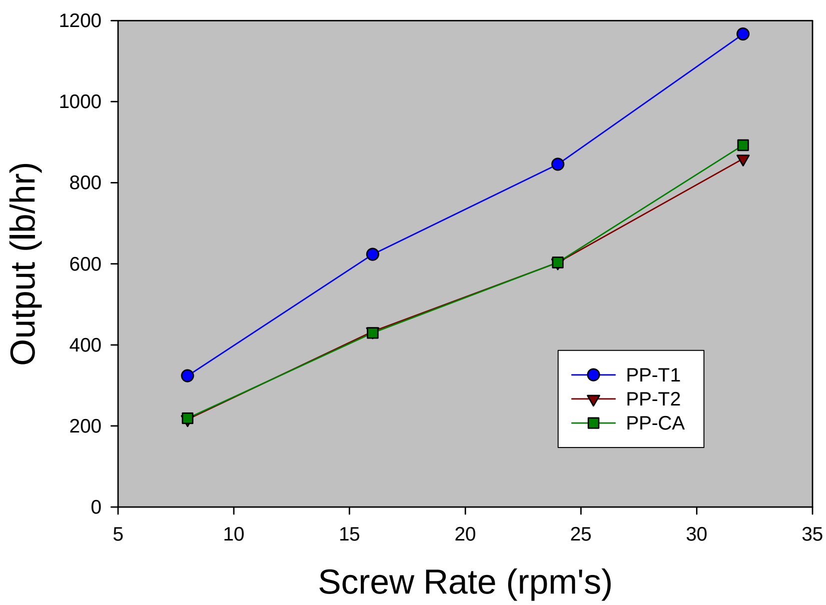

Figure 2. Output rate for the HDPE WPC at varying screw speeds and temperature profiles.

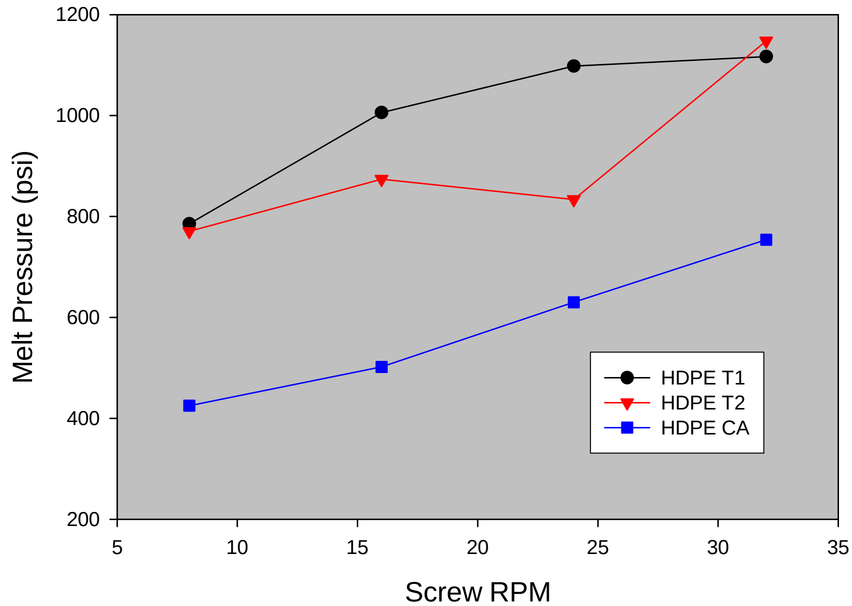

Figure 3. Melt pressure data for the HDPE WPC's at varying screw speeds.

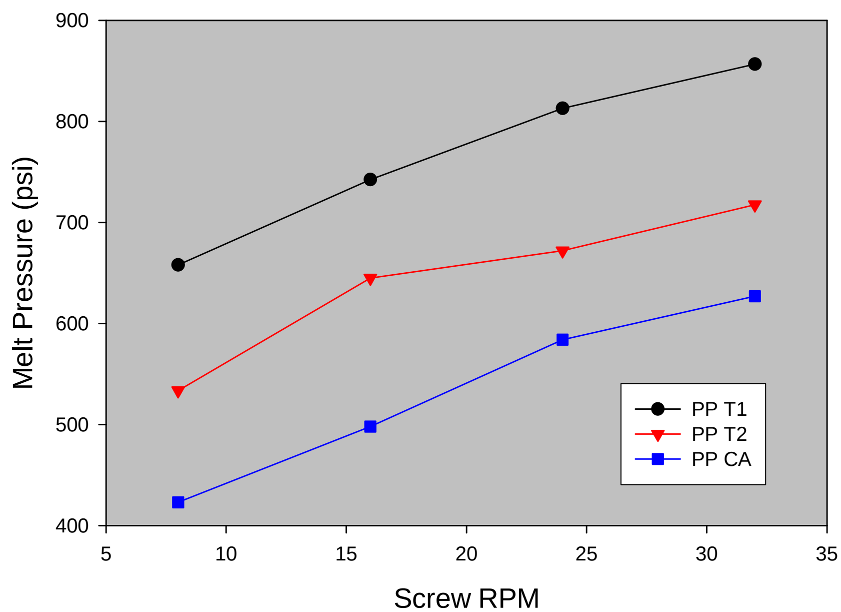

Figure 4. Melt pressure data for the PP WPC's at varying screw speeds.

Mechanical and Physical Testing

The flexural strength and stiffness of the WPC's were influenced by screw speed, formulation, and temperature profile (Figures 5-8). The strength (MOR) was found to be consistent with temperature and screw speed for the HDPE WPC's (Figure 5), however reductions were seen with the PP composites at increased screw speeds and lower temperature profiles (Figure 7). At the higher rate of 32 rpms, there was a distinct reduction of the PP composites at the lower temperature profile (T1) and with the coupled formulation. The HDPE composites showed little deviation except for a small drop in strength with the coupled system at higher screw rpm's. The stiffness of the WPC's was also influenced by screw rate and temperature, with the PP composites exhibiting the greatest reduction with screw speed and lower temperatures (Figure 8). The HDPE composites showed a uniform reduction in stiffness for both temperature profiles and coupled systems.

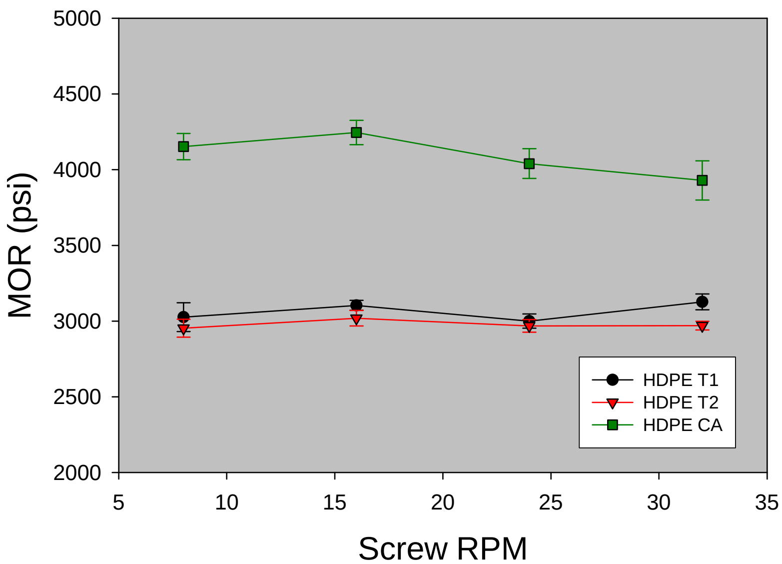

Figure 5. Flexural strength (MOR) of the HDPE WPC's with increasing screw speeds.

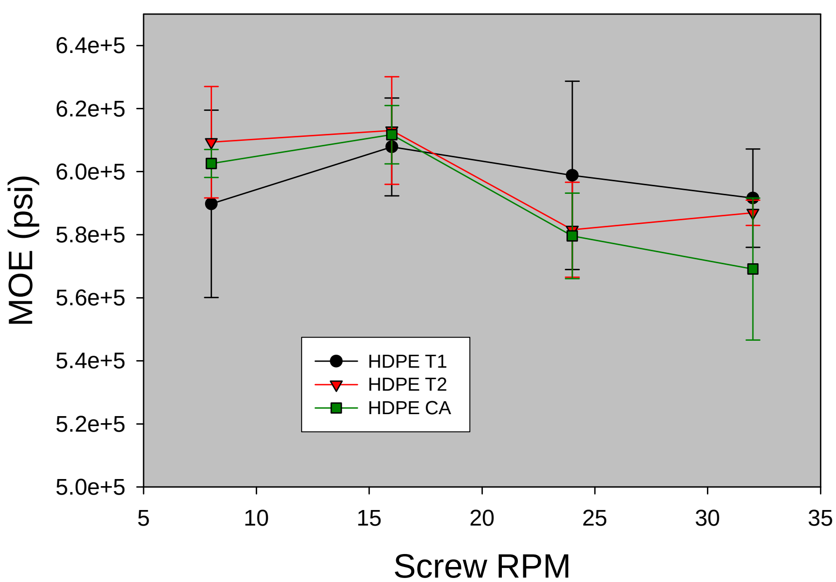

Figure 6. Flexural stiffness (MOE) of the HDPE WPC's with increasing screw speeds.

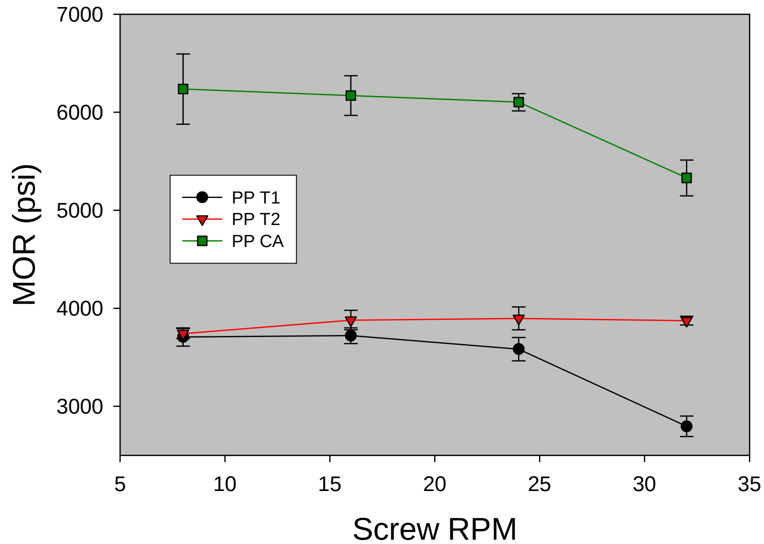

Figure 7. Flexural strength (MOR) of the PP WPC's with increasing screw speeds.

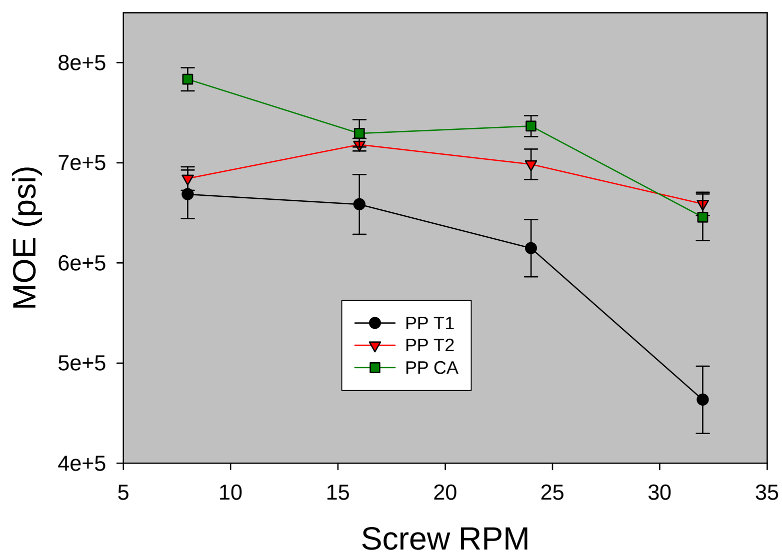

Figure 8. Flexural stiffness (MOE) of the PP WPC's with increasing screw speeds.

The water sorption behavior of the WPC's was quite different between the two polymer types. With the HDPE WPC's the sorption behavior changed quite dramatically for the coupled material (Figure 9), whereas with PP the trend remained similar (Figure 10). The coupled HDPE composites water sorption was found to be linear during the tested time frame and also influenced by the screw speed with higher speeds resulting in quicker water diffusion. The uncoupled HDPE and all of the PP composites exhibited a curvilinear sorption behavior.

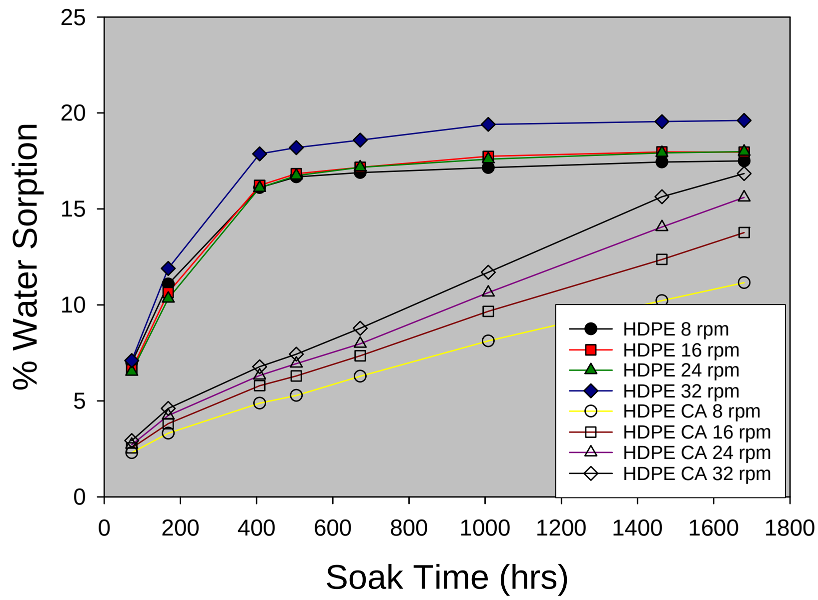

Figure 9. Water sorption of the coupled and uncoupled HDPE composites.

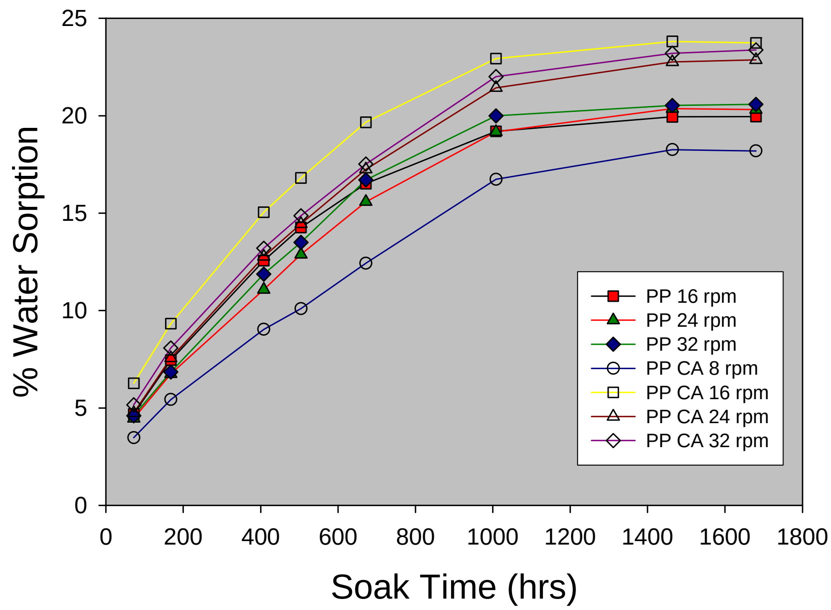

Figure 10. Water sorption of the coupled and uncoupled PP composites.

Conclusions

The use of a die-land relief system allowed for the commercial production of a high quality PP and HDPE coupled WPC. The processing parameters for WPC extrusions can be attribute to variations in product quality and process performance. As screw speeds are increased a general trend of property reductions can be seen, however, choosing the right temperature profile can help minimize the drop in product properties. Flexural properties were shown to be reduced with lower processing temperatures and higher screw speeds, most significantly with the PP composites. Water sorption behaviors were markedly different for the coupled HDPE systems, whereas little differences were found with the PP composites.

References

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ASTM. 1999.D1037-99 Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials. West Conshohocken, PA, ASTM.

Chowdhury, M. J. a. M. P. W. In Press. Compatibilizer selection to improve mechanical and moisture properties of extruded wood-HDPE composites. Forest Products Journal.

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Foundation Elements for Naval Low-Rise Buildings

Monotonic and Reverse Cyclic Testing of Light-Frame Shear Walls with Alternate Sill Plate Materials and Holdown Methods

Material Improvements Group

Task M3 – Evaluate new materials for mechanical performance, connection behavior, long-term loading and fatigue

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Project End Report

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Abstract

A construction challenge is presented by the use of holdowns in timber structures since they can be expensive and time consuming to install. Another challenge is to identify alternatives to preservative pressure treated (PPT) lumber for sill plates. The use of a wood-plastic composite (WPC) sill plate can replace the use of holdowns with an easier system to install due to its flexibility to be extruded into different shapes and by also eliminating the need for PPT lumber. Two such alternatives to holdowns are presented, one with a thicker WPC sill plate and light-gage steel gusset plates and the other with a WPC sill plate that is continuously embedded into the concrete foundation. Both alternatives were found to have slightly higher shear wall strengths as compared to conventionally framed shear walls with holdowns.

Introduction

Historically, two methods of designing light-frame shear walls have been used. One method is given in the International Residential Code (IRC) as prescriptive guidelines. These prescriptions call out spacing of anchor bolts, nailing schedules, and bracing. The second method is given in the International Building Code (IBC) which requires "engineered walls." These give specific strengths based upon nailing schedules and material used. The IBC also requires some means of restraining uplift either by the dead load of the building or holdown hardware.

A limiting factor of the IRC braced shear walls is their ability to resist the uplift caused by the horizontal forces acting on the wall. Without requiring holdowns, the sheathing nails and the sill plate are required to resist the uplift, which results in brittle failures (Mahaney 2002). Unfortunately, holdowns can be costly and difficult to install, so while requiring them in every IRC shear wall would improve the performance and safety of the structure, it may not be economical.

This study examines two alternatives to holdowns in comparison to prescriptive IRC shear walls, specifically in the maximum cyclic shear strength, stiffness, and ductility. The first alternative is a simple solution of adding a light-gauge metal gusset plate to the corner of the walls to help transfer uplift loads from the framing to a wood-plastic composite (WPC) sill plate. The WPC sill plate is thicker than conventional dimension lumber so localized bending moments are better resisted and fastener edge distances are increased. The second alternative is the use of an "L"-shaped sill plate that is continuously embedded into the concrete foundation. This method does not utilize any form of holdown or anchor bolts and it is anticipated that the intermediate studs would help resist the uplifting forces.

Both alternatives replace the PPT sill plate with a WPC, which resists decay without the use of preservative chemicals. Copper rich preservative chemicals can increase corrosion in the metal fasteners and weaken the system. Also the incising of the lumber required for the penetration of the chemicals weakens the sill plate in flexure (both cross grain and parallel to grain), which are primary failure mechanisms for walls without holdowns. By using a WPC, these problems can potentially be mitigated.

Literature Review

Many in the design community considered wood-frame buildings resistant to seismic loadings due to being highly redundant and ductile; however, the Northridge Earthquake on January 17, 1994 raised some serious questions. Over 95% of all fatalities in the Northridge Earthquake and one-half of all property damage occurred in wood-frame structures (Mahaney 2002). These events caused national concern because 90% of all residences in the United States are wood-frame (Bracci 1996). Sill plates were one of the major problems found in site visits after the Northridge Earthquake (Day 1996).

In light of the Northridge Earthquake, the Consortium of Universities for Research in Earthquake Engineering (CUREE) created the CUREE-Caltech Woodframe Project due to the obvious need for more understanding of earthquake phenomenon and wood structures. The CUREE researchers identified that sill plates are a weak link in wood-frame shear walls. The general failure of sill plates was identified as splitting due to cross-grain bending and twisting. The bending of the sill plate occurred because of the uplift due to the overturning of the wall. The twisting occurred because of the inherit eccentricity of the anchor bolts and sheathing (Mahaney 2002).

The uplift forces on the sill plate can cause a significant decrease in the capacity of the walls. In the CUREE testing, walls with different aspect ratios were tested to evaluate the effect of the uplift forces on capacity. Walls with an aspect ratio of 1:1 and no holdowns held only one-fourth the amount as a wall with an aspect ratio of 1:4 (Mahaney 2002.) One possible solution to resist uplift forces is placing holdowns on the wall (Mahaney 2002). When holdowns are added, the walls' capacity can increase by a factor of three (Cobeen 2004). However, holdowns are often complex to install and require time consuming tasks for those working on the concrete and framing of the structure. It is estimated that nearly 22% of all holdowns are misinstalled (Lebeda 2005). Even with properly installed holdowns, the ultimate failure of the sill plate is brittle. In fact, the large diameter bolts used in holdowns can cause a Mode I yielding (AF&PA 2005) and cause the sill plate to split (Bracci 1996).

One way to reduce splitting of the sill plate due to twisting and tension perpendicular to grain is to increase the thickness of the sill plates to 6.35 cm; however, these can still exhibit brittle failure (Bracci 1996). Another solution is to increase the size of the washers on the anchor bolts to increase the bearing area to offset the eccentricity on the sill plates. Increasing from a 5 cm square washer to a 6.35 cm washer can improve the capacity of the walls by as much as 20% (Mahaney 2002). Similarly, sill plates confined with steel straps or similar devices can resist higher loads and have the added advantage of maintaining 75% of the walls' maximum strength after the sill plate has split (Bracci 1996).

Another possible solution purposed by Duchateau (2005) is to create a WPC sill plate that is continuously embedded into the concrete foundation. Also, WPCs resist decay, which was a considerable cause of failure in the North Ridge Earthquake (Day 1996). Generally, the bottom 15 cm of woodframe walls is susceptible to decay (Duchateau 2005). A WPC sill plate together with proper house wraps and flashing should adequately protect this area. Additionally, an embedded WPC sill plate would provide an insect barrier and reduce air infiltration.

Duchateau (2005) proposed a continuously embedded sill plate after testing a variety of WPC sill plates. The most successful was a stranded section shown in Figure 1, with pockets to facilitate connection of the studs to the sill plate. Steel dowels were inserted through the end stud and cavity of the WPC sill plate to create a holdown. The primary failure modes were in flexure of the sill plate and tension perpendicular to the extrusion. Duchateau commented that these failures might be prevented if the WPC sill plate were continuously embedded into the concrete to remove flexure and to reduce the tension forces by sharing them with intermediate studs. The continuously embedded sill plate examined herein is to test Duchateu's hypothesis. The other sill plate in this study is a simpler, non-continuously embedded system that has a sill plate without pockets for studs, and the anchor bolts closer to the end studs to reduce flexure of the sill plate. Steel gusset plates were used to help transfer the uplift forces from the stud into the sill plate.

Materials and Methods

Materials

The sill plates were made with a WPC formulation of 55% pine flour, 41% polyethylene, and 4% lubricant by weight. The lubricant was TPW Structural 104. The WPC was extruded with a Milacron TC86 with Barrel-Zones 1 through 4 and the screws at 171° C. All three die zones were 177° C. The WPC was extruded as a 14 cm by 2.5 cm deck-board, which was subsequently melt-bonded to form the final 13.7 cm by 14 cm sill plates.

Due to the high cost of manufacturing an extrusion die, two different prototype sill plates were created with a melt bonding process explained in the Methods Section. Eventually, these shapes could be achieved through extrusion without the need for melt bonding. One section was a 3 ply (6.8 cm) member that served as a thicker traditional sill plate made out of WPC. The other sill plate was 6 plies and was cut into the shape shown in Figure 2 with a table saw. This shape was designed to be imbedded into a concrete foundation to serve as a continuous attachment. The asymmetric cross section was chosen to avoid weakening the portion of the concrete nearest the outside face of the foundation.

The load path for the continuously embedded sill plate has to transfer the uplift forces from the studs to the sill plate and finally to the concrete foundation. To achieve this load path for a proof of concept, the sill plate for the continuous foundation was attached to 16 gauge (0.15 cm) A569 sheet metal which attached the sill plate to the studs (Figure 2). The metal was to approximate Duchateu's system and provide load transfer from the studs to the sill plate. Such a heavy gauge metal was chosen to force the failure to be in the WPC. The metal was attached to the WPC with 11, 1.9 cm long by 0.3 cm wide sheet metal screws. Holes were predrilled into the WPC with a diameter of 0.32 cm to facilitate screw insertion. The layout of these screws on the sheet metal is shown in Figure 3a.

The concrete foundations were constructed to be 30.5 cm wide and tall by 3.35 m long. The concrete was a 6 sack concrete with a max aggregate size of 1.9 cm and 4 to 7% air entrapment. The mixture represented a typical residential mix for the local area. It was reinforced with two #4 rebars at mid-height of the foundation. The continuous foundation was further reinforced with five #3 rebars bent into an inverted "U" shape to reinforce the concrete edge undergoing tension to resist sill plate uplift. This reinforcing was placed 15 cm from the edge of the foundations and 30 cm o.c. with the top of the inverted “U” being 30 cm in length.

For the non-continuous foundations, three 1.59 cm diameter holes were drilled into the concrete to post-install anchor bolts. Simpson RFB #4X10 retrofit bolts were then installed with Simpson’s SETPAC-EZ high strength epoxy. The anchor bolts had a diameter of 1.3 cm and a length of 25.4 cm and were embedded 15.3 cm into the concrete. The end anchor bolts were placed 11.4 cm from the end of each wall. This placement created a 1.3 cm gap between the edge of the 5 cm square washer and the double end stud. Similarly, the middle anchor bolt was placed so that a 1.3 cm gap would exist between the washer and the center stud.

The walls were constructed with Douglas-fir 3.8 x 14 cm lumber. Stud grade was used for the studs and No. 2 or better were used for the top plates. The studs were spaced 40.6 cm o.c. with a double stud at the ends of each wall. The sheathing was 11 mm thick and was nailed 15.2 cm o.c. around the edges and 30.5 cm o.c. in the middle of the panels. The nails used for framing the studs were galvanized 10d (3.3x89 mm) box nails. A total of six nails were used to tie the double end studs together. Three rows of two nails were used, and the rows were 61 cm apart. Similarly, two nails were driven into the top of each stud through the bottom piece of the top plate. Three nails were driven at each stud to tie the two pieces of the top plates together. The lumber had an average moisture content of 13% (dry basis) at the time of construction as measured by a capacitance meter. The average moisture content at the time of testing was 7.9%.

The control walls had an incised PPT sill plate that was Hem-fir graded as No. 2 or better 3.8 cm thick. The studs were nailed through the sill plate and into the end grain of the studs. The thick, non-continuously embedded WPC sill plate also had a 61 by 61 cm right-triangle steel gusset plate attached to the end of each wall. The steel was galvanized 24 gauge attached to the outside of the sheathing. The attachment of the metal consisted of two nails equally spaced between the sheathing nails that were 15.2 cm o.c. The nailing configuration is shown in Figure 3. The nails used for the sheathing of both the control walls and the walls with thickened sill plates and their gusset plates were bright 8d (3.3x64 mm) common nails. All the nails were driven with a pneumatic nail gun without predrilling.

The walls with a continuously embedded sill plate had 16 gauge sheet metal attached to each stud with nails equally spaced between the sheathing nails. The plates extended 61 cm up from concrete foundation. The nails were 8d (3.9x76 mm) common nails and were used for both the attachment of the metal and the sheathing.

Methods

The melt bonding process consisted of placing two deck-boards 46 cm under two Fostoria 135kW infrared heat lamps. The surface temperature of the WPC was monitored using a Fisher Scientific IR thermometer. After approximately 15 minutes, the WPC reached 140° C. One of the deck-boards was then flipped on top of the other, and both were placed in a hydraulic press. A jig was made to improve the accuracy of aligning the two boards and to prevent a board from slipping under the pressure applied by the press. The press was displacement controlled to the thickness of the combined deck-boards minus 0.8 mm for the WPC to squeeze out of the sides. Generally, the press read a pressure of 518 kPa. The press was held for five minutes at the determined thickness before releasing the boards.

The melt bonding of multi-ply deck-boards followed the same procedure, only more time was needed to heat the WPC to 145° C. A higher temperature was needed to offset the conductive heat losses to the material behind the heated surface.

All shear walls were tested according to Method C, the CUREE protocol, in ASTM E 2126 (2007). A monotonic test was performed on walls with the thickened sill plate and the continuous embedment to find the appropriate D, the reference deformation for cyclic tests upon which the displacement of each cycle is calculated. The D for the control walls was estimated from previous experience. The D of the walls without holdowns, steel gusset plates, and continuously embedded sill plate were 1.56 cm, 2.16 cm, and 2.5 cm respectively. All tests were performed at frequency of 0.5 Hz.

Four resistance potentiometers were used to measure displacements. One was attached to the top plate of the wall to measure the global displacement. Another was attached to the sill plate to measure rigid body translation with respect to the concrete foundation. The other two measured the uplift of the end studs.

A 50 kN double acting hydraulic actuator with a 100 kN load cell applied the load to the top of the walls. The actuator was attached to the wall with a pin connection to prevent moment from being transferred into the load cell. The weight of the actuator was not applied to the top of the walls – this was accomplished by extending the top plate of each wall by 61 cm with a double stud at the end to hold up the actuator. Out-of-plane lateral displacement was prevented by attaching rollers that glided on fins attached to the testing frame. The concrete foundations were attached to the laboratory strongfloor with four 3.8 cm diameter threaded rods that went through vertical conduits left in the foundations and were screwed into the floor. For the walls with continuously embedded sill plates, bracing was added to the end of the concrete foundation to prevent possible translation.

Results and Discussion

Definition of Calculated Values

The results calculated for the cyclic wall tests followed ASTM E 2126-07 procedures; however, some discussion is needed as to how these values were calculated. Nearly all walls failed in a brittle manner, so the failure was defined as the peak displacement instead of degradation to 80% of peak. The brittle failure of the walls also caused one direction of the hysteresis to undergo a peak that the other direction did not. Since the actuator first pushed on the wall, which was recorded as a negative displacement and load, most of the walls failed at a negative peak. The exceptions to this were the walls with a triangular gusset plates because the nail withdrawal governed their failure, which was less sensitive to direction and less brittle.

The value of the maximum load resisted is defined as the largest load the wall resisted in either direction. The shear strength, displacement at peak, and ductility are all based on the stronger direction of the wall. The stiffness is based upon the average of both directions since initial stiffness is not influenced by the ultimate load or displacement.

The values were also calculated to reduce the effect of the translation during testing. The feedback of the actuator was used to measure the global displacement of the walls during testing; however, for the walls with the gusset plates, the concrete foundation slid as much as plus or minus 0.7 cm. Unfortunately, this was not noticed until analysis and can not be compensated for. The walls with a continuously embedded foundation had the concrete braced to remove any translation. The displacement of the concrete was then measured and found to be zero. Similarly, the values given have been modified to account for the translation of the sill plate relative to the concrete, which was subtracted from displacements given so that only shear and rotation are presented.

Since the walls had a concrete foundation, the sheathing of the walls would bear on the concrete when loaded. This effect caused the center of rotation of the panels to not be in the center of the panel. While this difference probably more accurately mimics a wall in the field, many wall tests do not have any foundations that influence the rotation of the panels. This difference most likely gives these walls a higher stiffness than if they were mounted on a steel channel.

Values for the hysteretic energy absorbed or damping could not be accurately calculated with the test data. Unfortunately, the equipment used had a maximum data acquisition rate of eight points per second, and since the walls were tested at a rate of 0.5 Hz, only eight points were recorded over a typical movement of 2 cm at the peak load. Such few points make calculating energy inaccurate.

Failure Modes

The control walls with a PPT sill plate and no holdowns failed in a similar manner described by Mahaney (2002). The sill plate split due to cross-grain bending along the line of the anchor bolts. The split was sudden and brittle, and once split, the wall could not resist load and would translate back and forth with the actuator. Figure 4 shows a typical split of the sill plate. The nails that attached the sheathing to the sill plate at the corners also underwent withdrawal from the sheathing as shown in Figure 5. Little damage was visually apparent outside of the two corners.

The monotonic test of the wall with a triangular gusset plate failed with the nails withdrawing from the WPC sill plate as shown in Figure 6. No damage was observable on the gusset plates, which suggests that an even lighter gage sheet metal might be adequate. The gusset plate also prevented the two primary failure mechanisms of the sheathing nails in the control wall. It prevented the nails from pulling through or tearing out the OSB. Significant bending was seen in the sill plate and separation of the melt bonds was seen during testing as shown in Figures 7 and 8 respectively.

The cyclic tests with the gusset plates failed in a similar manner. The nails ultimately failed in withdraw from the WPC. Replacing the smooth nails with threaded nails would likely improve the system. While not the primary failure mechanism, the corner of the OSB broke off at 5 to 7 cm. from the edge due to compressing against the concrete. The gusset plate similarly buckled from the compression. An example is shown in Figure 9. The nails on the shared stud of the panels also ripped out of the OSB.

The monotonic test for the wall with continuously embedded WPC sill plate showed the potential of such a system. During testing it was noted that the double top plate was bending and causing the actuator to push upwards on the wall. To help prevent this effect, a restraining chain was wrapped over the top plate at the connection to the actuator. Unfortunately, this prevented uplift from occurring on the wall as shown in Figure 10. However, it also prevented the major failure of the cyclic tests: delamination of the melt bond. Since a true commercial product would not be melt bonded, but simply extruded into the correct shape, the plane of weakness might not govern. The monotonic results suggest the capability of such a system, which is nearly twice the strength of the other walls tested as summarized in Tables 1 and 2.

The cyclic tests with the embedded WPC sill plate failed primarily at the melt bond. Since the quality of the melt bond was variable, the performance of these walls was variable as well. The first cyclic wall was considerably stronger, and the reason was easily seen when viewing the foundation after failure. The WPC failed at a combination of the melt bond and extruded WPC as shown in Figure 11. It was estimated that 80% of the failure was material failure and 20% was melt bond failure. The second cyclic wall was the weakest and the melt bond failure was estimated at nearly 80%. The third wall was in between the other two with an estimated 60% failure due to the melt bond.

Since the melt bond caused premature failures, the expected failures of nail-shear around the metal sheet or nail withdrawal did not happen. In fact, very little damage existed outside of the sill plate.

Comparison of Wall Types

The walls with the gusset plates were the easiest alternative to install and have the largest ultimate displacement; however, due to the translation of the concrete foundation for that series of tests, this value is questionable. If the speculated value of 0.7 cm of translation is subtracted from the ultimate displacement of the walls with gusset plates, the value becomes nearly the same as that of the control walls. The walls with the continuously embedded sill plate showed the smallest ultimate displacement. This result is likely due to the lack of rotational translation undergone by these walls. The configuration required less rotation before resisting uplift, so smaller drift was expected.

The shear walls with embedded WPC sill plates were the stiffest, but while such a sill plate would likely be stiffer than the others, the sheet metal likely caused the greatest contribution. The metal caused fixity to the bottom of the studs which caused bending rather than racking of the studs. While such foundations studied previously by Duchateau would obviously cause some fixity to exist, it is doubtful that it would be as much as caused by the steel in this experiment. The significant improvements made by both the triangular gusset plate and the continuously embedded sill plate can be seen in Table 2 which has the individual and average values of the three cyclic walls including the outlier second, continuously embedded wall.

On average, the walls with the gusset plates are shown to be the strongest, but this superior strength is likely due only to the premature failure of the melt bond of the continuously embedded sill plates. This explanation is presumed due to the continuously embedded wall with the best melt bonding being significantly stronger than the walls with the gusset plates. In fact, if the continuously embedded wall with the failure being nearly completely melt bond is considered an outlier, the embedded walls are stronger on average by 13% or 1.5 kN/m.

In comparison to the capacity of walls with holdowns as given in Special Design Provisions for Wind and Seismic Supplement (AF&PA 2005) Table 4.3A, the walls with the steel gusset plates and the continuously embedment were 7% stronger. Duchateau (2005) tested walls with a thickened sill plate that had cavities which allowed steel rods to be placed through the end studs and act as a holdown. Duchateau's walls were about the same strength as the walls tested in this study; her walls were only stronger by 1.7%. However, the walls with gusset plates were 61% stiffer, and the walls with continuous embedment were 145% stiffer than the walls in Duchateau's study.

Conclusion

This study tested an alternative to the use of PPT lumber as a sill plate by using WPC. Since WPCs can be extruded into shapes the might reduce the labor or improve the properties of shear walls, two alternatives were tested to remove holdowns. One alternative was a 6.8 cm thick, solid WPC sill plate with two 24 gauge steel gusset plates. The other alternative was a sill plate that was continuously embedded into the concrete.

Both studied alternatives have been shown to be viable options to resist the uplifting forces on shear walls. The continuously embedded walls were the stiffest and strongest if the wall test with the weakest melt bond is ignored, but showed the smallest ultimate displacement and ductility. The triangular gusset plate system would clearly be the easiest to install and inspect. Both wall types had an average strength of approximately 11.5 kN/m, which is nearly double the strength of a light-frame shear wall without holdowns and a 7% increase in capacity compared to walls with holdowns.

The walls with gusset plates showed a similar improvement of strength to a holdown, yet their installation is not as complex. The gusset plates did not fail but the nails withdrew from the WPC sill plate, and the gusset plate prevented nail pullout or tearing of the OSB. Further study of gusset plates with fasteners better capable of resisting withdrawal should be conducted. Similarly, a "U"-shaped, double sided gusset plate that wraps under the sill plate might also prevent this primary failure mechanism by more directly transferring the load into the anchor bolt.

Unfortunately the poor melt bonding of the continuously embedded sill plates caused premature failures that would not exist in a commercial product; however, this study does show the potential of such a system. If a better method of melt bonding is developed or directly extruding the desired shape is possible, further studies should provide better results. Until then, the melt bond remains a difficulty of testing these types of walls.

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Notation

The following symbols are used in this paper

D_e = the deformation at 0.4 Peak

D_u = the ultimate deformation

D_{yield} =P_{yield} / K_e

A = area under the envelope curve

COV = coefficient of variation

Ductility = D_{yield} / D_u

K_e = 0.4 Peak / D_e

P_{yield} = $\left(\Delta_u - \sqrt{\Delta_u^2 - \frac{2A}{K_e}}\right)K_e$

Figures

Figure 1 Duchateu's (2005) WPC sill plate section with steel dowels running through the cavities of the sill plate and into studs which are pocketed in the sill plate.

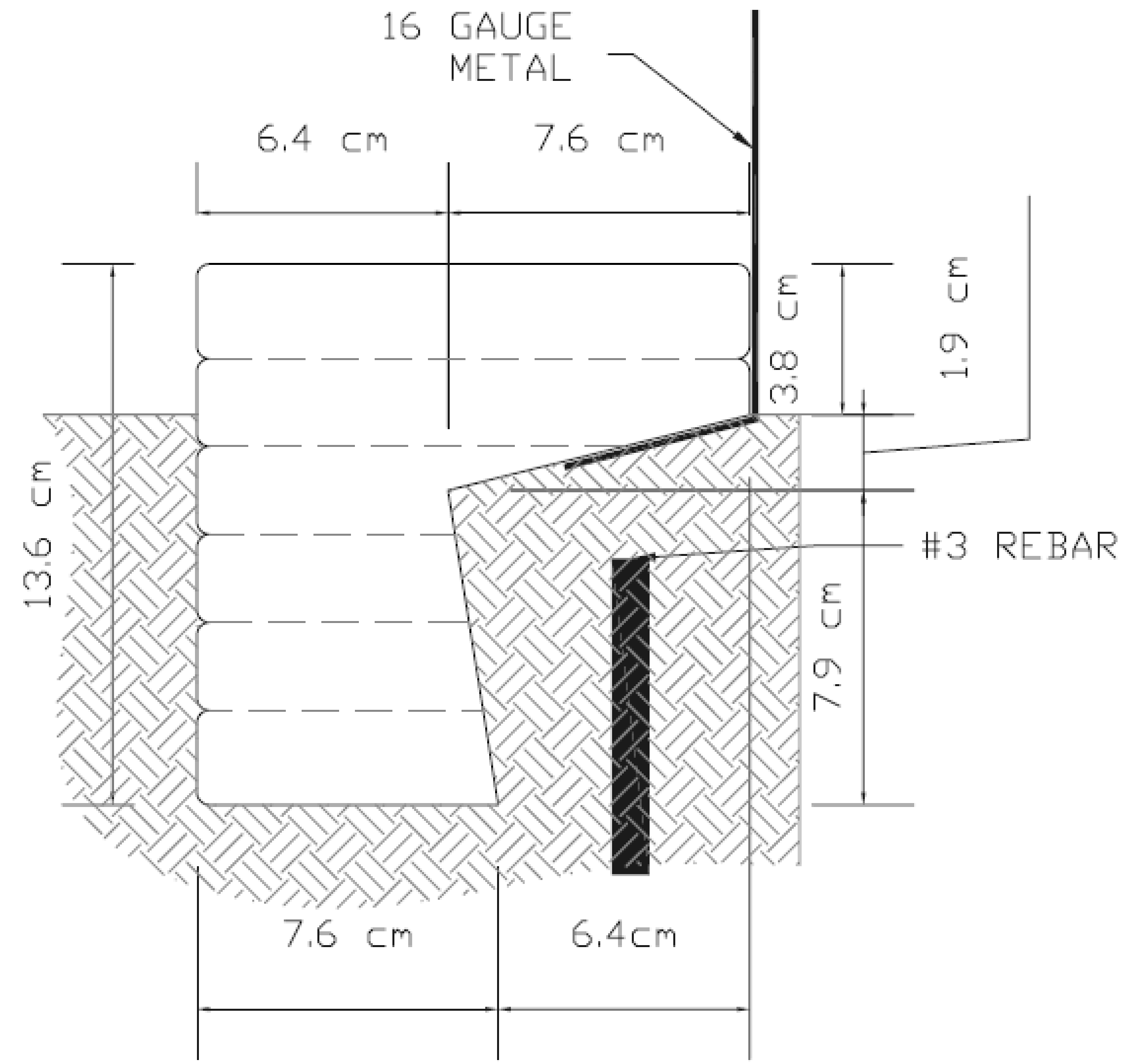

Figure 2 Section of the continuously embedded sill plate. Dashed lines show locations of melt bonding.

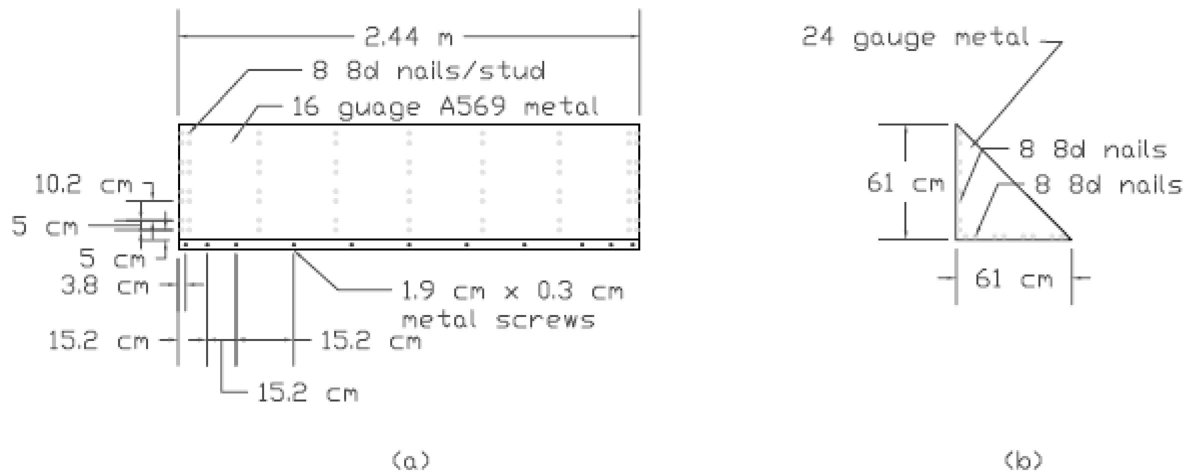

Figure 3a and 3b Layout of sheet metal and fasteners for the (a) continuously embedded sill plates and the (b) guest plates

Figure 4 Splitting of PPT Hem-fir sill plate without holdowns

Figure 5 Nail head pull-through from sheathing of walls without holdowns

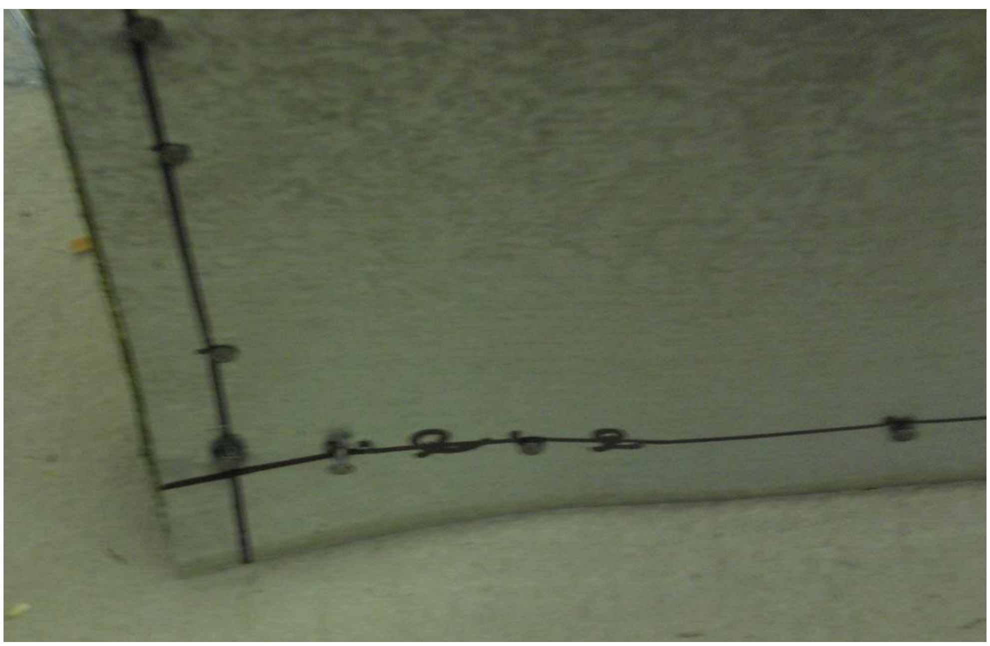

Figure 6 Nail withdrawal of triangular gusset plate at corner of wall

Figure 7 Bending of thickened WPC sill plate with triangular gusset plates (attached to other side)

Figure 8 Separation of the sill plate along the melt bond

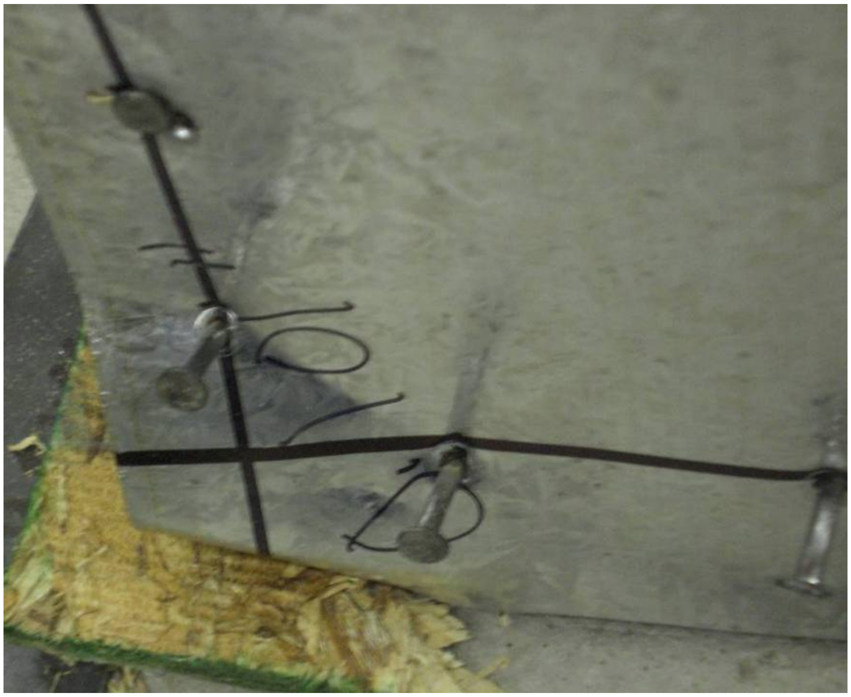

Figure 9 Buckling of metal gusset plate and damage of OSB at corner of wall

Figure 10 Restraint of uplift forces on the monotonic wall with a continuously embedded sill plate

Figure 11 Failure of the first continuously embedded wall. Light colored area is WPC failure and the dark colored area is melt bond failure.

Tables

Table 1 Monotonic test results

Monotonic Wall Type	Max Load	Shear Strength	K_e
	kN	kN/m	kN/cm
Continuous Foundation	53	21.7	14.72
Triangle Gusset	19	7.7	15.92

Table 2 Reverse cyclic test results

Wall Type	Iteration Number	Shear Strength kN/m	Ductility Value	P_{yield} kN	D_u cm	K_e kN/cm
Continuous Foundation	1	14.3	2.8	30	2.410	32.05
	2	8.3	1.6	31	0.846	30.09
	3	11.4	1.7	22	1.420	26.00
	Average	11.4	2.0	27	1.559	29.38
	COV	22%	27%	15%	41%	9%
Triangle Gusset	1	10.7	2.5	18	2.695	19.02
	2	12.5	2.6	25	3.327	17.88
	3	11.3	3.7	23	4.450	21.28
	Average	11.5	2.9	22	3.491	19.39
	COV	6%	19%	13%	21%	7%
Control	1	5.9	6.5	12	4.260	18.60
	2	5.6	2.3	12	1.481	18.50
	Average	5.8	4.4	12	2.870	18.6
	COV	2%	48%	0%	48%	0%

Foundation Elements for Naval Low-Rise Buildings

Performance of Post-Frame Shear Walls with a Wood Plastic Composite Skirtboard Subjected to Monotonic Racking Loads

Material Improvements Group

Task M3 – Evaluate new materials for mechanical performance, connection behavior, long-term loading and fatigue

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Abstract

Shear walls in post-frame buildings are commonly constructed with timber posts and horizontally framed wall girts. The bottom wall girt, called the skirtboard or splashboard, is typically pressure preservative-treated (PPT) due its location near the ground. Wood plastic composite (WPC) lumber is an environmentally benign alternative to PPT lumber, and the WPCs avoid the copper-rich chemical formulations found in PPT lumber that potentially accelerate the corrosion of the steel panels and fasteners. WPC products have different mechanical properties than lumber, so testing is required when substituting WPC products for PPT lumber in post-frame shear wall assemblies.

In this study a commercially available WPC product and PPT lumber were used as skirtboards in two common framing configurations of post-frame endwalls to evaluate possible effects on shear strength and stiffness. The study found that two 38 mm by 140 mm WPC boards can be substituted for a single 38mm by 235mm PPT board without significantly affecting the strength or stiffness of the shear walls. A high-density polyethylene WPC formulation was chosen for this study due to its relatively low modulus of elasticity as compared to other commercially available WPC formulations (e.g. using polypropylene or polyvinyl chloride). No significant buckling of the WPC members was observed during the tests. The dominant failure mode of the shear walls was buckling of the ribbed steel sheathing. It should be noted that this study only included a relatively limited sample of two wall constructions. Additional testing is recommended for wall constructions and materials not studied herein.

Introduction

According to the National Frame Builders Association (NFBA), the post-frame industry was valued at between 10 and 11 billion U.S. dollars in 2002. Post-frame construction differs from traditional light-frame wood construction in that instead of stud walls, post-frame buildings have timber posts, usually spaced 1.83 m to 3.66 m apart that directly support the roof. Wall girts are fastened across posts to allow attachment of sheathing. There are two typical ways to fasten girts to posts. Dimension lumber can be mounted on the outside surface of the post in a flatwise orientation. This method requires minimal labor, yet it causes girts to bend about their weak axis to resist transverse loads such as wind. Another method of construction is to inset girts between posts with the larger dimension parallel with the ground so that girts are loaded edgewise. Blocking, toe-nailing, or proprietary fasteners are needed for the edgewise girt-to-post connection, which requires more material and labor than the first method.

In either configuration, the bottom girt, called the skirtboard or splashboard, is typically exposed to wet conditions because it is located near ground level. In addition, the skirtboard is often used as formwork for casting a concrete floor inside the building.

Not only must skirtboards resist significant environmental loadings, but they also act as important components of the load path for post-frame buildings. The skirtboard collects forces from the sheathing and transfers them into the posts and foundation; thus, durability of the skirtboard is structurally important.

Methods of increasing durability of wood changed significantly when the Environmental Protection Agency announced that arsenic would no longer be permitted for residential and certain non-industrial uses (Lebow et al., 2003). Instead of chromated copper arsenate (CCA), chemical formulations with higher copper contents gained market share such as alkaline copper quaternary (ACQ) and copper azole (CuAz). The down side to these copper-rich formulations is the increased galvanic corrosion of fasteners in the treated wood. While this voluntary phase-out of CCA does not have a direct effect on agricultural and commercial post-frame construction, it has increased the difficulty in procuring CCA treated skirtboard material and has created a movement towards further reducing the use of CCA (Bohnhoff, 2002).

Replacing copper-rich PPT lumber with wood-plastic composite (WPC) material is one alternative, and its feasibility is assessed in this study. Four 3.7m by 3.7 m wall configurations were constructed, half with a commercially available WPC skirtboard and the other half with a PPT lumber skirtboard. All configurations were subjected to monotonic wall racking tests to evaluate their shear performance. The specific objective of this study was to determine possible influences of skirtboard material (PPT lumber vs. WPC) and girt orientation (flatwise vs. edgewise) on the following structural properties:

- peak and design lateral resistance
- displacements at maximum and design loads
- shear stiffness

Materials and Methods

Materials

Two types of skirtboad materials were used. The control case was pressure preservative-treated (PPT), incised 38mm by 235mm Hem-fir No. 2 lumber. A commercial wood plastic composite (WPC) made from a high density polyethylene formulation was chosen to represent the most common polymer currently used and one which has a relatively low modulus of elasticity compared to other polymer types such as polypropylene and polyvinyl chloride (Bender et al., 2006). Specifically, the WPC skirtboard was Trex Accents® with dimensions of 38mm by 140mm having a design modulus of elasticity (E) of 689,000 kPa. Other design properties for the Trex product can be found in ESR-1190 (ICC, 2005). All non-treated lumber, used for wall girts and blocking, was Douglas-fir No. 2 and was either a 38mm by 140mm or 38mm by 89mm, depending on location within the wall. Posts were Hem-Fir No. 2 with dimensions of 140mm by 140mm and were incised and pressure-treated with CCA.

Fasteners for the walls were 20d bright, common nails with a length of 102 mm and a diameter of 4.88 mm for wood to wood connections. Smooth nails were chosen over threaded nails for a direct comparison to previous studies (Braun Intertec, 1996); also, smooth nails provide a more conservative resultant strength compared to threaded nails. For a metal to wood connection, Fabral WoodFast 38.1 mm long, galvanized screws were used. Similarly, Fabral WoodFast 25.4 mm screws were used for stitch screws which secured overlapping metal sheets together. Both screws had a diameter of 4 mm. The metal was 29 gauge Delta Rib by Jenysis.

Wall Construction

Two factors were examined in this study: 1) PPT lumber vs. WPC and 2) edgewise vs. flatwise girt construction. The different wall configurations are shown in Figures 1 and 2. Posts for all configurations were 4 m long with a wall height of 3.7 m. The extra 0.3 m post length was used to attach the walls to the testing floor. Wall construction and fixtures generally followed methods given in the Braun Intertec (1996) report to the National Frame Builders Association.

For edgewise girt orientations, interior girts were offset to be in the same plane as the flatwise mounted skirtboard and top girt. Blocking between girts was attached with two 20d nails to the posts, and then two more nails were driven through the top of the girt into the blocking. To allow metal sheathing to be attached around the edges of the walls, a 38mm by 89mm Douglas-fir No. 2 board was attached to the face of the post. For the flatwise girts, two nails were driven through the face of the girt into the post on each side.

The 20d nails were driven by hand with 3.6 mm diameter holes predrilled into the WPC. Eight nails were used for each side of the skirtboard. For the PPT skirtboards, 16 nails were driven into each side without predrilling.

The Fabral screws were driven with a variable speed screwdriver. The screws were driven according to Fabral's instructions, which stated that the neoprene washer should not "mushroom" beyond the metal top of the washer (Fabral, 2000). For the stitch screws, overdriving was avoided by setting the clutch of the power drill used as a screwdriver. Overdrilling was prevented with the metal-to-wood connection screws by controlling the speed of the screwdriver.

Test Methods

Monotonic testes were performed according to ASTM E 564 (ASTM, 2006) and ASABE EP558 (ASABE, 2004). When the two standards conflicted, the method that was followed was carefully documented. For example, ASTM E 564 requires a preload of 10% of the ultimate load; whereas, ASABE EP558 only requires a 5% preload. The ASTM E 564 preload of 10% was followed. Similarly, ASABE EP558 requires that the ultimate load is reached "in not less than 10 min" versus the 5 min required by ASTM, so the ASABE method was followed.

The ASABE EP558 method of loading the wall at a constant rate of displacement was followed over the ASTM E 564 method of stepped incremental loads. The load rate was 6.35 mm/min and was calculated from Alumax Powerpanel Test Data (Alumax, 1992) and two trial walls whose construction and testing were used for calibration of the testing procedures. Load was applied uniformly across the top of the wall by attaching the top girt, which simulated a bottom chord of a truss, to a steel channel. The channel was attached by twelve, 6.35 mm diameter by 51 mm long self-drilling screws spaced 30.5 cm apart and 15.25 cm from each end of the girt. A 445 kN rated hydraulic actuator was then attached to the steel channel to apply load into the wall.

Posts were attached to the testing floor through pin-connections. While actual posts might have some moment-resisting capacity due to embedment, pin-connections were conservatively used in testing to require the skirtboards to resist more load. Pin-connections were created by sandwiching the posts with 6.35 mm metal plates. Four 1.59 cm diameter bolts attached the metal plates to the posts. On the other end of the plates, a single 2.54 cm diameter threaded bar was passed through the metal plates with a 10.2 cm by 10.2 cm metal square tube between the plates. This metal tube was then attached to the strong-floor with four 2.54 cm diameter bolts.

Since walls were constructed and tested parallel with the ground, rollers were placed under the center of each girt to minimize deflection due to self-weight of the wall. For the WPC skirtboards, two rollers were necessary since WPC has a lower modulus of elasticity than wood. Similarly, two rollers were placed under the steel channel so that its weight was not carried by the wall. Steel tubing was also place just above the steel channel to resist lateral deflection at the top of the wall. The steel tubing did not rest on the channel, and since significant buckling of the top chord never occurred during testing, top chords never made contact with the channel. A roller was also placed under each post to carry its self weight.

Deflection data were collected in four locations on the wall according to ASTM E 564 (ASTM, 2006). These locations were as follows:

1) Lateral displacement of the top of the wall

2) Uplift of the bottom corner of the wall on the side of the actuator

3) Crushing of the bottom corner of the wall opposite the actuator

4) Lateral slip at the bottom of the wall of the corner opposite the actuator.

All displacements were measured with linear potentiometers (string pots). Figure 3 shows a diagram of where string pots were located

Moisture content of wood members was taken with a resistance meter. Average moisture content for the posts was 30.5% and 9.6% for all other lumber.

Results and Discussion

A total of twelve walls were tested with six using edgewise girt construction and the other six using flatwise. Similarly, six of the walls had PPT lumber skirtboards and the six had WPC skirtboards. The nomenclature used for naming walls was that the first letter represents the wall girt orientation - edgewise (E) or flatwise (F). The second set of letters designates the skirtboard material - pressure-treated (PT) lumber or WPC (WP). The ending number represents the replication of that type of wall. For example EWP3 would be the third edgewise girt wall with a WPC skirtboard.

Definitions of Calculated Parameters

Walls subjected to monotonic tests undergo rigid body rotation and translation as well as shear displacement; however, it is only the shear displacement that is of interest. Rigid body translation was measured using string pot #4 on Figure 3. Rigid body rotation was a more difficult process. The values of string pots #2 and #3 were combined with the distance between string pots to provide the rigid body rotation. The distance between measurement points were 3.52 m and 3.72 m for the width and height, respectively. Figure 4 shows various types of displacements of wall EWP1. Displacement due to bending was assumed to be minimal for walls of this construction and is not required to be calculated by either the ASTM or ASABE standard.

As can be seen in Figure 4, early displacement was caused by rotation and translation. These displacements occurred largely due to crushing of the posts around the four bolts connecting the posts to the metal plates. There appeared to be minimal slippage of the metal fixtures before their engagement with the reaction floor.

The ultimate load for each specimen was determined as the maximum load the wall resisted during testing. The primary yield mode occurring at the maximum load was sheathing buckling. Tests were run well past the buckling load to guarantee that the peak load was reached. Usually, tests were run until the wall only resisted 90% of the maximum force measured. For clarity, all charts in this article stop at the maximum load of the wall.

Shear strengths of the twelve walls tested were considerably higher than the walls tested in the Alumax (1992) study. Alumax "Q-2" category of walls is closest to walls tested in this study; however, Alumax design strength for flatwise girt walls with pressure-treated skirtboards was 2.48 kN/m compared to 3.08 kN/m obtained in this study. Alumax walls differed in two significant areas: post spacing and girt spacing. Alumax posts were spaced 2.44 m on center (o.c.), which is a common spacing in the eastern United States. Posts in this study were spaced approximately 3.66 m o.c., which is a more common spacing for the western U.S. This difference, however, should have made Alumax's walls stronger. The second difference apparently had more impact on strength. Alumax's walls had girts spaced at 0.91 m o.c.; whereas, the walls in this study had girt spacing of 0.61 m o.c. Since a primary failure mechanism of the walls was buckling of the metal sheathing, reducing the distance between girts significantly increased buckling capacity.

Design shear strengths of walls were found by taking the maximum load and dividing by the width of the wall (3.66 m) and by a safety factor of 2.5. The ASABE procedure of averaging all three walls per configuration was used instead of the ASTM method of averaging the weakest two of the three walls. Table 1 shows the ultimate shear strength and design strength of each wall. The coefficients of variation (COV) calculated from three wall replications per configuration are given in Table 2.

Once shear displacement and design load were calculated, shear stiffness was determined. This value was calculated by dividing design load by shear displacement at that load (corrected for translation and rotation), and then multiplying by the height-to-width ratio of the wall. This ratio was 1.0 for these walls. According to ASABE EP558, the stiffness value is found by averaging all three walls. Table 1 shows the average value for each configuration.

As Table 1 indicates, shear displacements of all wall configurations were similar. A statistical ANOVA test was conducted and no significant differences were found between flatwise and edgewise girt orientations or between PPT and WPC skirtboards. Figures 5 through 8 show load versus displacement plots for each wall organized by configuration.

An unexpected result of this study was that the COV of wall stiffness with WPC skirtboards was higher than that of the PPT skirtboards. This result was unexpected since WPC products are generally more homogeneous than wood and have a smaller COV for material properties. The most probable explanation for this apparently counterintuitive outcome was variability in how the test wall specimens were fabricated – i.e. two different laboratory technicians assembled the walls.

Failure Modes

The primary yield mode for the walls was buckling of metal sheathing, with failure being defined as the ultimate load. Buckling started between the second and third girt (including the skirtboard as a girt) from the bottom. This location was the first gap between girts that spanned a full 0.61 m. Apparently, the decreased span of the metal between the skirtboard and the second girt increased the capacity of the metal enough that the next span became the weakest location. Buckling created a crease along the space between the second and third girt and eventually created diagonal waves throughout the panel sheathing. Buckling occurred approximately 30° from the rib axis.

Stitch screws and screws attaching the metal to the girts were another failure mode for the tested specimens. Screws would either pull out of the wood or metal or the metal would tear around the screws. This failure mode did not occur in all walls, but would most frequently happen on the side of the wall opposite the actuator, which was undergoing compression. Once a screw failed, buckling of the sheathing was affected as forces were redistributed around that failed section. It was observed that underdriving or overdriving screws negatively affected their performance, highlighting the need for correct and consistent attachment of screws for optimal wall performance.

Skirtboards exhibited minimal buckling during testing, with out-of-plane displacements less than 5 mm. They formed a full sine wave about their weak axis from post to post. The WPC skirtboard buckled most, as would be expected with its lower modulus of elasticity; however, buckling of either type of skirtboard was slight and did not appear to affect wall behavior.

Summary and Conclusions

Monotonic shear wall tests were performed on four configurations of post-frame walls. Potential differences between a PPT lumber and a WPC skirtboard were investigated for both flatwise and edgewise wall girt constructions. Shear wall tests were performed using the provisions of ASTM E 564 (ASTM, 2006) and ASABE EP558 (ASABE, 2004).

As shown in Table 2, strengths and stiffness of walls with WPC skirtboards were nearly equal to values with pressure treated skirtboards. ANOVA testing found no statistically significant differences between strengths and stiffnesses for flatwise versus edgewise girt orientation nor for PPT versus WPC skirtboards. This result suggests a nominal 38mm by 235mm pressure-treated lumber skirtboard can be replaced by two nominal 38mm by 140mm WPC boards for the wall configurations, sample size and materials presented in this study without sacrificing ultimate strength or stiffness of the walls. It should be noted that a commercially available WPC was selected for this study that is based on a high-density polyethylene (HDPE) formulation. The modulus of elasticity of WPCs made from this polymer resin are less than for other common polymer types such as polypropylene (PP) and polyvinyl chloride (PVC). The rationale was that WPCs with higher MOE values than reported here could be conservatively substituted. Hence, the possibility of utilizing WPCs for skirtboards shows promise and would provide an alternative to copper-rich preservative chemical formulations that accelerate corrosion in steel and aluminum sheathing, flashing and fastening materials. Further research is needed to examine possible effects of substituting WPCs for PPT lumber for other end wall constructions and fastening systems.

When comparing the strength of these walls with those tested in the Alumax study (1992), the impact of girt spacing was shown to be a significant factor. By decreasing spacing between girts, designers can expect a significant improvement of shear wall buckling capacity due to reduced unsupported span of the steel panels.

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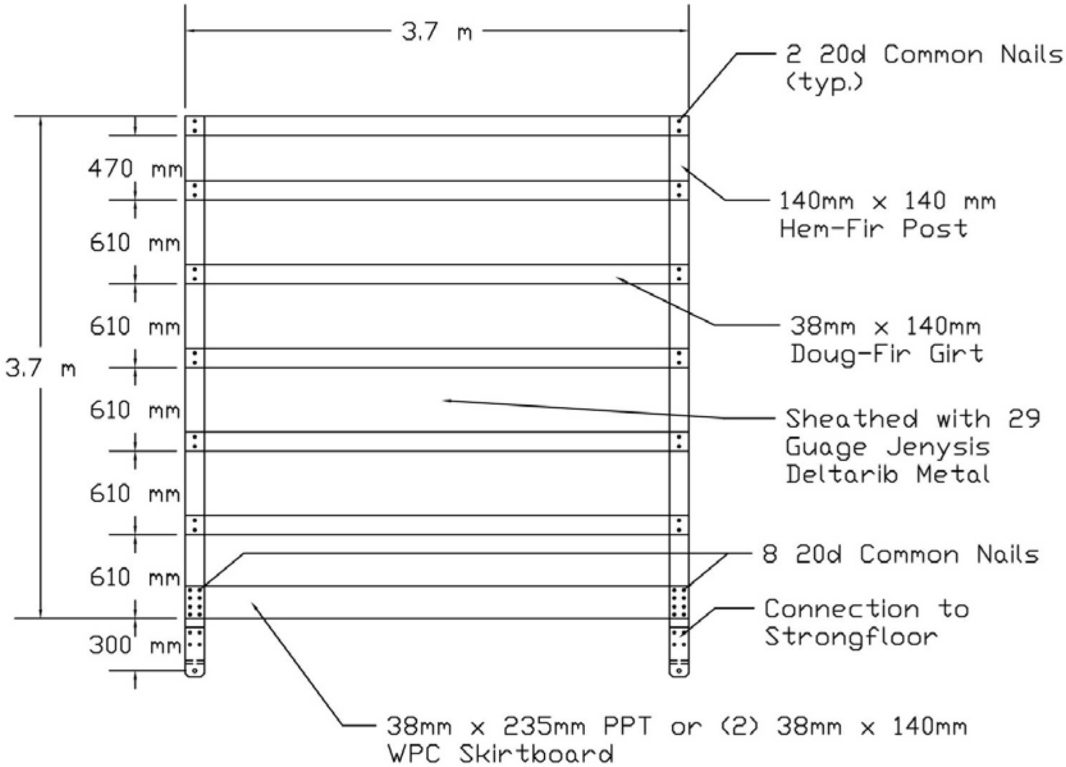

Figure 1 Flatwise wall girt orientation.

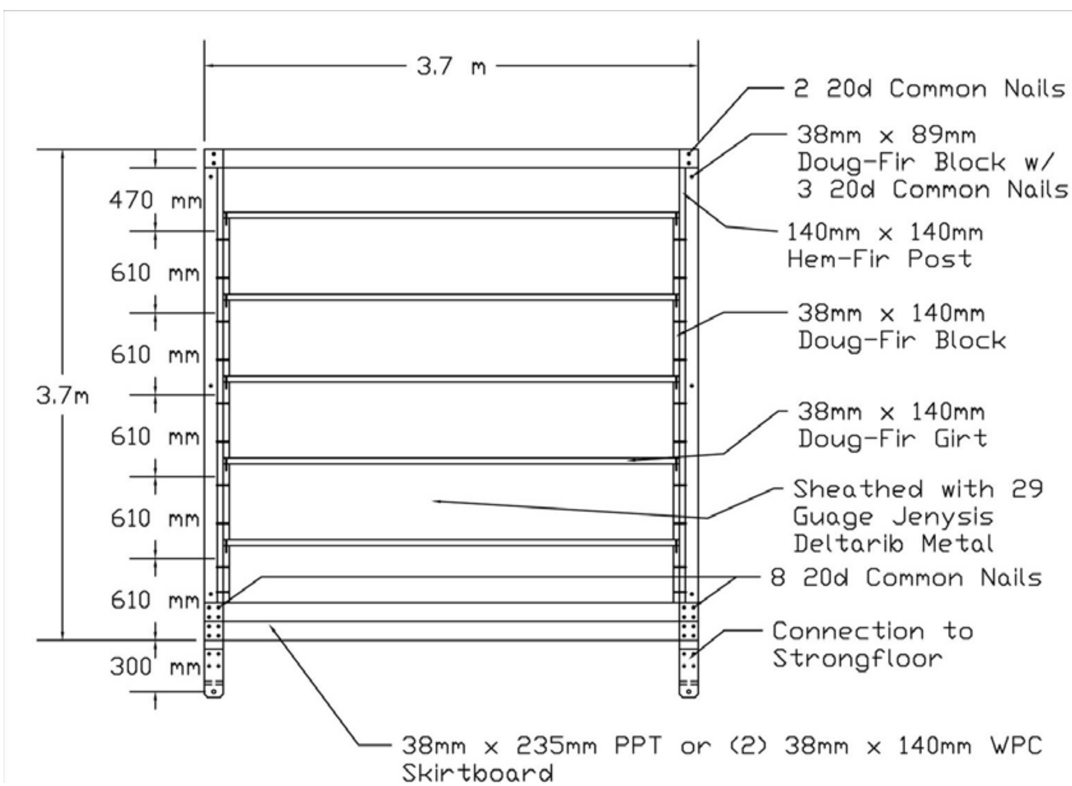

Figure 2 Edgewise wall girt orientation.

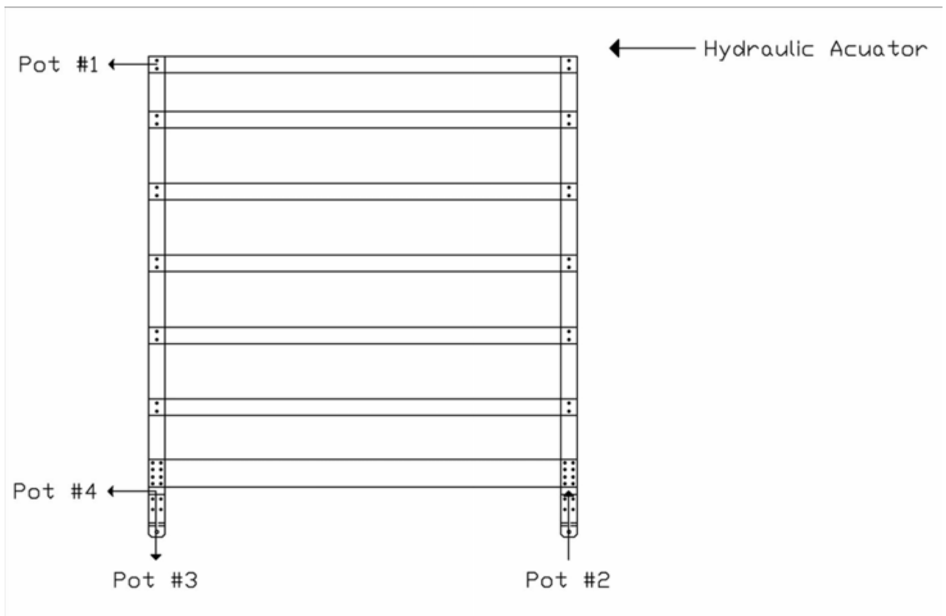

Figure 3 Location of string potentiometers to measure rigid body translation, rotation, and shear displacement.

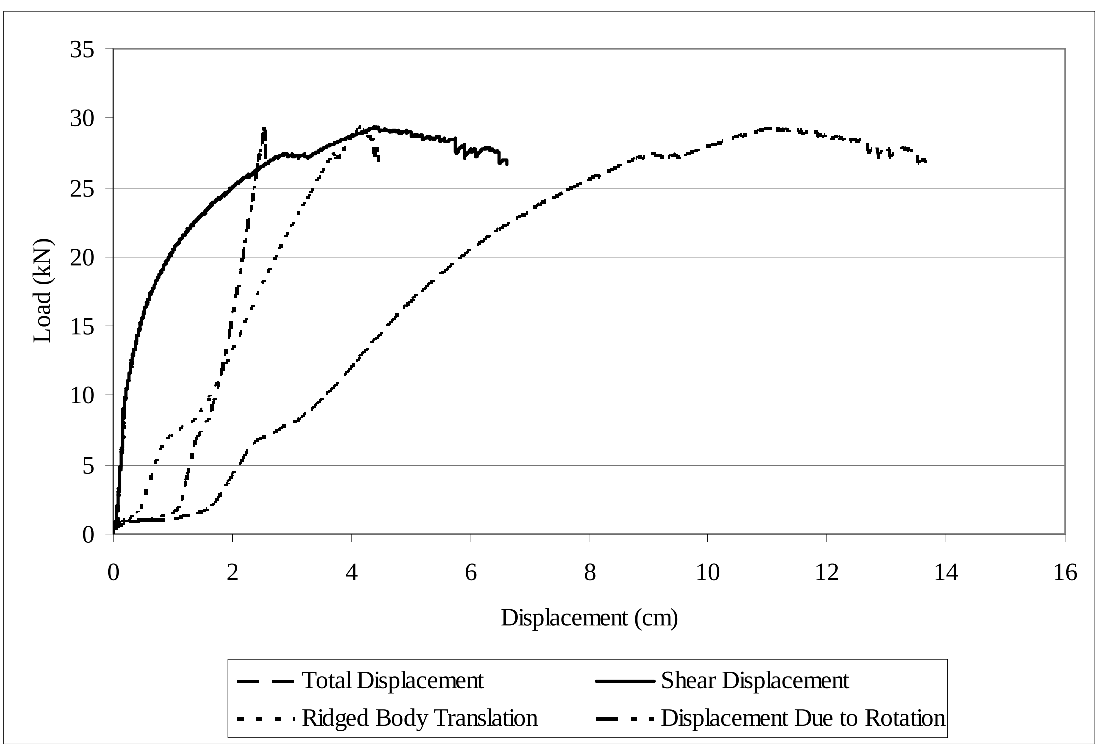

Figure 4 Displacements of a wall with edgewise girts and WPC skirtboard.

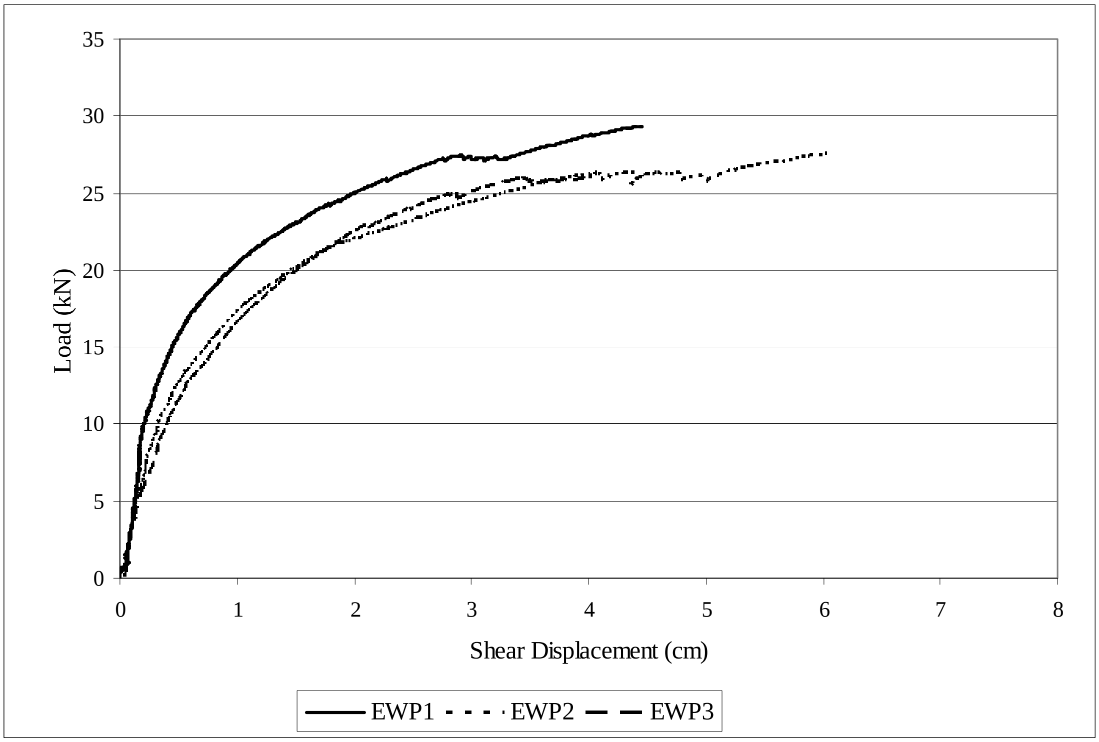

Figure 5 Shear displacements of walls with edgewise girts and WPC skirtboards.

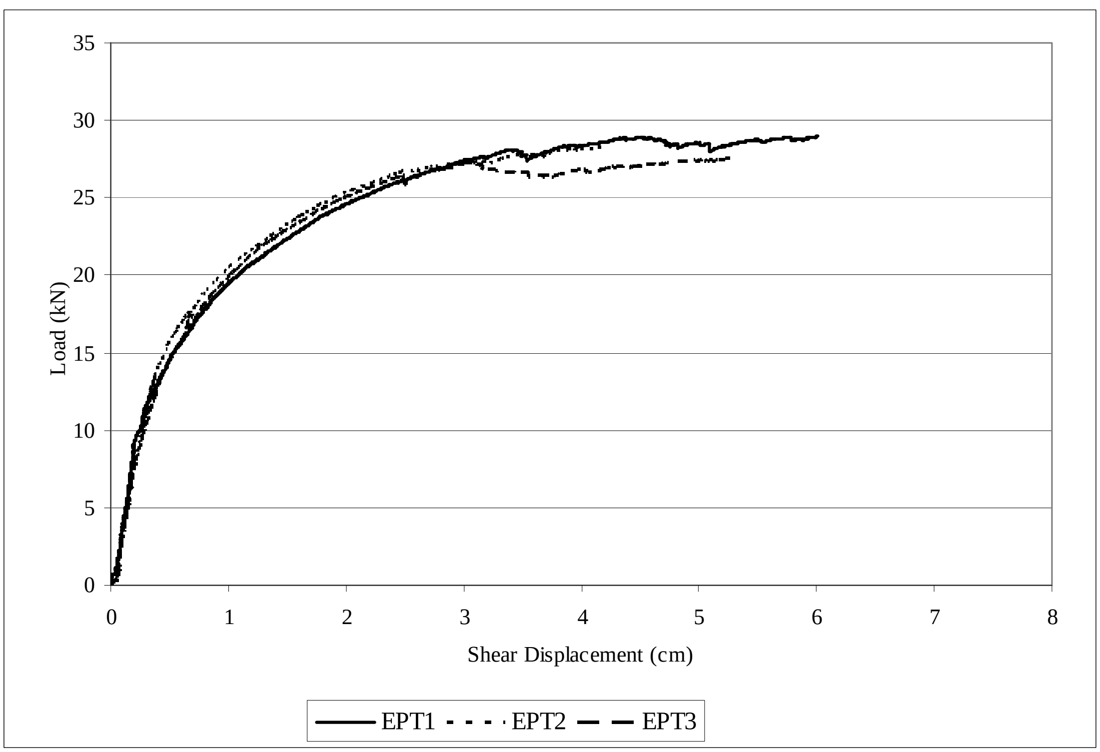

Figure 6 Shear displacements of walls with edgewise girts and PPT skirtboards.

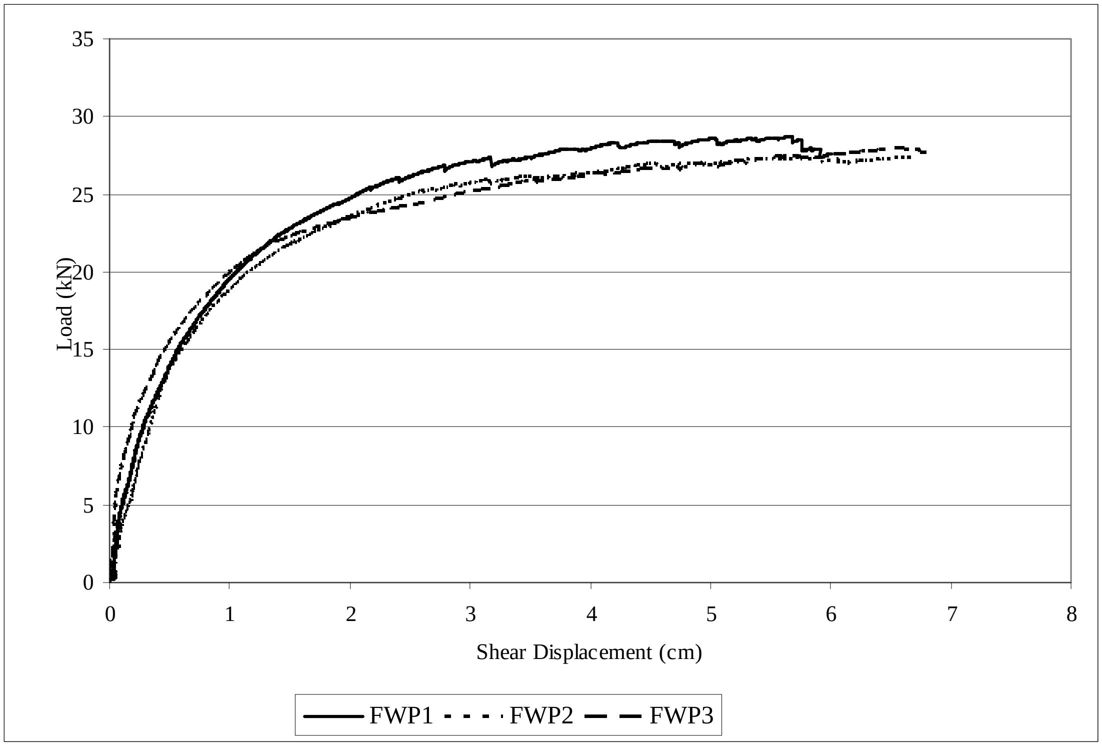

Figure 7 Shear displacements for walls with flatwise girts and WPC skirtboards.

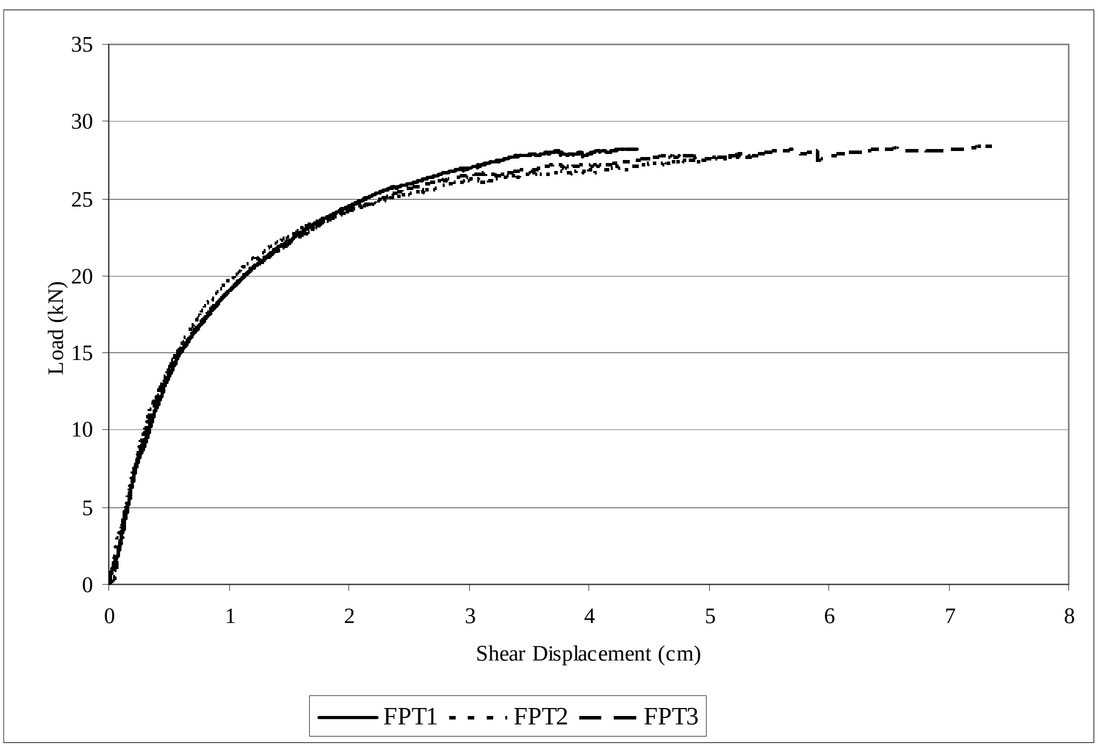

Figure 8 Shear displacements of walls with flatwise girts and PPT skirtboards.

Table 1 Results of each wall test

Wall	Shear Displacement at Max Load cm	Shear Displacement at Design Load cm	Shear Stiffness kN/m	Ultimate Shear Strength kN/m	Design Strength with 2.5 Safety Factor kN/m
EPT1	6.01	0.30	3,862	7.92	3.17
EPT2	4.16	0.31	3,647	7.73	3.09
EPT3	5.28	0.32	3,410	7.55	3.02
EWP1	4.46	0.29	4,048	8.02	3.21
EWP2	6.09	0.39	2,852	7.54	3.02
EWP3	4.03	0.43	2,438	7.14	2.86
FPT1	4.41	0.39	2,915	7.72	3.09
FPT2	5.47	0.34	3,239	7.63	3.05
FPT3	7.37	0.37	3,090	7.78	3.11
FWP1	5.67	0.35	3,248	7.85	3.14
FWP2	7.12	0.23	4,885	7.49	3.00
FWP3	6.66	0.37	2,977	7.67	3.07

Table 2 Average properties of each wall configuration

Wall Type	Shear Stiffness Average kN/m	Shear Stiffness COV %	Ultimate Shear Strength Average kN/m	Ultimate Shear Strength COV %	Design Strength with 2.5 Safety Factor kN/m
EPT	3,640	5.1	7.73	2.0	3.09
EWP	3,112	21.9	7.57	4.7	3.03
FPT	3,082	4.3	7.71	0.8	3.08
FWP	3,703	22.8	7.67	1.9	3.07

Table 3 Properties of WPC used (ICC, 2005)

Property	Allowable Stress Design (ASD) Value (kPa)
Flexural stress	1,725
Tension	1,725
Modulus of Elasticity	6.895×10^5
Compression parallel to grain	3,790
Compression perpendicular to grain	4,300
Shear	1,380

Foundation Elements for Naval Low-Rise Buildings

Foundation-to-Wall Connector Element

Connector Element Group

Task F1 – Develop conceptual and engineering designs for shape of connector element

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Project End Report

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Abstract

The potential to improve the strength of light-frame wood shear walls is significant if the connection between the wall and the foundation were to be formed into a different shape than the current rectangle of lumber. The improvement would result in lower damage to housing and other light-frame buildings subjected to wind or earthquakes. The objective of this project was to numerically model the cross-section of the sill plate of light-frame walls to develop an optimal shape to be used in extruded wood-plastic composites. This report contains the development of a finite element model that is useful for investigating the behavior of Wood-Plastic Composite (WPC) sill plates, designed to provide continuous anchorage for light-frame wood shear walls. The model was validated using a modified cross-section that was easily manufactured and tested. The resulting model indicated that the continuous anchorage concept is viable, and shear walls with continuous anchorage can achieve strengths over 2 times that of unrestrained shear walls currently built following prescriptive methods. The model showed that continuous anchorage provided shear strengths comparable to the strength of engineered shear walls that utilize mechanical overturning restraint.

Introduction

The principle weaknesses of wood light-frame shear walls is the connection between the end studs and the sill plate and the connection between the sill plate and the foundation. The end stud to sill plate connection is typically a nailed connection where the nail is actually driven into the end grain of the stud. This connection has a design strength of zero, and a realized strength very close to zero. If this connection were to be changed to a side grain connection, the strength could be increased from zero to a minimum of 2.7 to 5.4 kN per nail per connection.

Previous research illustrated that the strength and stiffness of light-frame shear walls can be improved if the connection between the studs and the sill plate are strengthened, and if the sill plate bending stiffness is increased (DuChateau 2005). DuChateau used a sill plate that was machined from a previously developed 150 mm deep cross section, and bolted the section to the test frame. DuChateau showed that improvements of 27-31 kN in uplift resistance over traditional end stud-to-sill connections without hold-down hardware could be achieved. One wood-plastic composite (WPC) sill plate wall configuration tested by DuChateau is shown in Figure 1. This wall configuration had substantial improvements in capacities, racking behavior, and associated failure modes.

Based on this proof of concept testing, numerical analysis of a theoretical cross section was completed in this project to try and optimize the cross section and develop a cross section that was 1) economical and 2) able to be extruded with current technologies. A finite element analysis was performed using ADINA and ABACUS, two commercial, general application finite element programs, on different cross sections to determine where stress concentrations were located and to minimize the volume of material used. ADINA was used to investigate the stress distribution using plane strain theory. ABACUS was used to investigate the effects of the sill plate within a full shear wall and determine the forces transferred to the sill plate and their locations.

Computer Analysis

Model Development

For this research, two finite element models were developed. The first was the sill plate model. This was a detailed model of the sill plate alone and was used to investigate the behavior of the sill plate. This model can be used in the future to fine tune the sill plate cross section.

The second model was the wall framing model. This was a model of the entire shear wall excluding the sill plate. This model was used to predict the forces expected to be transferred to the sill plate through the nailed connections.

The original concept of the sill plate cross-section is shown in Figure 2. This cross-sectional shape was arrived at after a stress concentration analysis. The shape has been idealized using three criteria; 1) efficient use of material, 2) a shape that can be effectively extruded, and 3) a shape that can accommodate typical construction practices, such as attaching interior cladding and using readily available pre-cut studs.

The fin on the bottom of the sill plate was the main feature of this cross-section under investigation, with hopes being that embedment of this fin into concrete would reduce bending demand on the sill plate and increase the overall strength of the shear wall. In addition to this fin, other features incorporated into the sill plate are the sheathing lip at the top and the stud pockets along the length of the sill plate. The section will be extruded as a single shape and the stud pockets will have to be routed out after cooling. The sill plate can be shipped from the manufacturer with stud pockets cut at standard 405 and 610 mm on center spacing. Non-standard spaced pockets (door and window locations, etc.) can be routed out on the job-site. The sheathing lip at the top is for attachment of the sheathing, which will act as blocking and also hold the sheathing flush with the outside to accommodate siding. The height of the section serves two purposes, first to act as flashing and protect the studs and sheathing from moisture damage, and second, it will allow for the stud pockets which allow for side grain nailing of the studs to the sill plate eliminating a weak link in typical light-frame wood walls.

The cross-section shown in Figure 2 is for use with 2X6 nominal lumber. If 2X4 nominal lumber is to be used, either the section can be extruded without the flat portion at the front of the section or this portion can be cut off at the job-site.

Because only the WPC is modeled, the boundary conditions in this model simulate the interaction between the sill plate and the foundation. It was assumed that concrete foundations have enough stiffness that they will only deform a negligible amount under the loads expected to be transferred by the shear wall. Because the focus of this investigation is on the WPC, it was also assumed that failure would occur in the sill plate, not the foundation. Because of the bulbous shape (upside-down triangular shape on the verification model) of the fin, the fin will provide bearing on the concrete in uplift. This assumption was justified by noting that the amount of material used in the cross section of the sill plate is small and therefore the horizontal strain without failure would not be sufficient to compress the sill plate enough to slide out of the concrete. By this reasoning, it was decided to model the boundary conditions of the sill plate model as bearing on a rigid body. A visual representation of this boundary condition is shown in Figure 3. In ADINA, the arrows pointing into the sill plate indicate the sill plate bearing on the rigid body (i.e., concrete). The arrows pointing away from the sill plate indicate the rigid body bearing on the sill plate.

The cross section shown in Figure 3 was “extruded” in ADINA to produce a three-dimensional sill plate for analysis. Forces were applied to the cross section at locations where connections between the sill plate and the studs and between the sill plate and the sheathing would occur. Figure 4 shows the 3D sill plate with the forces being applied. Further details of the specific element types and boundary conditions are available in O’Dell’s thesis. (2008).

The purpose of the wall framing model is to evaluate a wall under cyclic loading and predict the forces in the framing-to-sill plate and sheathing-to-sill plate connectors so that accurate loads can be applied to the sill plate model. The basis of this model is the finite element model created by Xu (2006) to test his hysteretic connector element. The analog for the finite element model used for the theoretical sill plate that is recommended is shown in Figure 5 along with the analog for the wall configuration actually tested to validate the computer analysis. The original finite element model was modified to match the verification tests by modifying the cross section and making the following changes:

1. Shell elements were added to model the sheet metal between the sheathing and framing.
2. A connection element, modeled after the bending stiffness of the cantilever portion of the sill plate cross section, was used to attach the sheet metal to the sill plate nodes.
3. Stud to sill plate connection elements were removed and replaced with bearing elements.

Connection Performance Characterization

The use of WPCs in conjunction with wood in structural applications is a fairly new practice, the behavior of the two materials functioning in a connection is not well studied. Therefore the hysteretic behavior of the nail connections between the sill plate and the studs had to be characterized for use in the numerical simulations.

There are two types of connections simulated in the finite element analysis: 1) nail connections between the WPC sill plate and the studs and 2) nail connections between the WPC sill plate and the OSB sheathing. In addition, the shear wall validation tests incorporated two additional connections: 1) nail connections between the WPC sill plate and sheet metal and 2) nail connections between sheet metal and OSB sheathing.

To characterize the hysteretic behavior of these connections, connection specimens for each combination were tested. Each specimen used a single nail and were tested using a cyclic protocol developed by the CUREE Woodframe Project (Krawinkler 2001). A schematic view of the connection test configuration and a photograph of an OSB to WPC connection test specimen are shown in Figure 6. Each connection configuration was tested using 10 repetitions. The Model parameters were obtained by using the genetic algorithm developed by Hiene (2001). The average of the parameter values was used in the finite element simulation. Results of the connection characterization are available in O’Dell (2008).

Verification

Originally, three main metrics were used to compare the walls tested using the modified sill plate and the model simulation. These metrics were the shear strength, elastic stiffness, ductility, and hysteretic energy dissipated by the wall during loading. Definitions for each of these metrics are given in O'Dell (2008).

The wall tests used to validate the finite element model were conducted by Ross (2008). This data proved to be problematic for use in validating the model because the data acquisition for the wall tests was too slow to provide accurate measurements of the load and displacements for the hysteretic curves. However, one of the walls was used to show the model's capability. The wall test and model simulation results are shown in Figure 7. Note that the model predicted the wall response reasonably well up until failure occurred at approximately -20 mm deflection.

The finite element model predicted the peak load to be 30.87 kN at a displacement of 17.8 mm. The test results were that the wall reached a peak load of 34.96 kN at a displacement of 22.1 mm.

The model under predicted the displacement and load due to problems in the manufacture of the sill plates used for the wall specimens. The ends of the sill plates were not bonded as well as the connection test specimens due to uneven heating of the sill plates. This caused the sill plate used in the wall tests to delaminate near the ends, where the highest uplift forces are present. This caused the wall to shift the failure to different positions than the wall model predicted. The shift of the failure position in the sill plate resulted in the failure occurring at a position with lower uplift forces, and allowed the wall to have a slightly higher capacity, but at a higher drift displacement.

Simulations

The finite element models were used to predict the behavior of full-scale light-frame walls using the idealized sill plate that provides continuous anchorage along the bottom of the wall. The cross section of the sill plate simulated is shown in Figure 3. The model predicted that the maximum load for the wall would be 24.1 kN, and this load would be reached at a displacement of 62.3 mm. The peak principal stress in the sill plate would be 6.9 MPa.

The results of the sill plate 3-D and 2-D analyses were within 10% of each other and can be seen in Figures 8 and 9 respectively. At first glance of these figures, it appears that there are some stresses that are higher than where the peak stress is indicated (i.e., the red areas). These are actually due to computer interpretation and can be ignored. These areas appear to have higher stress than they actually do because these are the points of load application (the red arrows indicate points of load application). Because loads were applied to the model as point loads, the computer interprets them as concentrated at a single point on the specimen. Because a single point has essentially no area, the stresses are depicted a lot higher than they actually are at these locations.

The results of the idealized model were compared to four past cyclic shear wall tests in order to assess the performance of the continuous anchorage WPC sill plate in relation to other configurations. To compare with shear walls built using typical construction practices, the model results were compared against shear wall results utilizing 2X4 (from Salenikovich 2000) and 2X6 (from Du Chateau 2005) nominal wood sill plates. To compare with a straight substitution WPC sill plate configuration, the model results were compared against the WPC sill plate tested by Du Chateau (2005) that had pockets for the studs and provided stud rotational resistance. This was the configuration that exhibited the best performance of all her specimens. The results of these tests and the model are summarized in Table 1.

Table 1: Shear Wall Capacities of Various Configurations

	Peak Load (kN)	Ultimate Displacement (mm)	Shear Strength (kN/m)	Stiffness (kN/mm)	Ductility	Energy Dissipation[c] (kN-mm)
2X4 Nominal Wood Sill Plate with No Anchorage[a] (Salenikovich 2000)	10.8	36	4.4	1.4	5.4	3,584
2X6 Nominal Wood Sill Plate with No Anchorage[b] (Duchateau 2005)	10.8	45	4.4	1.8	8.1	2,420
2X4 Nominal Wood Sill Plate with Full Anchorage[a] (Salenikovich 2000)	19.4	73	8.0	1.9	7.6	15,079
WPC Sill Plate With Stud Rotational Resistance Tested by Duchateau[b] (2005)	28.6	77	11.7	1.2	3.6	6,398
WPC Sill Plate with Continuous Anchorage[b] (model)	24.1	64	9.9	1.5	4.7	6,059

[a] values derived from testing using Sequential Phase Displacement (SPD) Protocol
[b] values derived from testing using CUREE basic load protocol
[c] energy dissipation cannot be directly compared between SPD and CUREE protocols

From Table 1, it can be noted that, in terms of strength, the performance of a shear wall utilizing a continuous anchorage sill plate is more than twice that of a typical unanchored shear wall and slightly better than a typical fully anchored shear wall.

When compared to Duchateau's 2005 shear wall test incorporating the WPC sill plate with stud rotational resistance, the results are a slight decrease in strength and energy dissipation. However, the continuously anchored shear wall did show an increase in ductility over the straight substitution WPC sill plate. The increase in ductility was caused by the increase in stiffness shifting the yield displacement to a lower value. The increased stiffness is due to both the continuous anchorage and the direct sheathing-to-sill plate connections incorporated in the continuously anchored shear wall.

To evaluate the performance of the continuous anchorage shear wall concept in the field, the model results were compared to current design codes. The Building Seismic Safety Counsel TS-7 suggests a maximum value of 2.6 kN/m nominal when designing unrestrained light-frame wood shear walls (Dolan 2007). The FE model presented in this thesis gives a nominal value of 9.8 kN/m. From the National Design Specification (2005), the nominal shear strength of an engineered shear wall of similar nailing schedule and sheathing type to that modeled is 7.0 kN/m. The results of the FE model yield a capacity 40 percent higher. The continuously anchored shear wall model was shown to be reasonably accurate. The model was used to predict the performance of a shear wall utilizing an idealized WPC sill plate. The results of the analysis were encouraging.

Conclusion

The finite element modeling to investigate the performance of a continuous anchorage WPC sill plate has shown the concept to be beneficial to the performance of shear walls. The model incorporates hysteretic connection behavior at its core to accurately predict shear wall behavior. This hysteretic connection behavior was derived from testing of single connections.

Based on the finite element model developed, continuously anchored light-frame wood shear walls show increased performance over typical shear walls in regards to capacity. The continuously anchored shear wall has an increased capacity over typical unrestrained shear wall test results of 230% and over typical overturning restrained shear wall test results of 24%. The continuously anchored shear wall demonstrated a 40% increase in unit shear strength when compared alongside engineered shear wall from design standards and an increase of 277% in relation to assumed resistances for prescriptive shear walls.

The shear wall configuration proposed in this project has the potential of replacing shear walls with overturning restraint and a 6/12 nailing schedule as the WPC provides increased strength and additional benefits in regards to moisture related decay. The addition of the continuous anchorage eliminates sill plate bending, eliminating one of the major modes of failure in shear walls during earthquakes.

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Figures

Figure 1: Light-frame shear wall using a hollow sill plate as tested by DuChateau (2005).

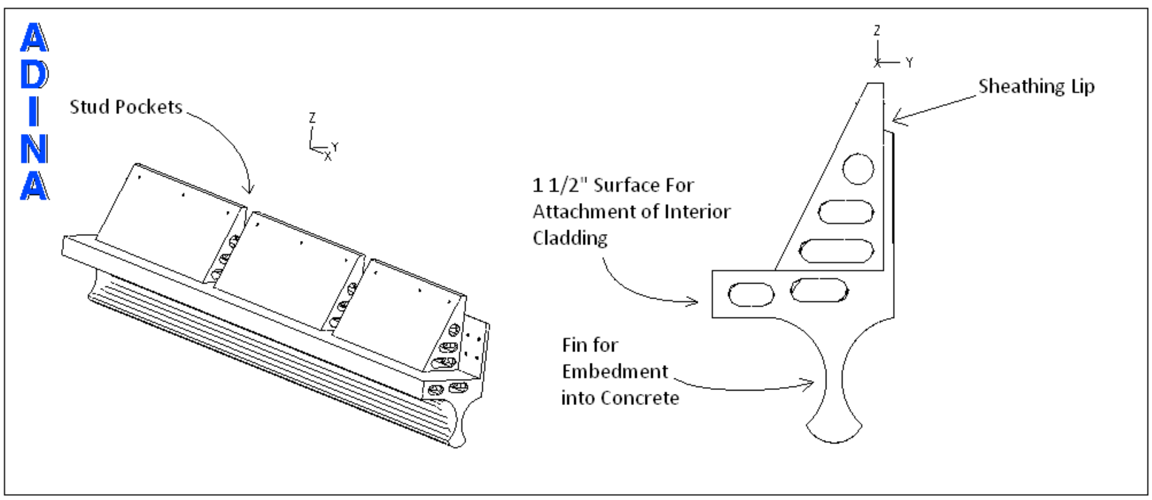

Figure 2: Original Concept WPC Sill Plate

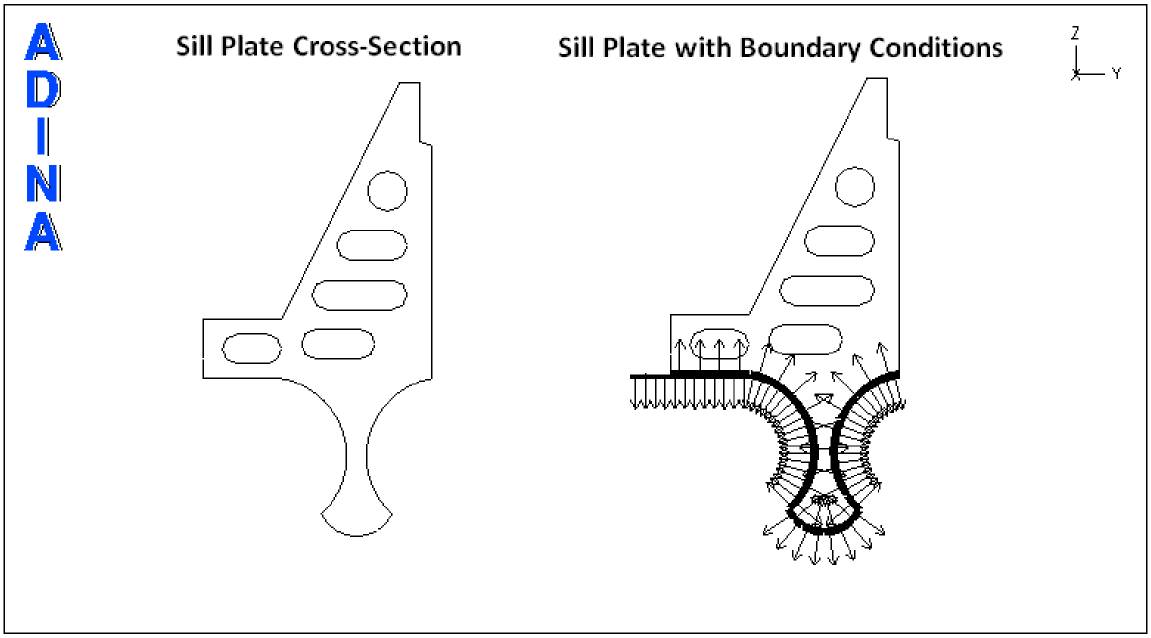

Figure 3: Boundary Conditions on Sill Plate Model

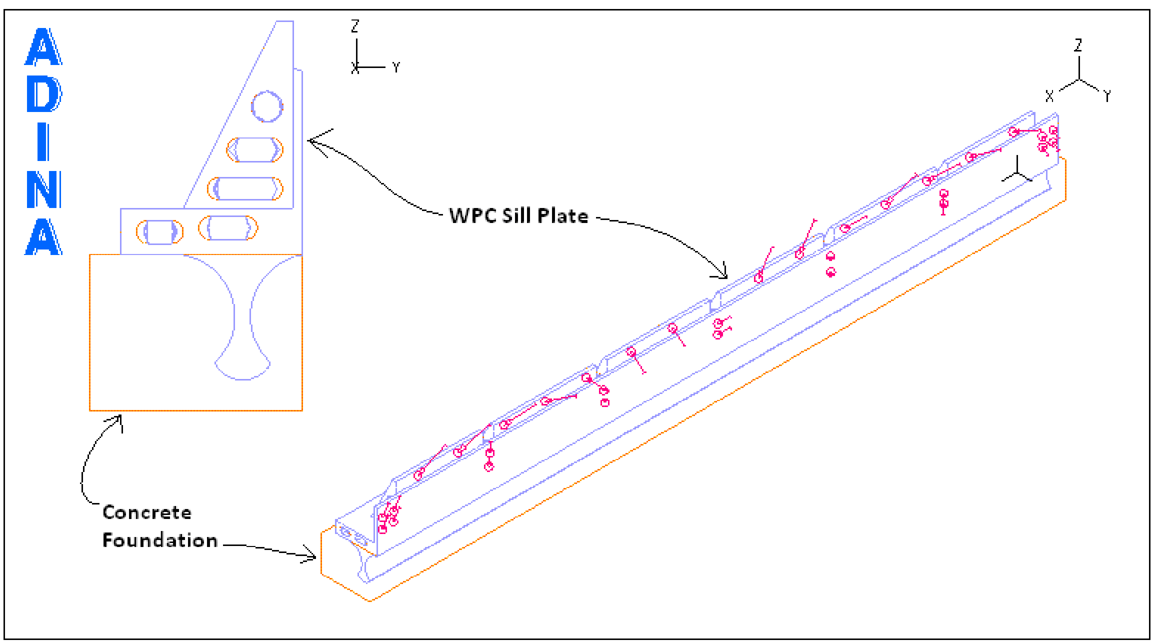

Figure 4: Sill Plate Element Model

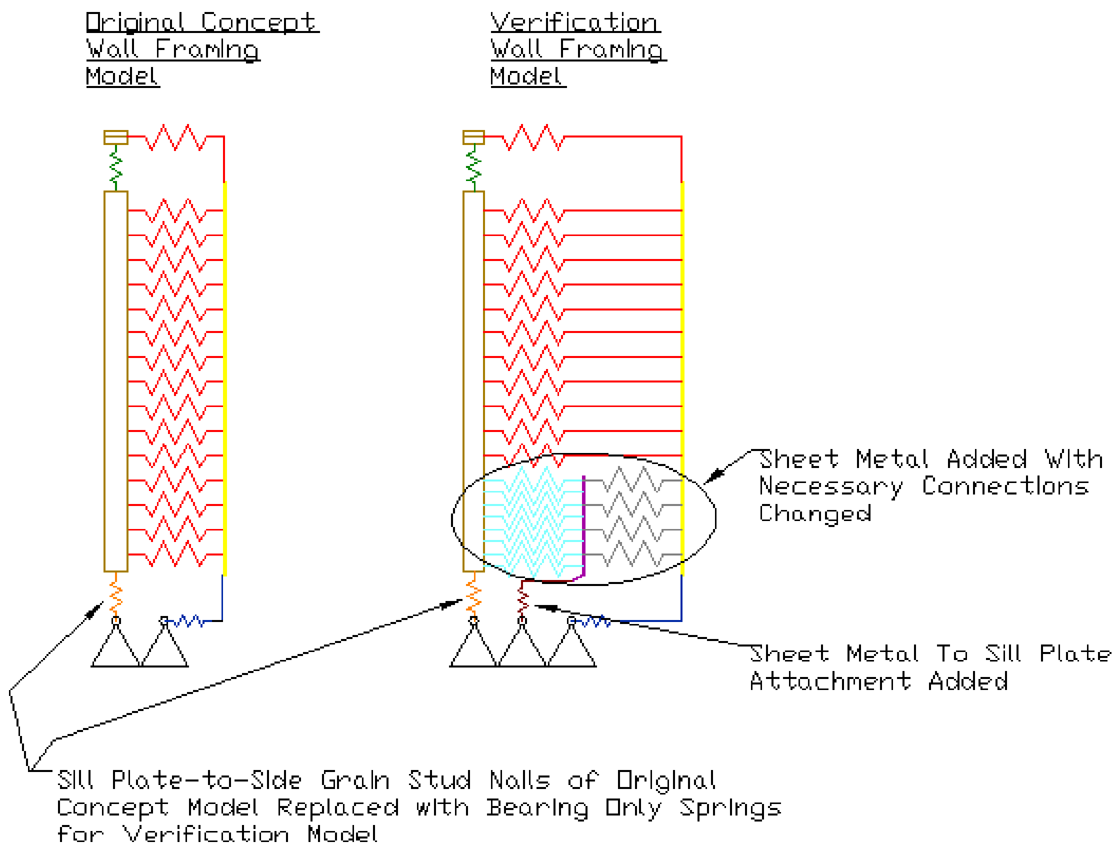

Figure 5: Original Wall Model for Conceptual Sill Plate and Model to Simulate the Verification Wall Configuration

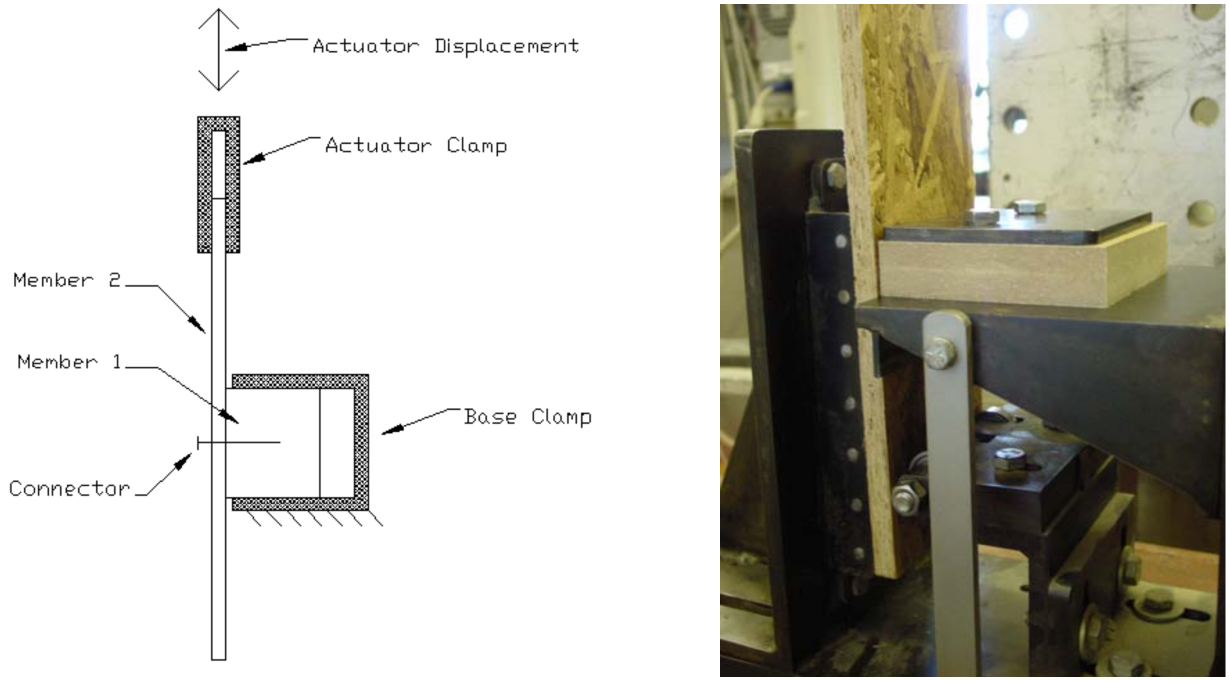

Figure 6: Schematic of Connection Test Configuration and Photograph of Nail Connection between OSB Sheathing and WPC Specimen being Tested.

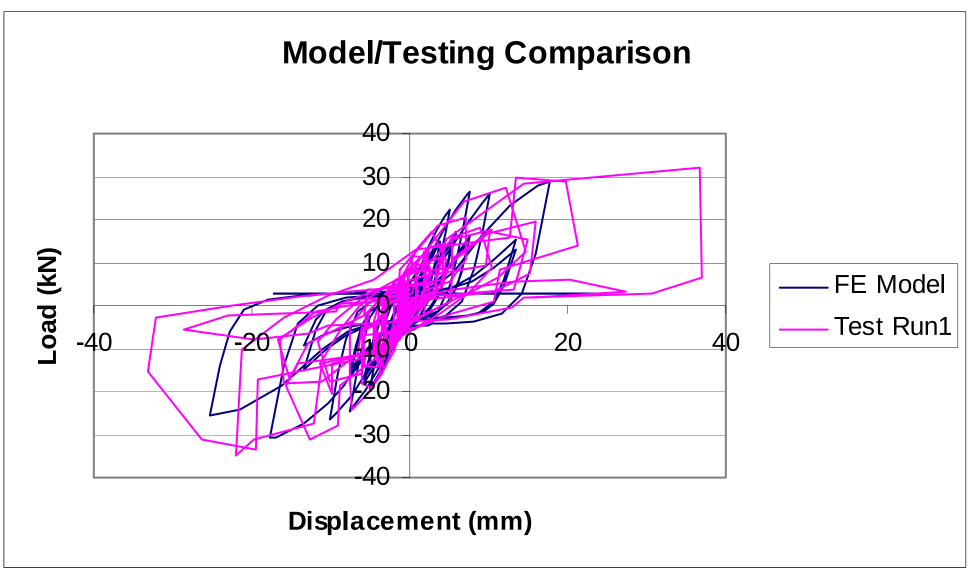

Figure 7: Shear Wall Test results Superimposed on the Finite Element Simulation Results.

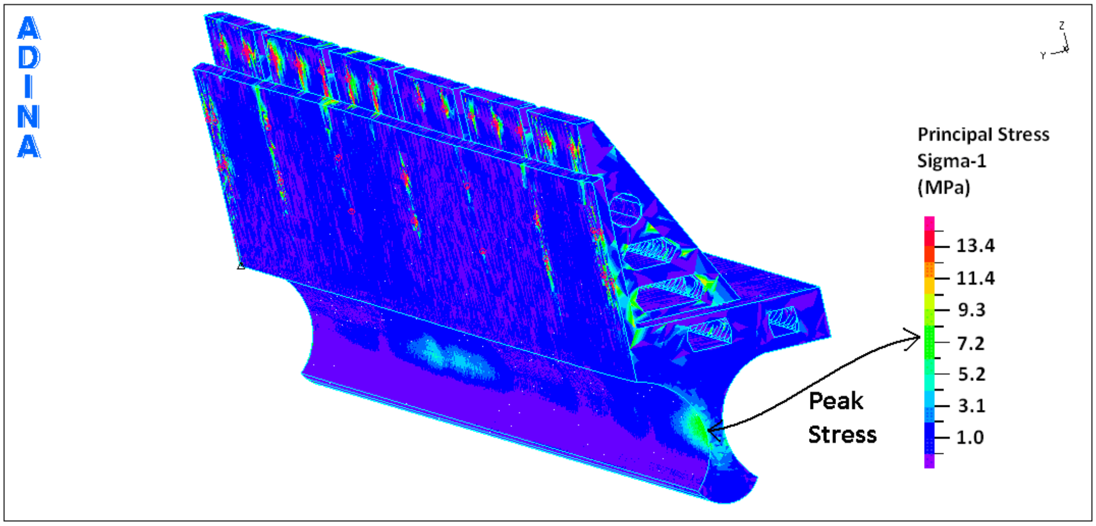

Figure 8: 3-D Stress Analysis Results

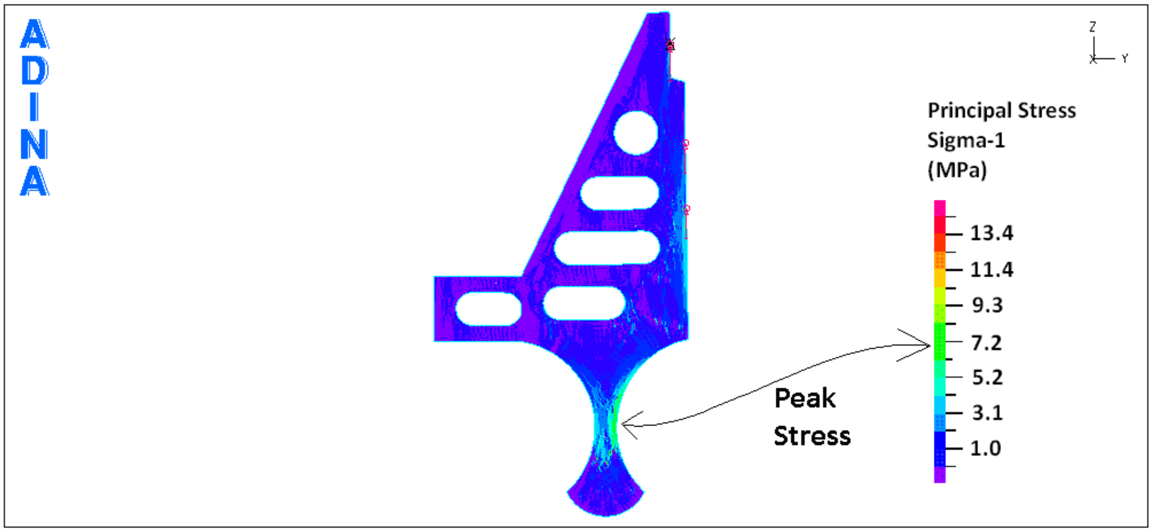

Figure 9: 2-D Plane Stress Analysis Results

Foundation Elements for Naval Low-Rise Buildings

Melt-Bond Lamination of WPC Boards

Connector Element Group

Task F2 – Manufacturing design for element

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Project End Report

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ABSTRACT

During the past few years new interest in wood plastic composites, WPCs, has been fueled by the success of several WPC decking products. Since WPCs absorb less moisture and at a slower rate than solid wood, they have a better resistance to insects, fungal attack and are more dimensionally stable when exposed to moisture. These interests go beyond decking into structural applications in the light-frame construction market. Although WPCs can be extruded in nearly any profile geometry, there is a need to develop the methodology for melt-bonding multiple WPC members together to add versatility without incurring the expense of cutting new dies for each application. The objective of this study was to develop and demonstrate laboratory processing procedures for melt bonding pairs of 1x6x8 ft. WPC boards. Since the majority of WPCs are made with polyethylene resin, HDPE boards were used. The boards were heated under infrared heat lamps until the surface layer melted and then they were pressed together. After the boards cooled, specimens were sampled to test the glue-line shear strength. It was found that the melt-bond process utilizing infrared heat lamps produced glue-line shear strength properties similar to the bulk composite properties.

INTRODUCTION

The International Building Code (IBC 2006), Section 2304.3.1, requires that studs shall have full bearing on an actual 1-1/2 in (3.8 cm) thick or thicker plate or sill. A die for a nominal 2 by 6 was not available for this research; therefore, it was not possible to extrude a solid wood plastic composite (WPC) board to use as a sill plate at the Washington State University Composite Materials & Engineering Center (CMEC). Due to the high cost of manufacturing an extrusion die, it was determined that two 1 in. by 5-1/2 in. (2.5 cm by 14 cm) WPC boards, which could be extruded at CMEC, would be melt-bonded together to make a board thick enough to use for a shear wall sill plate.

BACKGROUND INFORMATION

Wood plastic composites are comprised of wood flour or particles and a thermoplastic polymer, along with other minor ingredients (e.g. lubricants, UV stabilizers). The typical wood particle size ranges from 10 to 80 mesh. Some common wood species used in WPCs include pine, oak and maple. Thermoplastic polymers such as polyethylene, polypropylene and polyvinyl chloride (PVC) can be repeatedly melted. There are many diverse commercial uses for thermoplastic products such as milk jugs, grocery bags and siding for houses.

Commercial interest has been fueled by the success of WPC products in decking applications. Greater awareness and understanding of wood resources, more recycling sources of plastic along with equipment manufacturer developments and opportunities to enter new markets are all factors that are increasing demand in the WPC markets. The forest products industries are changing their view of WPCs as a way to increase wood durability and reduce maintenance for the consumer.

Since WPCs absorb less moisture and at a slower rate than solid wood, they have a better resistance to insects, fungal attack and are more dimensionally stable when exposed to moisture. Unfilled plastic absorbs little, if any, moisture. However, most plastics do expand when heated, therefore, the addition of wood decreases thermal expansion. Because wood has a limited thermal stability, only thermoplastics that melt or can be processed at temperatures below 392°F (200°C) are commonly used in WPCs. In WPC the wood component is hydrophilic (can transiently bond with water through hydrogen bonding) and the plastic component is hydrophobic (it repels moisture). Therefore, a compatibilizer is often used to improve the interfacial bond of the two different phases.

The majority of WPCs are made with polyethylene. The source of polyethylene used in building materials comes from both recycled and new sources. In the manufacturing of thermoplastic composites, the raw materials are mixed in an initial process called compounding. During compounding, fillers and additives are dispersed in the molten polymer. The material that is compounding is, either immediately shaped into an end product or pressed into pellets for future processing. There are several manufacturing options for the molten WPC material. The molten material could be forced through a die (profile extrusion), cold mold (injection molding), calendars (calendaring) or just into molds (thermoforming and compression molding) (Caulfield, Clemons, Jacobson 2005). When the compounding and product manufacturing steps are combined, it is called in-line processing such, as in profile extrusion. In-line processing is where molten composite material is forced through a die to make a continuous desired shape or profile. During the extrusion process many operating parameters can influence the product qualities, such as extruder screw speed, temperature profile in the extruder barrel, die, and with the cooling rate (Chang 2006). The majority of WPCs are produced by a profile extrusion.

For WPCs the greatest industry growth is in building products that have minimal structural requirements, including decking, railings, moldings, fencing, landscaping timbers, roofing and industrial flooring. The voluntary phase-out of chromated copper arsenate (CCA) was a contributing factor in WPCs gaining market share over pressure preservative treated lumber (PPT).

Research by Englund and Wolcott (2005) determined that it was technically feasible to melt bond wood plastic composite (WPC) boards together by utilizing an infrared heating apparatus. Gardner (2001) determined that melt-bonding WPC boards manufactured from polyethylene was a possible adhesion method. Other attempts to reinforce WPC by using an infrared heater to melt reinforcement sheets onto the surface of deck boards have also been proven successful (Jiang et. al. 2007). Previous attempts to laminate (melt-bond) large-scale lamina (greater than 2 ft.) were limited by the size of the heat source. Englund and Wolcott were successful in melt-bonding 30 in. (76.2 cm) WPC boards, where the interfacial shear stress values were similar or greater than the bulk composite properties.

OBJECTIVES

The objectives of this study were to develop and demonstrate laboratory processing procedures for melt bonding pairs of 1x6x8 ft. WPC boards. Bond quality was measured by block shear tests of the unbonded boards and then comparing with the shear strength developed at the melt bond interface.

PROCEDURE

One wood plastic composite material (WPC) material formulation was considered for this study with the following ingredients:

55%	*Pine flour*
41%	*polyethylene*
4%	*Struktol™ TWP 104*

The size of the Pine flour for this formulation was a US sieve #60 which is equivalent to 0.0099 in. (0.251 mm) particle size. The flour was dried to 2% or less moisture content before dry blending.

High density polyethylene (HDPE) was used for this study which had a density of 59.5 lb./ft.^{3} (953.1 kg/m^3). This polyethylene had a vicat softening point temperature of 253.4˚F (123˚C). The vicat softening point is taken as the temperature at which the specimen is penetrated to a depth of 0.04 in. (1 mm) by a flat-ended needle having a 0.0016 sq. in. (1 sq. mm) circular or square cross-section as described in ASTM D 1525.

Struktol™ TWP 104 is a blend of lubricants designed specifically for wood fiber/flour filled polyolefins. It is used to improve the process ability and surface quality of the WPC material.

Ingredients were dry blended in 360 lbs. (163 kg) batches using a drum mixer and extruded using a Cincinnati-Milacron TC86 3-7/16 in. (86mm) conical intermeshing twin-screw extruder with crammer feed. The temperature profile that was used for the extrusion is shown in Table 1.

During the WPC extrusion process, the extruder screw rotation rates were adjusted until acceptable surface properties were obtained. The final screw and feed speeds were 12 and 9 RPM, respectively. The dimension of the extruded WPC die was 1-3/16 in. by 5-1/2 in. (3 cm by 14 cm). Immediately after exiting the die, the WPC was cooled in a Conair water spray bath. Using a Conair flying cut off saw, the boards were rough cut into approximately 102 in. (2.6 m) lengths.

Since the International Building Code (IBC 2006) requires an actual 1-1/2 in. (3.8 cm) thick or thicker plate or sill, the extruded WPC board was melt bonded into a two-ply solid section having the final dimension of 2-7/8 in. by 5-1/2 in. (7.3 cm by 14 cm). This process of melt bonding the WPC boards consisted of placing two extruded 1-3/16 in. by 5-1/2 in. (3 cm by 14 cm) WPC boards side by side under three Fostoria FHK-1324-3A 13.5 kW infrared heat lamps Figure 1. The heat lamps were modified by removing the top ends of the heat shield on two of the lamps (lamps 1 and 3) and removing the top and bottom ends of the heat shield on the remaining lamp (lamp 2). The heat lamps were then mounted in series onto two 10 ft. (3 m) sections of slotted metal framing channel (uni-strut). This assembly was then elevated 104 in. (2.64 m) above the floor and secured with four legs consisting of slotted metal framing channel. The WPC boards were placed on a scissor table and raised to a distance of 16-1/2 in. (50 cm) from the heater elements.

It was observed that the three heaters had different temperature outputs. This difference in temperature was primarily due to the heater element ages and amounts of prior use. One end of the WPC boards had to be elevated 3 in. (7.6 cm) to maintain a more uniform temperature along the length of the boards Figure 2. The surface temperature of the WPC was monitored using a (Fluke model 53II) thermometer with a Type-J thermocouple. In order to obtain an accurate temperature reading with the thermocouple, a small piece of aluminum foil was placed over the thermocouple to shield it from the infrared heater elements.

After approximately 10 minutes, the outer layer of the WPC boards reached an average temperature of 284°F (140°C) along the length. One of the WPC boards was then rolled over on top of the other, which was already placed in an alignment jig. A jig was needed to keep the edges of the WPC boards aligned and to prevent them from sliding when the hydraulic press was activated. This assembly was placed into a computer controlled 4 ft. by 8 ft. (1.2 m by 2.4 m) hydraulic press. The press was controlled by a PressMan protocol and closed to a final displacement of 3.348 in. (8.5 cm), which was the combined thickness of the two WPC boards and the alignment jig minus 0.152 in. (3.86 mm) for the molten WPC to squeeze out of the sides. The PressMan consol recorded an average pressure of about 120 psi. (827 kPa), which was held for 10 minutes. After the WPC boards exited the hydraulic press, they were allowed to cool overnight. The cooled WPC boards then had the squeeze out bead shown in Figure 3 removed with a table saw.

One WPC board assembly was sampled at random and cut into 2 in. x 2 in. (51 mm x 51 mm) glue line shear blocks and tested following the ASTM D 1037-06a (2008) Glue-Line Shear (Block Type) standard. Three glue-line shear blocks were sampled every 16 in. (40.6 cm) along the length of the board as shown in Figure 4.

RESULTS AND DISCUSSION

Glue-line shear block test results are presented in Table2. The average glue-line shear strength of the WPC was determined from testing eighteen specimens in accordance with ASTM D 1037-06a (2008) to be 977 psi. (6737 kPa). This was compared to the interfacial shear stress values of the bulk shear block test. As can be seen in Figure 5 the values are similar or greater than the bulk composite properties. One other thing worth noting is the fact that 83% of the glue-line shear blocks tested had a 90% or greater WPC bulk failure, as shown in Figures 5 and 6.

SUMMARY AND CONCLUSION

The cost of extrusion dies can be significant. One way to gain more versatility and value in WPC processing is to develop a full-scale melt-bonding technique. The objective of this study was to explore the technical feasibility of melt bonding two wood plastic composite (WPC) boards together by utilizing an infrared heating apparatus.

The three Fostoria FHK-1324-3A 13.5 kW infrared heat lamps were modified so they could be mounted in series to perform as one long heat lamp. This heater assembly was supported 16-1/2 in. (50 cm) above the surface of the WPC boards to be heated. Due to a slight difference in heater element temperatures, one end of the boards had to be elevated 3 in. (7.6 cm) closer to the heat lamps in order to equalize the surface temperature of the boards.

In order to monitor the surface temperature of the boards, a Type-J thermocouple with a heat shield to reflect the heat from the heaters was used. Once the WPC boards reached an average temperature of 284˚F (140˚C) along the length of the boards, one board was rolled on top of the other. It took approximately 10 minutes for the WPC boards to reach this temperature under the heat lamps.

The stacked WPC board assembly was pressed to a final displacement of 0.152 in. (3.86 mm) less the overall thickness of both WPC boards plus the alignment jig. This assembly was held in the press for 10 minutes at an average pressure of 120 psi. (827 kPa).

Upon exiting the press, the WPC boards were carefully removed from the alignment jig and allowed to cool over night on a flat surface before machining. Machining consisted of trimming the excess material with a table saw.

Random specimens were sampled for glue-line block shear tests. It was found that the glue-line shear strength properties were similar or greater than the bulk composite properties. The melt-bond lamination had an average glue-line shear strength of 977 psi. (6736 kPa) compared to the WPC bulk shear strength of 949 psi. (6543 kPa).

This research used just one method to laminate WPC board together utilizing an infrared heating apparatus, however further study should be done using other heat sources. Heat sources which could heat the surface of the WPC quicker may produce better surface bonds by not allowing the heat to slowly penetrate deep into the material.

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Jiang, L., M.P. Wolcott, J. Zhang, and K. Englund. 2007. Flexural Properties of Surface Reinforced Wood/Plastic Deck Boards. Polymer Engineering and Science, Wiley InterScience, pp. 281-288

Figure 1 Fostoria FHK-1324-3A 13.5 kW infrared heat lamp

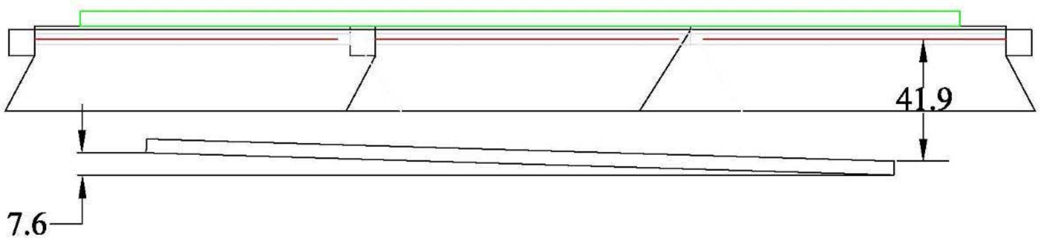

Figure 2 WPC under heater elements

Figure 3 WPC with Squeeze-out

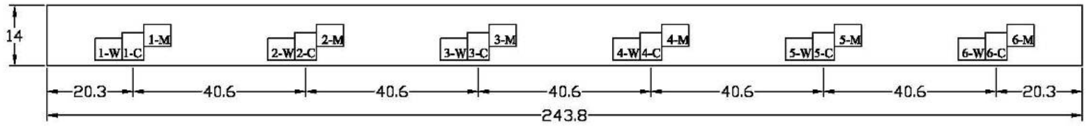

Figure 4 Layout of shear block samples

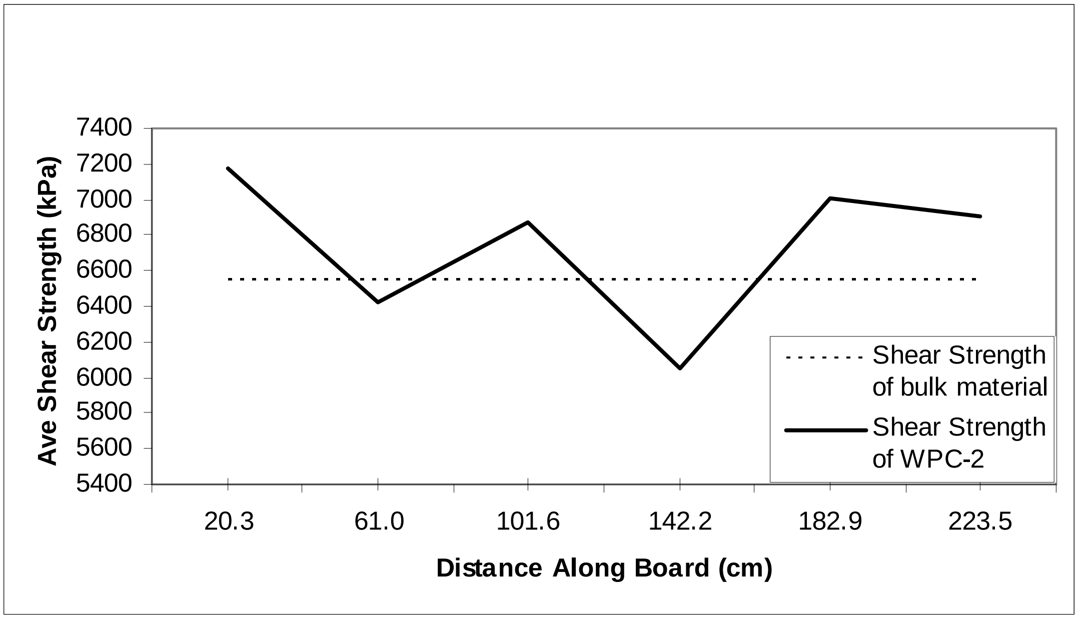

Figure 5 Average Shear Strength Along Board

Figure 6 Glue-line shear block failure

Table 1 Extruder temperature profile

Zone	Temperature	
	˚C	(˚F)
Barrel Zone 1	171	(340)
Barrel Zone 2	171	(340)
Barrel Zone 3	171	(340)
Barrel Zone 4	171	(340)
Screw	171	(340)
Die Zone 1	177	(350)
Die Zone 2	177	(350)
Die Zone 3	177	(350)

Table 2 Interfacial shear results

Sample	Glue Line Failure (%)	Max Shear kPa	(psi)
1-C2	100	7405	(1074)
2-C2	100	6929	(1005)
3-C2	85	6605	(958)
4-C2	66	6314	(916)
5-C2	100	7484	(1086)
6-C2	100	7500	(1088)
1-W2	100	7127	(1034)
2-W2	100	5195	(754)
3-W2	95	7171	(1040)
4-W2	50	4954	(719)
5-W2	100	6733	(977)
6-W2	100	6641	(963)
1-M2	100	6977	(1012)
2-M2	100	7138	(1035)
3-M2	100	6843	(993)
4-M2	100	6886	(999)
5-M2	100	6800	(986)
6-M2	90	6566	(952)
Avg.		6737	(977)
COV		0.10	

Foundation Elements for Naval Low-Rise Buildings

Foundation-to-Wall Connector Element

Connector Element Group

Task F3 – Evaluate prototype performance in wall system

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Project End Report

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Abstract

The potential to improve the strength of light-frame wood shear walls is significant if the connection between the wall and the foundation were to be formed into a different shape than the current rectangle of lumber. The improvement would result in lower damage to housing and other light-frame buildings subjected to wind or earthquakes. The objective of this project was to validate the concept of continuous overturning anchorage and improvement of the connection between the sill plate and the end stud. The results indicate that the finite element analysis conducted in another part of this project was accurate and can be use to optimize the cross section of the sill plate. Comparison cyclic racking tests of full-scale shear walls were conducted to quantify the improved racking strength of walls constructed using the sill plate providing continuous anchorage to the concrete foundation, and an improved nail connection between the sill plate and the end stud. Results of the testing indicate that the racking strength of light-frame shear walls can be more than doubled and in fact, have a strength above equivalent engineered, fully anchored walls. If either a complete cross-section could be extruded or improved adhesion between laminations of a built-up section could be developed, further strength improvements could be obtained.

Introduction

If the mechanism of how the framing elements for light-frame wood shear walls were changed from the current end-grain nailing, the capacity of the wall could be significantly increased. An easy way to accomplish this improvement is to change the shape of the bottom plate or sill plate of the wall so that the connection between the studs and the sill plate is made with nails that are in the side grain of the stud and continuous overturning anchorage of the wall to the foundation is provided.

In part F1 of this project, a finite element model was developed to investigate the form of the sill plate and to predict the improvement of the overall wall performance. The sill plate modeled included a fin along the bottom of the sill plate that would be imbedded into the concrete foundation to provide continuous uplift and lateral anchorage to the sill plate and eliminate bending in the sill plate. The form of the sill plate was also altered to change the nail connection between the sill plate and the studs from an end-grain nail configuration, typically used in wood construction, to a side-grain nail configuration which is significantly stronger. Finally, the form incorporated a lip that allowed the sheathing to be directly attached to the sill plate to improve the transfer of shear forces to the sill plate.

It is desirable to validate numerical models when possible to provide a level of confidence that the model predictions are accurate. However, due to financial and time constraints, it was not possible to manufacture a special extrusion die to extrude the optimum shape developed by O'Dell (2008), which is shown in Figure 1. Therefore, hot-melt bonding technology was used to manufacture a proof-of-concept configuration of the sill plate for testing full-scale shear walls.

Initially, prototype walls using a built-up sill plate configuration were tested by Ross (2007), but the attempt to validate the program failed show good results in two respects. First, the hot-melt bonding method used by Ross resulted in a weak bond forming due to uneven heating. Second, the data acquisition rate used to acquire the load-displacement performance of the wall tests was not sufficient to capture the complete hysteretic response of the walls. Therefore, the wall tests discussed in this report were completed to try and correct the two deficiencies with the testing conducted by Ross.

O'Dell also analyzed this sill plate form and the results of these tests are compared to the model prediction to show that the model does an acceptable job of predicting the performance. Details on the numerical model are available in O'Dell (2008).

Shear Wall Tests

Materials and Sill Plate Simulation

With the exception of the WPC material, all of the materials used to construct the shear wall specimens were purchased from local suppliers. The wood framing members for the studs were Douglas-fir lumber 89 x 140 mm , graded as STUD and Better. The conventional sill plate was an incised, preservative treated Hem-fir graded as No. 2 and Better. The top plates were Douglas-fir, graded as No. 2.

The framing nails used were bulk 4.11 x 88.9 mm bright common nails, and the nails to attach the sheathing to the framing were 3.9 x 76 mm bright common nails. Sheathing nails were pneumatically driven nails.

Due to the high cost of manufacturing a new extrusion die, the prototype sill plate was fabricated by melt-bonding extruded WPC deck boards and then manufacturing the desired shape from the resulting block. Steel sheet metal was used to connect the studs to the manufactured sill plate via side grain nail connections. The details of the melt bonding process and manufacturing of the sill plates are available in Ross (2008) and Johnson (2008). The WPC used for the fabrication of the sill plates is the same formulation as used by Du Chateau (2005) and Ross (2008).

All of the wall specimens were sheathed with OSB on one side and 12 mm gypsum wall board on the other. The gypsum was attached to the framing using 4 x 32 mm drywall screws, spaced at 178 mm o.c. around the parameter and 250 mm o. c. on the intermediate supports. The drywall was not taped or finished. Full details on the specimen fabrication are availed in Johnson (2008).

Test Protocol

The walls used for this project were tested following the displacement protocol developed by Krawinkler et al (2001) for the CUREE/Caltech Woodframe Project. This protocol was used because it is the protocol that is widely accepted and referenced in several testing standards around the world. The protocol is intended to be used for products subjected to seismic loading.

Results

The configuration of the sill plate using WPC materials and providing continuous overturning restraint resulted in significant improvements over both prescriptive and engineered construction. The WPC sill plate configuration is illustrated in Figure 2. The sill plate shown in the figure has a triangular bulb configuration on the bottom side of the sill pate that is embedded into the concrete when it is placed in the forms. The concrete is first placed in the forms and then the sill plate is placed in the concrete and positioned with the aid of a vibrator to insure good consolidation of the concrete around the bulb. The same sill plate is shown in Figure 3 with the wall framing and OSB sheathing in place. The framing of the wall is the same as for traditional light-frame walls, except that the sill plate is positioned when the concrete is being placed and the rest of the wall is then constructed after the concrete has cured for a minimum of 24 hours.

In order to quantify the improvements achieved by the change in the form of the sill plate, walls utilizing the traditional wool sill plate were tested first. A typical hysteretic response for a wall with a wood sill plate is shown in Figure 4. The ultimate capacity for this wall was 7.1 kN/m which is equivalent to what the National Design Specification for Engineered Wood Construction (NDS) Special Provisions for Wind and Seismic (2005) lists as the nominal design value for shear wall with this combination of sheathing, framing, and nail schedule. The peak load occurred at 90 mm deflection.

The typical failure of the wood sill plate is shown in Figure 5. Notice the longitudinal splitting of the sill plate that is caused by uplift of the sheathing with respect to the sill plate, which causes cross-grain bending to occur in the sill plate. This, along with the overall uplift of the end of the sill plate causes the sill plate to split and the wall to fail. This type of failure in the sill plate is commonly observed in post earthquake investigations of damage.

Typical hysteretic responses of walls with the new WPC sill plate are shown in Figures 6 and 7. The non-symmetric response that occurs when the sill plate delaminates on one end and maintains its integrity on the other is shown Figure 6. The symmetric response of the wall that occurs when ether both ends of the wall maintain their integrity or both ends delaminate at close to the same load is shown in Figure 7. The observations of the damaged or undamaged sill plate conditions associated with these two types of response are presented in Figures 8 and 9.

The racking capacity of the walls with the new form of WPC sill plate was 8.8 kN/m, which is 24 percent higher than an equivalent engineered shear wall that utilizes mechanical overturning anchorage. The capacity was reached at an average displacement of 33 mm, which is a bit more than 1/3 the displacement of the traditional wall. O'Dell (2008) predicted that the racking strength of the wall would be 9.9 kN/m which is just over 12 percent higher than the average strength of the specimen, but within the normal variation expected in shear wall testing.

If a comparison were to be made to traditional braced wall segments, which are also known as prescriptive wall segments, the strength of the wall using the WPC sill plate is 226 percent stronger than the braced wall. Since, sill plates are required in all light-frame construction, using the WPC sill plate essentially will make the walls 3.26 times as strong as prescriptive walls. This will translate to lower damage levels and offer more opportunities for architectural modifications.

Together these improvements would result in lower damage to the building during low and moderate intensity earthquakes, and an overall reduction in damage from high wind events. This is because the walls would be stronger and more stiff than the traditional walls. The durability of the building would also be improved because the WPC is decay resistant and the new form of the sill plate would raise the sheathing, which is not decay resistant, up out of the zone where moisture typically is present due to splashing along the ground outside of the building. The new sill plate could result in lower damage during severe earthquakes if the length of the wall segments were not reduced to take advantage of the stronger resistance during design.

If the melt bonding technology were to be improved to where WPC would not delaminate along the bond line, or if a die were cut to allow the sill plate to be extruded as a single piece, the improvement in strength would be further increased. It is conceivable that the potential increase in strength of approximately 10 kN/m that O'Dell predicted using finite element analysis (2008) can be achieved. This would be a 41 percent improvement over current engineered construction practice and would eliminate the need for mechanical overturning anchors. If the bonding issues were eliminated, the improvement over prescriptive construction would be 272 percent. Together, these improvements would make the economics of using the probably more expensive sill plate attractive when compared to the current use of mechanical anchors. The current price of mechanical anchors is between \$25 - \$50 per connection, and some designers estimate an installed cost for mechanical anchors on the order of \$100 - \$500 per connection (Dolan 2008).

Conclusion

A proof of concept sill plate configuration for light-frame wood shear walls was tested. The WPC sill plate form was built-up using rectangular WPC sections and melt-bond technologies. The tests were conducted to validate the analytical investigation of the advantages of using a WCP sill plate with a structural form that allowed side grain nail connections to be used to connect the studs to the sill plate and continuous overturning anchorage for the length of the sill plate.

The results indicate that the analytical model was indeed accurate enough to use for optimizing the cross section of the sill plate. The new form for the sill plate was also shown to improve the strength by 226 percent over prescriptive construction and 24 percent over engineered construction. If the melt-bond technology were to be improved, or the sill plate were to be extruded as a single piece, the strength improvements would be 227 percent or 3.72 times as strong over prescriptive construction and 41 percent or 1.41 times as strong as engineered walls using mechanical overturning anchors.

If the economics of the new sill plate were compared, the increased cost of the WPC sill plate would be off set by the savings achieved by not using mechanical overturning anchors and the increased options afforded the designer for architectural modifications.

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Figures

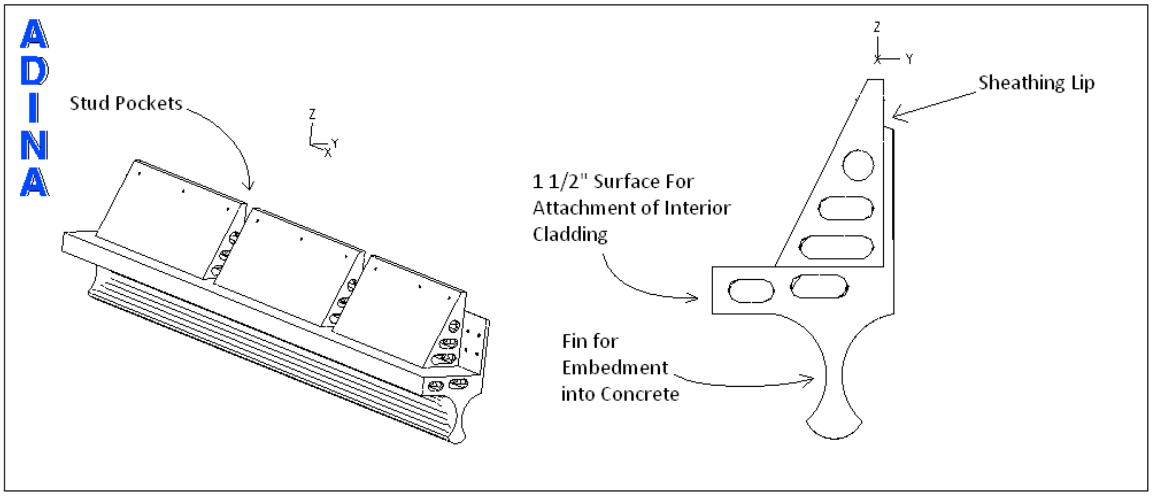

Figure 1: Original Concept WPC Sill Plate

Figure 2: WPC Sill Plate with Continuous Overturning Anchorage Placed in Concrete

Figure 3: WPC Sill Plate With Wall Framing and OSB Sheathing

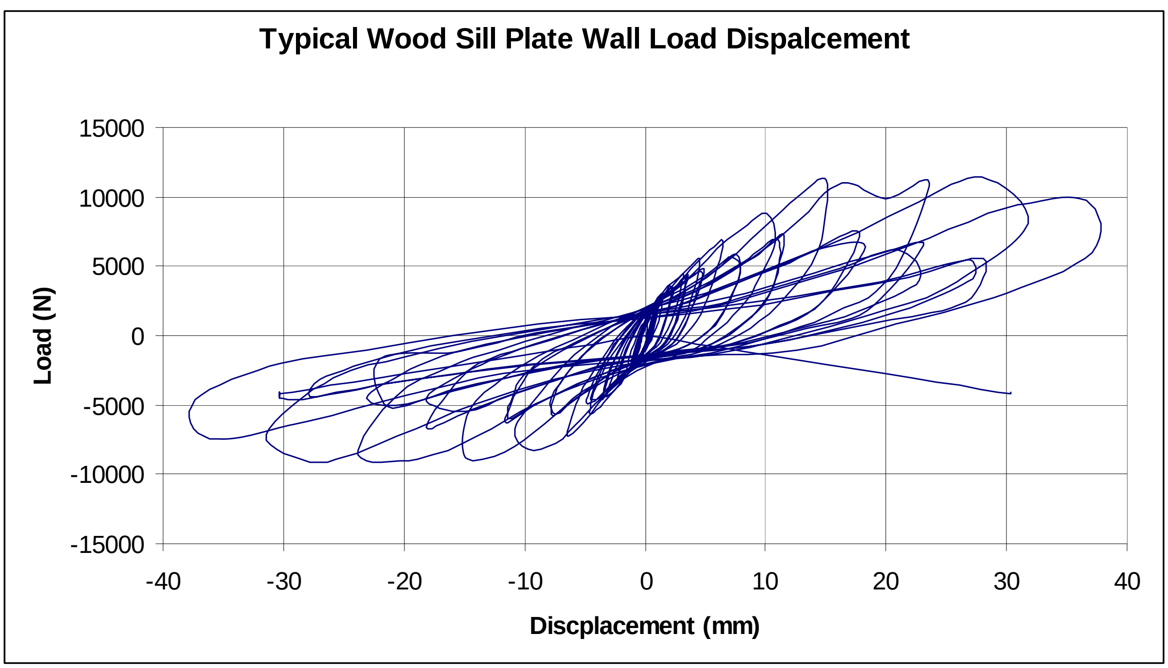

Figure 4: Typical Load-Displacement Curve for Traditional Wood Sill Plate Wall.

Figure 5: Typical Failure of Sill Plate for Traditional Wood Sill Plate

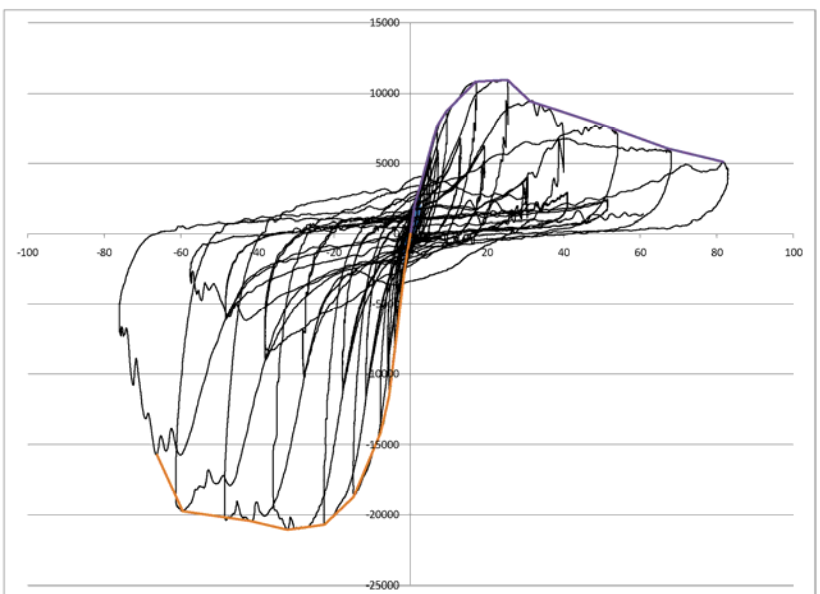

Figure 6: Typical Load-Deflection Curved for Walls with Continuous Overturning Anchorage WCP Sill Plate when Sill Plate Delaminates.

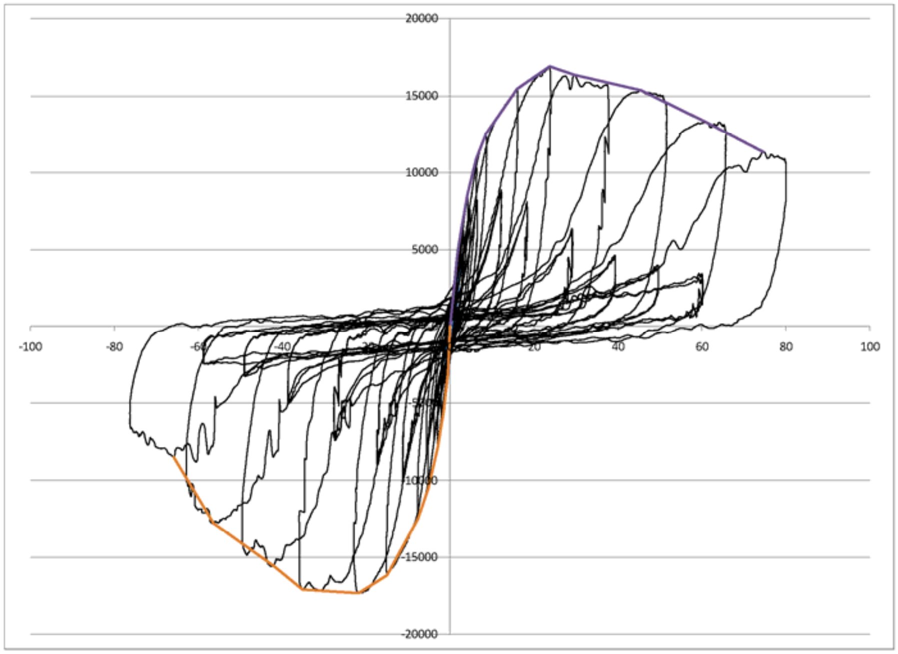

Figure 7: Typical Load-Deflection Curved for Walls with Continuous Overturning Anchorage WCP Sill Plate when Sill Plate Does Not Fail.

Figure 8: Typical Delamination Failure of Built-up Prototype WPC Sill Plate with Continuous Overturning Anchorage.

Figure 9: Failure of Wall when Sill Plate does not Delaminate.

Foundation Elements for Naval Low-Rise Buildings

Installation and Design Capacities of 4x12 PVC Deckboard for the US Naval Academy Wave Screen

Demonstration and Markets

Task D2 – Demonstrate Pier Member

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Donald A. Bender *Washington State University*

Prepared for
Office of Naval Research
under Grant N00014-06-1-0874

Project End Report

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Introduction

This report documents the Wave Screen Demonstration Project at the US Naval Academy (USNA) in Annapolis, MD. This work supports the rehabilitation of the marina facility at the USNA. The deckboard products were specified as vertical members in the wave screen component pictured in Figure 1. Washington State University provided computations to support the USNA contractors in estimating the capacity of the deckboards. The deckboards were commercially produced and supplied to the USNA prior to the beginning of construction. Due to contracting delays, the material was stored on site until construction began.

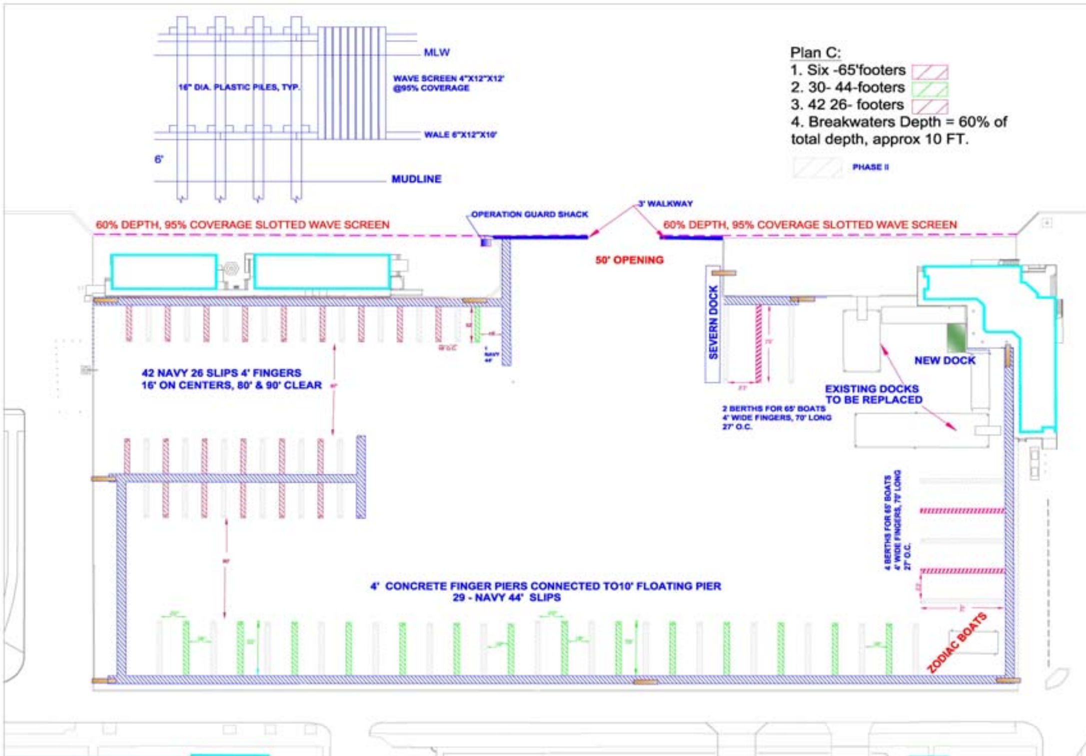

Figure 1: Plan view of the marina facility at the US Naval Academy in Annapolis, MD.

This report documents the computation of the design capacity for the deckboards installed as a vertical wavescreen member. In addition, photos of the components are provided in the Appendix.

Design Scope

This report was prepared to provide design capacities for 4x12 PVC wood-plastic composite members for use in a vertical wave screen. Specifically, moment capacities were developed as well as capacities of a clip connection system.

Loadings from extreme wave events were not calculated. It is assumed that other team members with experience in determining wave loadings will perform this check. In addition, timber piles and timber cross members were not checked.

Design Background

Procedures for developing allowable stress design values for wood-plastic composites are outlined in Bender et al. (2006). The starting point for deriving allowable stress design values for wood-plastic composites is to determine *characteristic values* derived from test data. Characteristic values have a statistical basis to account for variability in the material properties, which are then are adjusted with a safety factor. WPCs typically have relatively consistent, low coefficients of variation in mechanical properties (less than 15%). As such, the characteristic value specified in draft ASTM standard WK8568 (ASTM, 2006) is the mean strength. The corresponding safety factor specified in ASTM WK8568 is 2.5. Once the characteristic value has been determined and adjusted by an appropriate safety factor, additional adjustment factors may be needed to account for in-service conditions such as load duration, temperature, moisture, and ultraviolet (UV) light exposure.

Flexural Design Capacity

Nominal 4"x12"x7.5' PVC wood-plastic composite members were manufactured by Composatron in Toronto, Canada and shipped to Washington State University for testing (Figure 2). Flexural tests were conducted at a 72-inch span with third point loading. Details of the tests can be found in Carradine (2006).

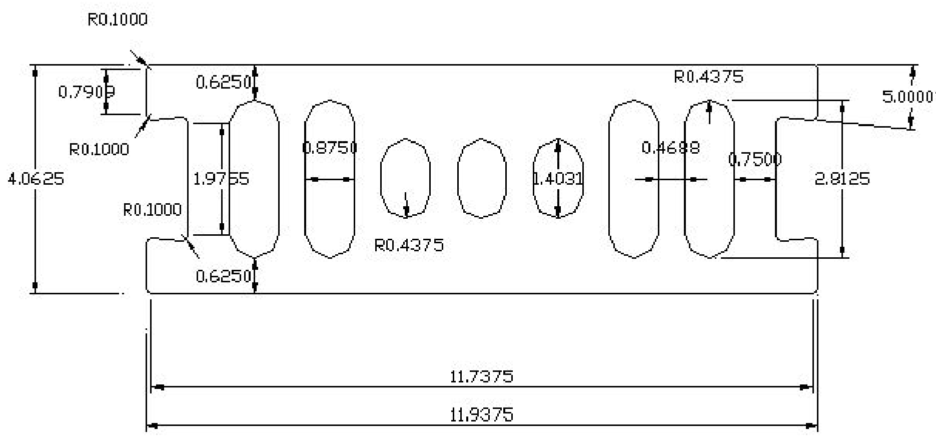

Figure 2. Cross section of 4x12 PVC wood-plastic composite.

Based on a sample size of 30 beams, the average ultimate moment was 13,400 ft-lb with a coefficient of variation of 6.7%. A safety factor of 2.5 was chosen as per ASTM WK8568. So, our baseline allowable moment capacity, prior to any adjustment for in-service conditions, is

$$M_{allowable} = M_{ultimate} / \text{safety factor} = 13{,}400 \text{ ft-lb} / 2.5 = 5{,}360 \text{ ft-lb}$$

We assume no adjustments are needed for temperature, load duration or UV exposure since the members will be submerged and extreme wave loading will be short term. However, an adjustment for moisture exposure is needed.

Jamond et al. (2000) evaluated wet/dry, freeze/thaw and salt fog exposures for the PVC formulation used in the 4x12 PVC prototype, along with a range of other wood-plastic composites made at Washington State University. The worst case reduction in strength for the PVC formulation "PVC 1" was for freeze/thaw and resulted in a 40% loss in bending strength. From this we define an environmental exposure factor of $C_e = (1 - 0.4) = 0.6$.

Applying the environmental exposure factor C_e, our final adjusted design moment, $M'_{allowable}$ is given by

$$\mathbf{M'_{allowable} = M_{allowable} * C_e = 5{,}360 \text{ ft-lb} * 0.6 = 3{,}216 \text{ ft-lb}}$$

Design Load

Figure 3 illustrates a wave screen configuration with two horizontal supports for the vertical 4x12 PVC members.

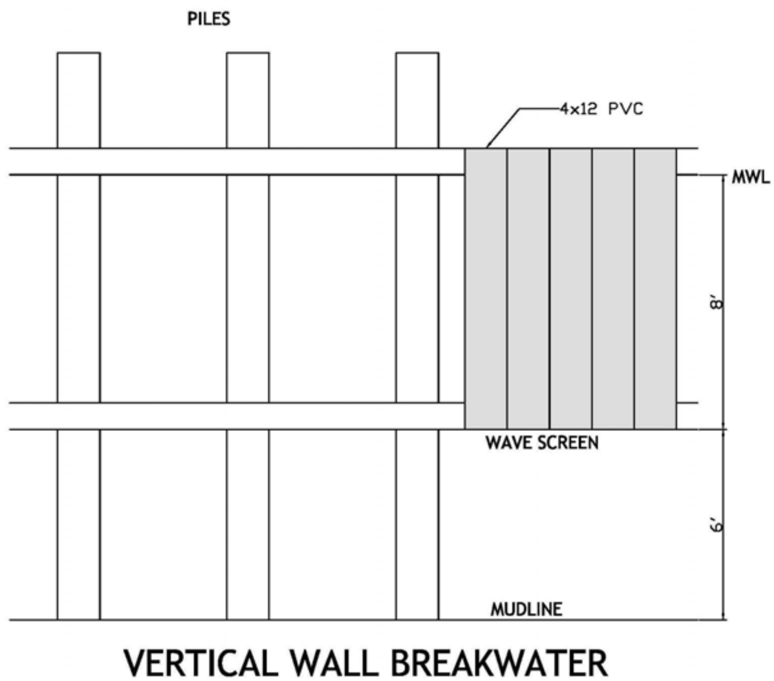

Figure 3. Configuration with two supports for 4x12 PVC member.

An 8-ft span with uniform loading on the 4x12 PVC member results in a moment demand of

$M = wL^2/8$

Solving for the allowable wave load

$w = 8M/L^2 = (8 * 3{,}216) / 8^2 =$ **400 lb/ft**

Figure 4 shows an alternate wave screen configuration with *three* horizontal supports.

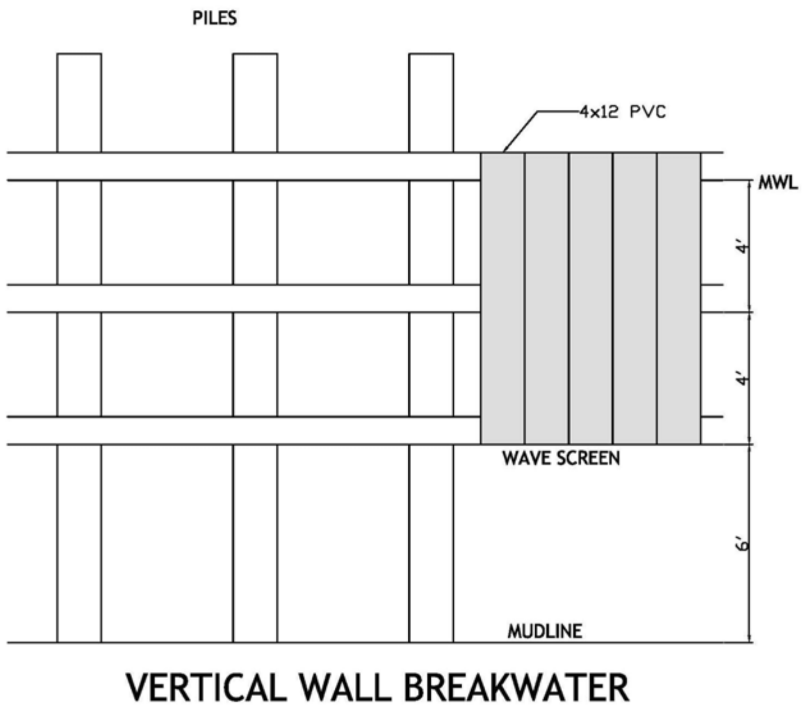

Figure 4. Configuration with three supports for 4x12 PVC member.

Adding an additional horizontal support, will cut the span on the 4x12 member to 4 ft. The maximum moment occurs at the center support, and the resulting allowable wave load is

$w = 8M/L^2 = (8 * 3{,}216) / 4^2 =$ **<u>1,600 lb/ft</u>**

Note: A design load of 840 lb/ft was estimated Yasin El-Mayta, P.E., Project Engineer, NAVFAC Washington. Under this load, the three horizontal support condition shown in Figure 3 would be required.

Connection Capacity

Stainless steel #14 x 6-in "Timber Tamer" screws with 5/16 hex washer head were provided by Swan Secure Products, Baltimore, MD. Root, shank and crest diameters were 0.176, 0.191 and 0.247 in, respectively. The threaded portion of the screw was 2 inches long neglecting the tapered point.

The injection molded polypropylene clip that was tested is shown in Figure 5.

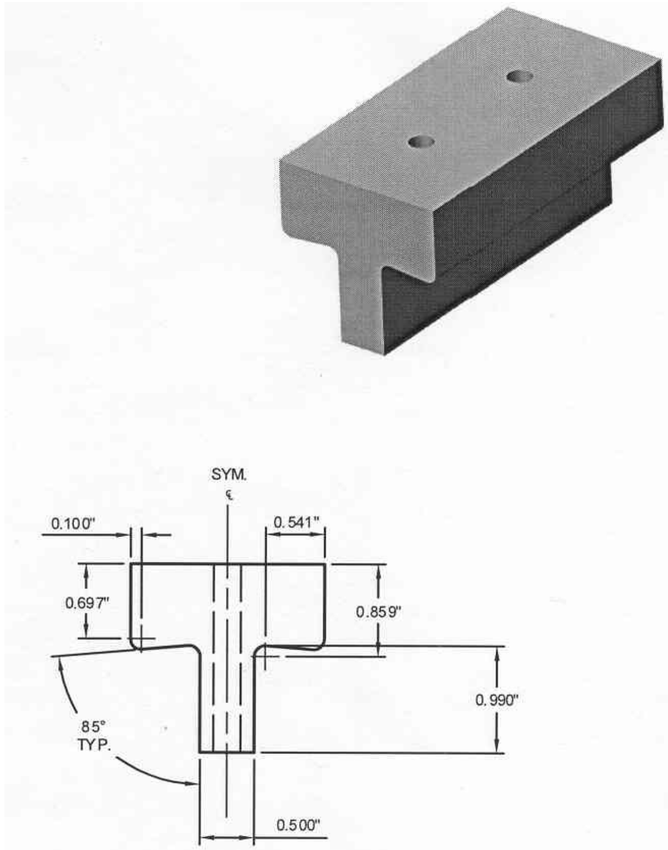

Figure 5. Clip connector.

Two sets of tests were conducted. In the first, withdrawal strengths were determined for the lag screws installed in Douglas fir timber. Lag screw withdrawal has been studied in the past; however, the screws examined in this study had unique thread characteristics. As such, a small sample of five screws was tested.

In the second set of tests, the entire clip assembly system was loaded as shown in Figure 6. The objective was to determine if some failure mode (beyond screw withdrawal) controlled, such as shear failure in the clip or edge of the 4x12 PVC or perhaps screw head pull-through.

Lag screw withdrawal tests -- Five lag screws were tested using solid sawn Douglas fir timber with nominal specific gravity of 0.50. Note that Southern Pine timber can be conservatively substituted since it has a higher nominal specific gravity of 0.55 (AF&PA, 2005). The average withdrawal strength for the screws with 2 inches of thread length was

P_{ult} = 1,926 lb/screw (COV = 16%)

The Wood Handbook (USDA, 1999) gives an equation to predict lag screw withdrawal strength based on tests of a range of wood specific gravities and lag screw diameters. The resulting prediction is within 2% of the average ultimate capacity found herein.

Clip assembly tests -- Clip assemblies were tested as shown in Figure 6.

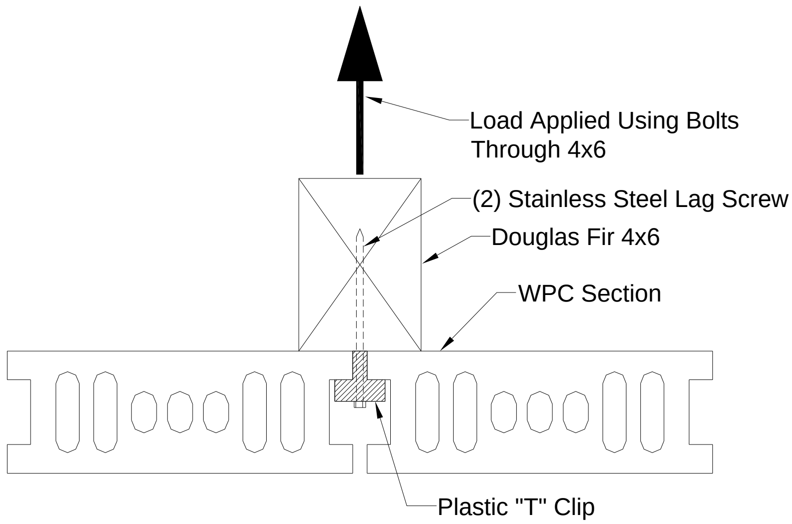

Figure 6. Test configuration for clip fastener.

Most clip assemblies failed as a combination of screw withdrawal and partial screw head pull-through. Since most failures involved some degree of screw withdrawal, the average ultimate capacity of the clips was nearly equal to the combined withdrawal strength of two lag screws:

$W_{ultimate}$ = 3,780 lb/clip (COV = 4%)

A safety factor of 2.5 has precedence in ASTM draft standard WK8568 as well as the International Building Code (ICC, 2006) but a more conservative factor of 3.0 was used to offset the relatively low level of structural redundancy. So, the baseline allowable withdrawal capacity of the clip, prior to any adjustment for in-service conditions, was

$W_{allowable} = W_{ultimate}$ / safety factor = 3,780 ft-lb / 3.0 = 1,260 lb/clip

We assume no adjustments are needed for temperature, load duration or UV exposure since the members will be submerged and extreme wave loading will be short term. However, an adjustment for moisture exposure is needed. Since the main member (receiving the threaded portion of the screw) is solid timber, we use the moisture adjustment factor from the National Design Specification for Wood Construction (AF&PA, 2005).

Applying the moisture factor C_M of 0.7 from the NDS, our final adjusted design value, $W'_{allowable}$ is given by

$W'_{allowable} = W_{allowable} * C_M$ = 1,260 ft-lb * 0.7 = 880 lb/clip

Assuming three cross supports as shown in Figure 3, the maximum reaction is at the center support, with reaction force

R = 10wL/8

Assuming the reaction R equals the clip capacity, and solving for wave load w

w = 8R/10L = (8 * 880) / (10 * 4) = **175 lb/ft**

Thus, the backflow force of the water (moving from the marina to the river) cannot exceed 175 lb/ft without overloading the clip connectors (Figure 7).

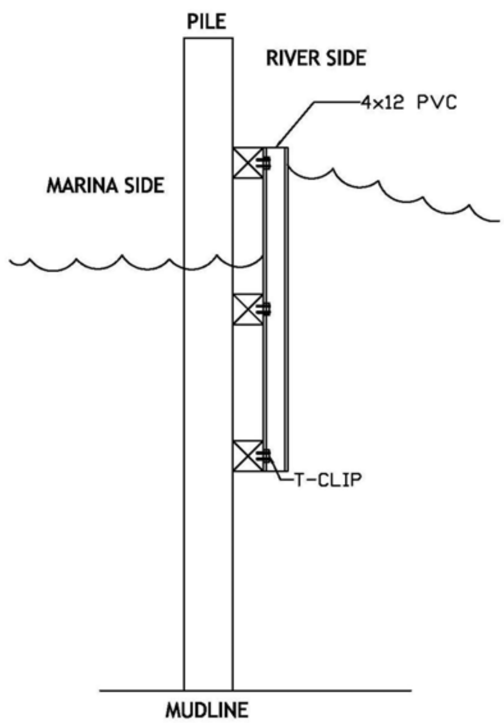

Figure 7. Side view of wave screen showing higher loading from river side controlling 4x12 PVC member design and marina side loading controlling clip fastener design.

Note: Another design issue with connections is to provide resistance from vertical movement. To facilitate installation and to resist vertical movement, a ledger on the bottom cross support member is recommended.

Summary

- Recommended wave screen configuration: three horizontal timbers to support the 4x12 PVC members as shown in Figures 3 and 6

- Maximum allowable wave load (river side) = 1,600 lb/ft
- Maximum allowable wave load (marina side) = 175 lb/ft
- Ledger is needed on the bottom horizontal timber support to resist downward vertical movement of 4x12 PVC members and to facilitate construction.

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Appendix

Delivered UMM deckboard material in storage at the USNA.

View of USNA marina pier at the beginning of construction. The crane is visible in front of the building.

Top of installed wavescreen on the marina pier. Note that the top of the screen is barely visible above the high tide.

Installed wavescreen.

Portion of wavescreen under construction.

Top view of installed UMM member used as the vertical member in the wavescreen.

Example of a pre-built wavescreen unit prior to installation.

Foundation Elements for Naval Low-Rise Buildings

Market Research of the WPC Extrusion Industry

Demonstration and Markets

Task D3 – Market Research of the WPC Extrusion Industry

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Prepared for
Office of Naval Research
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Project End Report

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Abstract

In order to gain an industry-wide perspective of the North American WPC industry, WPC producers were identified through Internet searches and contacts with industry experts and subsequently contacted in the Fall 2006 and Spring 2007. A web-based survey consisting of 13 questions was administered to a census of the 26 North American WPC extruders. Through these data we were able to estimate the 2006 WPC market at approximately $868 million in sales which translates to $1.043 billion retail.

With the growth of the WPC market, the number of WPC manufacturing firms and subsequently the number of brand names has also grown. In 2008, there were 23 North American manufacturers of extruded WPC products who collectively marketed over 90 trademarked/copyrighted brand names. Using data collected through secondary sources and semi-structured interviews (response rate of 60.9%), all North American WPC brands were identified and each manufacturer's brand portfolio was categorized according to a brand architecture scheme. Primary data findings indicate that WPC manufacturers perceive branding as an important marketing tool and utilize a wide array of resources when developing brand names. It was also found that product identification was the largest perceived benefit of employing brand strategies and that the proliferation of brand names that exist in the industry is largely a result of the proliferation of manufactures and the ability to differentiate product offerings.

As the WPC marketplace grows increasingly competitive, producers stand to benefit from a brand architecture strategy that will support future growth (Wheeler 2006). Coherent organization of brand portfolios will lead to impact, clarity, synergy, and leverage rather than weakness, confusion, waste, and missed opportunities (Aaker and Joachimsthaler 2000).

The WPC Industry Respondent Summary

Introduction

The commercial market for extruded wood-plastic composites (WPCs) has seen significant growth in the North American building materials industry over the past 18 years with a substantial growth stage between 1997 and 2006 as the number of WPC manufactures increased from 7 to 26 firms. The growth of the WPC market has been largely driven by four factors: value proposition in terms of life cycle costs, substitution for chemically treated lumber, general builder acceptance of wood composite building materials, and effective push/pull marketing communication (Smith and Wolcott 2006).

Production & Raw Materials

The first section of the web-based survey contained a series of questions concerning WPC production and raw materials. Questions included information on 2006 sales, the start-up date, equipment use, and raw material inputs.

Information concerning 2006 sales was gathered for all 26 firms. Through these data we were able to estimate the 2006 WPC market at approximately $868 million in sales which translates to $1.043 billion retail. As can be seen in Figure 1, the industry is highly concentrated with the Top 5 firms accounting for 72% of sales in 2006.

Information concerning the date that their firm started producing WPC products was gathered for 25 of the 26 firms representing an estimated 99% of the industry based on 2006 sales.

As can be seen in Figure 2, of the 25 responding firms 5 entered the market in 2000 followed by 4 entrants in 1997. Figure 3 shows the total number of WPC producers by year for the 25 responding firms.

Information concerning the type and number of extruders that WPC firms used to produce WPCs in 2006 was gathered from 10 respondents representing an estimated 58% of the industry based on 2006 sales. In addition, information on the brand of extruders they use without indicating the number of each was gathered for 16 firms representing an estimated 84% of the industry.

As can be seen in Figure 4, of the 10 firms indicating the number and type of extruders “Other” was the most used extruder (n = 41) followed by Milacrons (n = 36 – of which nearly half were CM80’s). Figure 5 shows that, of the 16 firms indicating the type of extruders they used in 2006, “Other” accounted for 64% of the production followed by 26% produced using Milacrons.

Information was gathered for 20 firms, representing an estimated 96% of the industry based on 2006 sales, concerning their wood flour input and 24 companies representing an estimated 98% of 2006 industry sales concerning the thermoplastics used in their WPC products in 2006.

As can be seen in Figure 6, 92% of the wood flour was purchased on the market (based on weighted 2006 sales). Figure 7 shows that nearly 90% of the WPC production used PE of which 68% was recycled (based on 2006 weighted sales).

Current & Future Products

The second section of the web-based survey contained a series of questions concerning WPC producers’ current products as well as their opinion concerning future products and threats to the industry. Questions included information on the percent of sales made up by each product produced in 2006, future products (next 2 years and next 5 years), and threats to the continued growth of the industry.

Information concerning the products that their firm produced in 2006 included all 26 firms or 100% of the industry (based on 2006 sales). In addition, the percent of sales accounted for by each of the products included all 26 firms or 100% of industry sales in 2006.

As can be seen in Figure 8, 21 of the 26 firms produced decking in 2006 followed by 17 firms that produced railing. Figure 9 shows that decking made up about 70% of 2006 weighted sales followed by railing with an estimated 15%.

Eight firms representing an estimated 60% of the industry (based on 2006 sales) provided information concerning future WPC products that they believed would be produced in the next 2 years and 4 of these firms representing an estimated 12% of industry sales in 2006 also indicated what new products they believed would be commercially available in the next 5 years.

As can be seen in Figure 10, 3 of the 8 responding firms believe that fencing products will be available in the next 2 years followed by 2 firms indicating that they think siding will be available in the next 2 years. Siding and structural components were the two products mentioned most that firms believed would be available in the next 5 years both being mentioned by 2 of the 4 firms.
Fourteen firms representing an estimated 68% of the industry (based on 2006 sales) provided information concerning threats that they though would affect the continued growth of the WPC industry.

As can be seen in Figure 11, competitive market issues were considered the greatest threat to the continued growth of the WPC industry by the 14 responding firms followed by raw material costs and product/material performance. Figure 12 provides a breakdown of the threats to the future grown of the WPC industry.

Distribution & Communications

The third section of the web-based survey contained a series of questions concerning WPC producers distribution and communication methods used to promote their products. Questions included information on their customers, communication methods, and sales of WPC products.

Information was gathered concerning the percent of their 2006 sales went to various customer types for 25 of the firms representing an estimated 99% of the industry (based on 2006 sales).

As can be seen in Figure 13, wholesalers were sold to most by 20 of the 25 responding firms followed by 12 of the firms selling direct to retailers. Figure 14 shows that wholesalers make up about 84% of the weighted 2006 sales followed by retailers with about 14%

Information was gathered from 16 firms representing an estimated 74% of the industry (based on 2006 sales) concerning the communication methods they used to promote their WPC products in 2006.

As can be seen in Figure 15, 15 of the 16 responding firms exhibited at trade shows to promote their products followed by material samples and websites as promotion tools indicated by 14 of the 16 respondents for both

Brand Name Development and Architectures in the North American Woodfiber Plastic Composite Industry

With the growth of the WPC market, the number of WPC manufacturing firms, and subsequently the number of brand names has also grown. In the Fall of 2008, 23 North American manufacturers of extruded WPC products collectively marketed over 90 trademarked/copyrighted brand names. The vast array of brands that now define the WPC marketplace is a relatively unique situation compared to that of traditional wood decking and railing products which generally have few consumer brands and are often sold as commodities graded according to classifications established by the U.S. Department of Commerce (Trex 2006). Thus, WPC manufacturers have the flexibility to differentiate on various tangible product attributes as well as a multitude of service/supplier attributes (Table 1).

Table 1. WPC Attributes

Product Attributes	Service/Supplier Attributes
• Resistance to Decay	• Availability
• Maintenance	• Ease of installation
• UV Resistance	• Installation Training
• Ease of Installation	• Demonstration Projects
• Surface Texture	• Warranty
• Color Options	• Packaging
• Thermal Expansion	• Availability of Product Info
• Resistance to Wear	• On-Time Delivery
• Strength	• Promotional Support
• Price	• Good Credit Terms
• Low Flame Spread	• Relationship w/ Distributors
• Recyclable	• Company Reputation
• Use of Waste/ Recyclable Material	• Brand Awareness
	• Competitive Pricing
	• Certified Contractors
	• Full Product Line/ Range of Products (decking & railing)

(Source: Clemons 2002, http://www.tangram.co.uk/, Sears 2006)

A literature review of secondary information provided considerable insights into brand name development, brand portfolio management, and the benefits of employing brand strategies. The literature review revealed that manufactures of both consumer and industrial products use a wide array of resources when developing brands and employ a variety of strategies when managing brands. In the WPC industry, where very little public domain research has been conducted on brand strategies, it is believed that as the industry matures, emphasis on market and brand strategies will increase and WPC producers will stand to benefit from a brand architecture strategy that will support future growth (Wheeler 2006). As branding guru Aaker (2004) states, "A key to managing brands in an environment of complexity is to consider them not only individual performers but members of a system of brands that must work to support one another. A brand system (architecture) can serve as a launching platform for new products or brands and as a foundation for all brands in the system." Understanding brand architectures is especially important for new market entrants and small, emerging companies, where the first products developed establish the brand of the company. If brands are developed by accident rather than by design, it becomes expensive and difficult to reinvent or clean up the brand later (Cagan and Vogal 2002). As the WPC industry continues to grow in new and existing markets, and as the market reaches maturity, managing brand architectures will be a strategic challenge each WPC manufacturer will face.

Brand Strategies

Individual Brand Roles

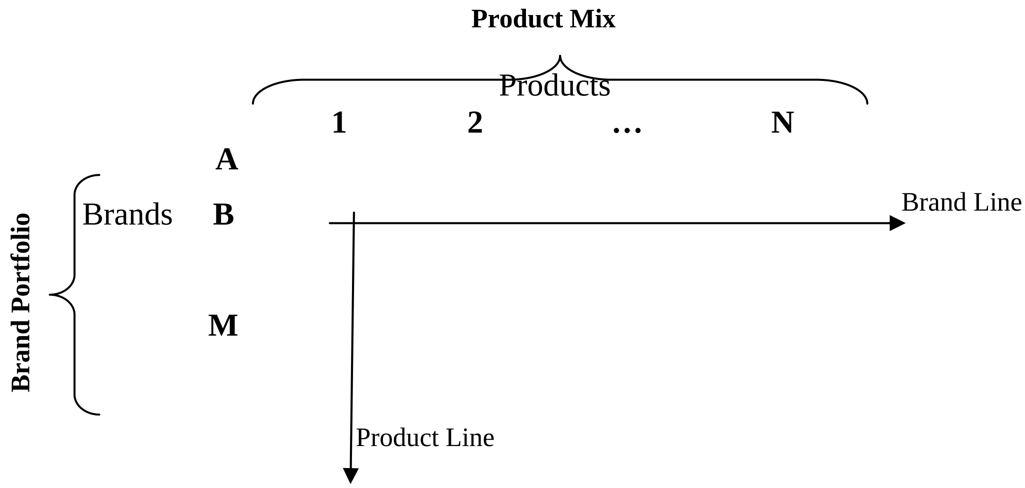
To create effective brand portfolios that will achieve their objectives, it is imperative to understand the namely 3 basic "product-defining building blocks" which defined by Aaker (2004) are as follows:

- **Masterbrand-** primary indicator of the offering
- **Subbrand-** augments or modifies the associations of the master brand
- **Endorsed Brand-** provide credibility and substance to an offering

For each individual brand within a brand portfolio, the degree to which masterbrands, subbrands, and endorsed brands are leveraged is a determining factor in the composition of a brand firm's brand architecture. Therefore the relationships between individual brands in a brand portfolio are based upon the degree to which an individual brand drives the purchase decision (Aaker 2004). Usually the masterbrand assumes the driver role but in some cases the subbrand, endorsed brand or even generic descriptors can assume the driver role. The strategic task for manufacturers is determining the degree of intensity each individual brand within a portfolio assumes when driving the purchase decision. As explained by Aaker (2004), "When a person is asked, 'What brand did you buy?' or 'What brand did you use?' the answer given will be the brand that had the primary driver role responsibility for the decision."

Brand-Product Matrix

To characterize the product and branding strategy of an individual firm, a graphical representation of all the products and brands a company sells, the brand-product matrix, is a useful tool (Keller 2003) (see diagram below). All the brand lines a firm offers is termed *brand* *portfolio*, while all the products lines a firm offers is termed a *product mix*. (Kotler and Keller 2006; Keller 2003)

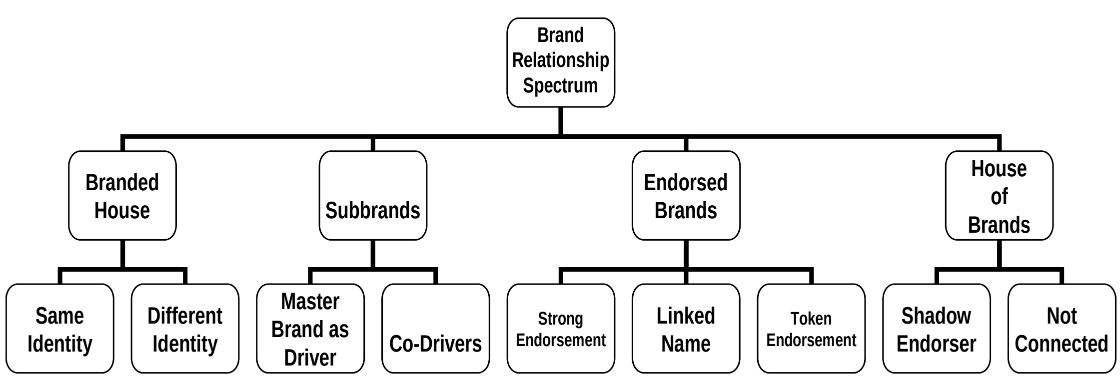


Brand-Product Matrix (Source: Keller 2003)

Once the relationship between a firm's brand portfolio and product mix are understood, each firm's brand-product matrix may be translated into what Aaker and Joachimsthaler (2000) term *brand architecture*.

Brand Architecture

Brand architecture is an organizing structure of the brand-product matrix that specifies brand roles and the nature of relationships between brands (Aaker and Joachimsthaler 2000) Building upon the work of Olins (1989) and Laforet and Saunders (1994, 1999), Aaker and Joachimsthaler (2000) designed *The Brand Relationship Spectrum (BRS)* as a way of classifying brand architecture (see architecture below).



Brand Relationship Spectrum (BRS) (Source: Aaker and Joachimsthaler 2000)

The *BRS* was developed primarily to help brand architecture strategists (brand managers) effectively employ subbrands and endorsed brands. Aaker and Joachimsthaler (2000) explain, "Without endorsed brands or subbrands the choice of a new product would be largely limited to either building a new brand (an expensive and difficult proposition) or extending an existing brand (and thereby risking image dilution). Subbrands and endorsed brands can play a key role in creating coherent and effective brands architecture." The position on the spectrum reflects the degree to which brands are separated in strategy execution and ultimately in the customer's mind. According to the *BRS* there are four main architectures in which a firm's brand-product matrix may be classified:

- Branded house
- Subbrands
- Endorsed Brands
- House of Brands

The *BRS* has a direct relationship to the driver role that each individual brand within the brand product-matrix assumes. On the right side of the spectrum in the house of brands architecture, a firm's brand-product matrix is comprised of multiple masterbrands, each assuming a driver role in the purchase decision. The implications of employing a house of brands architecture are summarized in Table 2.

Table 2. Implications of a House of Brands Architecture

Roles	Drawbacks
• Clearly position brands on functional benefits • Connect directly to niche customer with targeted value proposition • Avoid a brand association that would be incompatible • Signal breakthrough advantages of new offerings • Offer a new product class association by using a powerful name that reflects a key benefit • Avoid or minimize channel conflict	• Sacrifices economies of scale and synergies • Risk stagnation or decline from lack of resources • Sacrifice brand leverage

(Source: Aaker and Joachimsthaler 2000)

In the branded house architecture, at the far left of the *BRS* in a directly opposite strategy, a firm's brand-product matrix contains a single masterbrand which assumes the driver role. This single masterbrand may be used across a firm's entire product mix. The implications of employing a branded house architecture are summarized in Table 3.

Table 3. Implications of a Branded House Architecture

Roles	Drawbacks
• Enhances clarity • Enhances synergy • Enhances leverage	• Puts eggs in one basket • Difficult to maintain cool image or quality position • Limits ability to target specific groups

(Source: Aaker and Joachimsthaler 2000)

Between the two opposing architectures which anchor the spectrum are the endorsed brand architecture and the subbrand architecture. The *BRS* was developed with intent to help firms to employ, with insight and subtlety, endorsed brand and subbrand architectures. For endorsed brand and subbrand architectures, the role that a masterbrand assumes is diminished as you move from right to left on the spectrum. The implications of employing an endorsed and/or subbrand architecture are summarized in Table 4.

Table 4. Implications of a Mixed Architecture (subbrand/endorsed brand)

Benefits of Subbrand and/or Endorsed Brand Architectures
• allow brands to stretch across products and markets • address conflicting brand strategies • conserve brand building resources in part by leveraging brand equity • protect brands from being diluted by over-stretching • signal that an offer is new and different

(Source: Aaker and Joachimsthaler 2000)

The importance of strategically managing individual brands as a system of brands is best summed up by branding expert Aaker (1996), "The proliferation of brands within a single organization raises both concerns and challenges. A key to managing brands in an environment of complexity is to consider them not only individual performers but members of a system of brands that must work to support one another. A brand system can serve as a launching platform for new products or brands and as a foundation for all brands in the system." As companies grow, merge, and acquire new companies, WPC producers will benefit from a brand architecture strategy that will support future growth (Wheeler 2006). Coherent organization of brand portfolios will lead to impact, clarity, synergy and leverage rather then weakness, confusion, waste and missed opportunities (Aaker and Joachimsthaler 2000).

Methodology

Since there was not a methodology at the time of this study that specifically analyzed brand name architectures in a specific industry from the perspective of the manufacturer, a creative methodology was needed to address the objectives of the study. Although the methodology utilized in this study was a creative approach, the ideologies behind the qualitative research methods followed those as described by Daymon and Holloway (2002) in "Qualitative

Research Methods in Public Relations and Marketing Communications". The design and implementation of the research instrument (semi-structured telephone interviews) followed the "Tailored Design Method" of survey implementation as described by Dillman (2002) in "Mail and Internet Surveys: The Tailored Design Method".

The population of interest was all North American extruders of wood-plastic composites in the Fall of 2008. After a detailed literature review, including trade magazines, industry reports, academic publications, commercial research reports, websites and after talking to industry contacts, 23 North American WPC extruding firms were identified. This total included 20 U.S. extruders and 3 Canadian firms. No Mexican extruders were found to exist.

Data Collection

Secondary Data Collection

The objective of secondary data collection was to provide the foundation to generate the constructs for primary data collection (semi-structured telephone interviews). Sources of secondary data are summarized in Table 5.

Table 5. Sources of Secondary Data Collection

Sources of Secondary Data
• Company websites
• Conference proceedings
• Goggle, Yahoo Search Engines
• Industry association Websites
• Industry contacts
• Industry reports
• Product literature(print advertising)
• Scholarly journals
• Text books
• Trade journals

In order to identify and quantify the total number of brands identified in the WPC industry in the Fall of 2008, each identified brand was categorized according to the 3 basic product defining building blocks (masterbrands, subbrands, endorsed brands) as described by Aaker (2004), depending upon the driver role the brand played. Once individual brands were classified according to their driver role, a brand- product matrix (Keller 2003) was developed for each firm. Then each brand-product matrix was analyzed and initially fit according the *BRS* (Aaker and Joachimsthaler 2000).

For firms with only one masterbrand, and no subbrands or endorsed brands (instead generic descriptors i.e. deckboard, railing, fencing), they were into a branded house architecture. Figure 14 illustrates the brand-product matrix for LDI Composites, a WPC firm employing a branded house architecture.

For firms, such as Trex, who employed a single master brand in conjunction with subbrands that shared the driver role, they were fit into either a subbrand or endorsed brand architecture depending on the magnitude the driver role each subbrand assumed.

Once all WPC firms were fit into a brand architecture category the researcher was then able to generate the constructs for primary data collection (See Appendix A).

Primary Data Collection

Primary data was collected through semi structured telephone interviews with the person within each firm most responsible for managing their respective firm's WPC brand portfolio. The telephone interviews were intended to answer the questions that could not be answered through secondary data collection and to confirm secondary data on each firm's brand-product matrix and subsequently their position on the *BRS*. The semi-structured telephone interviews gave the researcher flexibility in terms of the timing, exact wording, and the time allocated to each research question which according to Aaker et al. (2004) is especially effective with busy executives, technical experts, and thought leaders.

Since the population of the industry was determined to consist of 23 firms, and it was a goal of the researcher to understand the brand strategies that existed throughout the entire WPC industry, all 23 firms were contacted for participation in the telephone interview.

Response Rate

- **14/23** extruders responded for a response rate of **60.87%.**
- The **14** respondents accounted for approx. **88.1%** of the est. $1 billion (retail) WPC industry sales in 2006.
- 9 out of the top 11 firms in 2006 sales responded; these **9** firms accounted for **85.9 %** of retail sales in 2006.

Firms were classified into "large" firms and "small" firms according to their est. sales for 2006 (Table 6).

Table 6. Respondent Firms (small vs. large)

	N	**n**	**Response Rate %**	**% of 2006 Sales** (respondents)	**µ Sales in 2006** (respondents)
Large	6	6	100	79.2	$114,738,521
Small	17	8	47.1	8.9	$9,662,906
All	23	14	60.9	88.1	$54, 695,313

Results & Discussion

The qualitative data collected through the semi-structured telephone interviews was subject to interpretation by the researcher with respondents providing any response they felt was appropriate (Mariampolski 2000). Therefore coding data for analysis was difficult and often the assignment of a response involved a judgment decision (Aaker et al. 2004) and was up to the discretion of the researcher. Quantitative data was analyzed using SPSS.

Brand Managers

To ensure that the participants in the telephone interview were knowledgeable about their firm's marketing/branding strategies and the respective histories, it was requested in the cover letter (See Appendix C) that the "Initial Request for Participation" be forwarded to the person within each firm most responsible for managing their firm's brand portfolio. Table 7 is a list of the respondent's respective job titles.

Table 7. Job Titles of Respondents

Job Titles	**Reponses** (n=14)
President/CEO/Owner	4
Sales/Marketing Manager	3
Senior VP Sales/Marketing	3
National Sales/Marketing Manager	2
Director of Consumer Products	1
Research & Development	1

Brand Name Development

To understand the brand name development process, we asked respondents through a fixed response construct to indicate the internal and/or external sources that were utilized when their firm developed its most recent brand. To mitigate the possibility that the most recent brand added to a firm's brand portfolio had been acquired by the firm, it was emphasized that the most recent developed brand name be used to answer the question.

The results show that WPC firms used a wide array of both internal and external sources when developing their firm's most recent brand. Furthermore, large firms utilized an average of 8.3 (50/6) sources per firm, while small firms utilized 3.75 (30/8) sources per firm. An interesting observation is that all large firms utilized both a marketing and sales manager in the development process and 5/6 large firms utilized both the CEO/president/owner and a product/brand manager. In comparison, 5/8 small firms utilized a marketing manager, only 2/8 utilized a sales manager, 5/8 utilized the CEO/President/Owner, and only 2/8 utilized a product/brand manager.

Proliferation of Brand Names

Through an open-ended question each respondent was asked their opinion on why a proliferation of brand names existed in the N.A. WPC industry for 2008 (Figure 17).

Respondents indicated that the proliferation of manufacturers was one of the two primary reasons for the proliferation of brand names. Under this assumption, each firm who enters the marketplace will develop at least one brand to identify their product offering(s), adding to the myriad of names that already exist. The other major reason for the proliferation of brand names was differentiation. Differentiation as an objective for brand development is consistent with brand architectures that are located towards the right hand side of the *BRS* and include the house of brands, the subbrand, and endorsed brand architectures.

Branded Products Manufactured

In secondary data collection each WPC firm's product mix and brand portfolio were sorted according to the three dominant product lines that define the WPC industry (decking, fencing, and railing). Then, through the telephone interviews, each respondent firm's brand-product matrix was confirmed. All branded WPC products other than decking, railing and fencing were labeled "other". Figure 18 depicts the number of manufacturers that were identified to manufacture branded products in each product line after primary data was collected.

Although 3 fewer firms produced WPCs in 2008, the same number of firms produced decking (n=21) and railing (n=17) brands as in 2006. However, fencing being a relatively new product application for the WPC industry grew from four firms producing branded fencing in 2006 to 10 firms producing brands in 2008.

Individual Brand Roles in the WPC industry

Through the confirmed brand-product matrices for the respondent firms (81.1% of the total brands), and the brand-product matrices generated through secondary data for non-respondent firms, a total number of 95 brands were identified to exist in the WPC industry in the Fall of 2008. To quantify the number of brands that existed in the WPC in the Fall of 2008, identified brands were first categorized by product line (decking, railing, fencing, and other) and then categorized by the driver role each brand played (materbrand, subbrand, endorsed brand, ingredient brand), so that brand-product matrices could be generated for each firm. Using the aforementioned categories, Table 8 summarizes the number of WPC brands that existed in the WPC industry in the Fall of 2008.

Table 8. Number of Brands in the WPC Industry

	Decking			**Railing**			**Fencing**			**Other**			**Total**		
Brand Type*	M	S	E	M	S	E	M	S	E	M	S	E	M	S	E
# Brands	2	3	5	27	2	3	1	5	0	8	2	0	**33**	**53**	**8**
Total # Brands	**68**			**50**			**16**			**10**			**94**		

* M= Master Brand; S= Subbrand; E= Endorsed Brand (Note: Only one ingredient brand was identified and is not represented in the table. The total number of brands in the industry would be 95 if included.)
** Primary data categorized 77 brands (81.1%); the other 18 brands (18.9%) were categorized from secondary data sources listed in Table 5.

The data reveals that branded decking, railing, and fencing products continue to dominate the WPC industry. This is consistent with data collected by Smith and Tichy (2007) where it was found that decking comprised 81.1 % of 2006 sales, followed by railing at 11.9%, and fencing at 2.4 % of 2006 sales. It is interesting to note that although the difference between sales in 2006 for decking and railing was rather large (81.10% vs. 11.85%), the difference in the number of brands was rather small (68 vs. 50). This could be explained by the fact that railings, as described by an industry participant, are a highly differentiated product line made up of many component parts adding to their complexity and the number of SKUs a company produces. Under this assumption, a hypothesis could be formed that the number of brands that exist in the WPC industry, especially the railing product mix, is due to the fact WPCs are differentiated upon a host of tangible (as well as intangible) product attributes. The products manufactured labeled "other" included fenestration materials, landscaping products (edging, stepping stones) exterior coverings, and trim/molding.

An interesting observation from the data is revealed in the fact that there were 33 total master brands identified in the WPC industry in the Fall of 2008 as a whole despite the fact there were 28 master brands in decking, 27 master brands in railing, 11 master brands in fencing, and 8 master brands in "other" products. Using the additive property one might conclude that 74 master brands existed. However, this observation can be explained by the fact that some firms employed a brand strategy that used a single master brand across multiple product categories. It is also interesting to note that there are almost twice as many subbrands (53) and endorsed brands (8) compared to master brands (33). These observations lead the researcher to believe WPC manufacturers are capitalizing on the advantages of subbrands and endorsed brands (See Table 4).

Brand Architecture

Secondary and primary data were used to classify each individual brand identified in the WPC industry according to the driver role the brand played (i.e. masterbrand, subbrand, endorsed brand, and ingredient brand) (Aaker 2004). Using the theories behind Aaker's (2004) product-defining building blocks, brand-product matrices (Keller 2004) were then able to be generated for each WPC firm. Once brand-product matrices were generated, the researcher was then able to preliminarily classify each firm's brand architecture according to the *BRS* (Aaker and Joachimsthaler 2000).

Each firm's (n=23) brand-product matrix was initially categorized into a house of brands, subbrand, endorsed brand, or branded house architecture. Then, to confirm the preliminary architecture classification, open-ended interview questions prompted respondents to explain the objectives and thought processes behind their respective brand architecture and strategy. Starting on the right side of the *BRS* with the house of brands architecture, Table 9 summarizes the objectives and reasons given by respondents for employing their firm's respective brand architecture.

Due to the qualitative nature of the data, the researcher categorized each responding firm with secondary data that was confirmed or adjusted through the open-ended telephone interviews. For non-responding firms, the researcher had to rely on secondary data and intuition in order to assign firms to a brand architecture type. It should be noted that one non-responding firm did not fit into any of the four architecture categories which is a result of the firm being an OEM supplying firm.

Table 9. Reasons Firms Employ Brand Architectures

Reasons for Employing Brand Architecture (n=14)*

House of Brands
- Distribution strategy (n=4)
- Differentiate product lines (n=3)
- Acquisition of brands (n=2)
- OEM conflicts with other firms (n=2)
- Distribution into foreign markets (Canada) (n=1)
- Market penetration (n=1)
- Resolve channel conflicts (n=1)

Subbrand & Endorsed Brands**
- Provide brand identity to new brands (n=2)
- Differentiate brands on product attributes (n=1)
- Extend the master brand across products (n=1)
- Keep the brand within the family (leverage family brand) (n=1)
  - word of mouth very strong in the industry
  - maintain positive brand experience with new brands
- Reach different market segments with subbrands brands (n=1)
  - focus subbrands to brands to b2b customers
  - focus family brand to consumer

Branded House
- Inexperience in marketing (n=2)
- Simplicity (n=2)
- Acquisition of the brand name and marketing strategy (n=1)
- Focus on pushing one brand through channels (efficiency) (n=1)
- Only manufacture one product line (n=1)

* There was not a limit on the # of responses per respondent. Responses were summarized from question # 6 in the personalized telephone scripts (See Appendix A)
** Subbrand and Endorsed brand strategies were combined to form "Mixed House"

Once the primary data on the objectives behind each firm's architecture was collected for the 14 respondent firms, a three category brand architecture spectrum emerged. Each of the 14 respondents was classified as one of the following architectures:
- Branded House
- Mixed House
- House of Brands

The 3 category brand architecture classification that emerged very closely represents the four architecture classification (branded house, subbrand, endorsed brand, and house of brand architectures) that comprise the *BRS* developed by Aaker and Joachimsthaler (2000). The primary difference between Aaker and Joachimsthaler's (2000) *BRS* and the emergent *BRS* that was used to analyze data in this study is the fact that the subbrand and endorsed brand architectures were combined into a single category labeled “mixed house”. Since there was only one company that the researcher truly felt represented the endorsed architecture it was convenient to combine the architecture endorsed architecture and subbrand architecture for the purpose of data analysis. Table 10 illustrates the number of respondent firms that fit into each *BRS* architecture before and after primary data collection (semi-structure interviews).

Table 10. Brand Architectures before and after Primary Data Collection

After Secondary Data Collection*		After Primary Data Collection	
Brand Architecture	**n=14**	**Brand Architecture**	**n=14**
Brand House	5	Brand House	4
Subbrand	3	Mixed House	4
Endorsed Brand	1		
House of Brands	5	House of Brands	6

* For respondent firms only

As table 10 illustrates, the number firms that were preliminarily fit as a subbrand or endorsed brand architecture according to the *BRS* using secondary data only did not change when firms were applied to the modified brand architecture after primary data was collected. The only change to subbrand and endorsed architectures was the fact they were combined to represent one brand architecture recategorized “mixed house”.

However, there were two firms that were preliminarily fit into a branded house architecture after secondary data collection that were re-fit into a house of brands architecture after primary data was collected. In addition there was one firm that was preliminarily fit into a house of brands architecture that was re-fit into a branded house after data collection. Therefore, for the 14 respondent firms there was a net change of one firm for the branded house and one firm for the house of brands architecture between secondary and primary data collection.

Brand Architecture vs. Firm Size

Table 11 illustrates the breakdown of large and small firms into brand architecture categories.

Table 11. Firm Size & Brand Architecture Matrix

	Brand Architecture		
Firm Size	BH(N=6; n=4)	MH(N=6; n=4)	HB(N=10;n=6)
Large (N=6; n=6)	0	3	3
Small (N=17, n=8)	6	3	7
Average Firm Size for Respondents (2006)	$6,494,725	$76,842,667	$44,285,004

* BH= branded house, MH= mixed house; HB=house of brands
** N=23; There was one firm (“small” firm) not categorized (ingredient brand)

Branded house firms were found to be much smaller then mixed house or house of brand firms with average sales for 2006 of $6,494,725. Mixed house firms were found to be the largest firm with average sales of $76,842,667.

Brand Strategy Benefits

Respondents were asked their agreement according to ten statements regarding the benefits of employing their firm's brand strategy using the following 7-point Likert scale:

1= Strongly Disagree
4 =Neither Agree nor Disagree
7= Strongly Agree

Table 12 summarizes the results of respondent's agreement to brand strategy benefits according to brand architecture type, and Table 13 summarizes the results according to firm size.

It is clear that WPC manufacturing firms agree that employing a brand strategies provide their firms wide array of benefits. The fact that manufacturers strongly disagreed with the fact that their brand strategy "affords no benefits" emphasizes that brand names are an important part of a firm's marketing success. The highest ranked benefit that firms perceived by employing a brand strategy was product identification. Product identification being ranked as the #1 benefit is consistent with the studies conducted by Sinclair and Seward (1988), Shipley and Howard (1993), and Mitchell et al (2001).

For firms in the branded house, "efficiency of marketing communication" was ranked as the #1 benefit of employing the respective strategy. This is not a surprise finding since the branded house is comprised of only one brand that needs to be communicated to its customers. In other brand architectures such as the house of brands and mixed brand architectures, there are a multitude of brands that require resources for communication. The branded house can also increase marketing efficiency due to its potential to maximize clarity to the customer and synergy across product offerings according to Aaker and Joachimsthaler (2000).

For firms in the mixed house, "product identification" was ranked as the #1 benefit of employing the respective strategy. It is interesting to note that all respondent mixed house firms strongly disagreed to the statement "Our brand strategy provides no benefits to our firm". This leads the researcher to believe that firms employing a mixed house strategy have a clear sense of their strategy's benefits, and are using their strategy to increase impact, clarity, synergy, and leverage rather than weakness, confusion, waste, and missed opportunities which are inherent setbacks of poorly managed brand architectures (Aaker and Joachimsthaler 2000).

Table 12. Agreement with Statements Related to Brand Strategy Benefits (by Brand Architecture)

		Architecture Type		
	Total (n=14)	BH (n=4)	MH (n=4)	HB (n=6)
Benefits of Employing a Brand Strategy	Mean	Mean	Mean	Mean
1. Provides product identification:	6.07	4.75	6.75	6.50
2. Creates differentiation among our firm's brands:	5.82	4.75	5.50	6.68
3. Creates differentiation from competing brands:	5.79	4.75	5.75	6.00
4. Helps in product positioning	5.57	4.25**	6.25**	6.00**
5. Increases the efficiency of marketing communication:	5.57	5.00	5.00	5.33
6. Generates a price premium:	5.29	4.75	5.75	5.33
7. Provides legal protection:	5.29	4.25	5.50	5.17
8. Promotes repeat purchasing (customer loyalty):	5.14	4.38*	6.50*	6.33*
9. Increases customer purchase confidence:	5.00	4.50	5.50	5.68
10. Affords no benefits:	2.00	3.50**	1.00**	1.68**

Note: BH= branded house; MH=mixed house; HB= house of brands
Note: Mean scores based upon 7-point Likert scale: 1=strongly disagree, 4=neither agree or disagree, 7=strongly agree
*Significant at .05 level;*Significant at .10 level

Table 13. Agreement with Statements Related to Brand Strategy Benefits (by Firm Size)

	Firm Size		
Benefits of Employing a Brand Strategy	Total (n=14) Mean	Large (n=6) Mean	Small (n=8) Mean
1. Provides product identification:	6.07	6.67	5.63
2. Creates differentiation among our firm's brands:	5.82	6.17	5.50
3. Creates differentiation from competing brands:	5.79	5.83	5.38
4. Helps in product positioning	5.57	6.17	5.13
5. Increases the efficiency of marketing communication:	5.57	5.33	5.00
6. Generates a price premium:	5.29	5.33	5.25
7. Provides legal protection:	5.29	4.68	5.25
8. Promotes repeat purchasing (customer loyalty):	5.14	6.50	5.31
9. Increases customer purchase confidence:	5.00	5.50	5.13
10. Affords no benefits:	2.00	1.00*	2.75*

Note: BH= branded house; MH=mixed house; HB= house of brands
* Significant at .05 level

For firms in the house of brands, “creates differentiation among our firm’s brands” was ranked as the #1 benefit of employing the respective strategy. This is an expected finding since a house of brands strategy involves an independent set of stand-alone brands each focused on maximizing the impact on a market. The house of brands strategy allows firms to clearly position brands on functional benefits and dominate niche segments (Aaker and Joachimsthaler 2000).

Using a one-way analysis of variance test (SPSS statistical software) to compare means across different brand architectures provided some significant findings. Overall the statistics revealed that branded house firms do not agree as highly towards statements regarding the benefits of brand strategies as those firms who employed a mixed house or house of brands strategy. The most significant difference (at the .05 level) between agreement with brand strategy benefits is observed between branded house firms agreement (4.38) on the benefit “promotes repeat purchasing” compared to the mixed house (6.5) and house of brands (6.33) firms. Other significant differences (at the .10 level) were observed between brand architectures in regard to the benefit “helps in product positioning”. Firms in the branded house ranked their agreement significantly lower than the firms in the other two architectures. This is an expected finding and it confirms that a house of brands, subbrand, and endorsed brand architecture facilitate in product positioning.

The only significant difference at the .05 level between large and small firms in their agreement with statements regarding their firm’s brand strategy was whether their firm’s brand strategy “provided no benefits”. All large firms strongly disagreed with the statement which suggests that larger firms value their branding strategies more then small firms. All other mean scores were higher for large firms regarding benefits of their brand strategy except for “provides legal protection” which further supports the conclusion that large firms value their branding strategies in comparison to small firms. The fact that large firms agree with the benefit “provides legal protection” more than small firms may be attributed to the fact that large firms have legal support more widely available.

Conclusion

The WPC Industry Respondent Summary

These summary results provide a benchmark for the industry in terms of some of the key indicators for the industry. This information can be used as a starting place and point of comparison for future WPC industry studies. In addition, this “snapshot” of the industry provides the ability to track the “state of the WPC industry” over time. Summary highlights of this study include:

In 2006:

- There were 26 WPC firms in N. America producing approximately $1.043 Billion (retail)
- Peak years for new start-ups were 1997 (n=4), 2000 (n=5), 2002 (n=3), and 2004 (n=3)
- Only 8% of wood flour was produced “In-House”; 92% was purchased
- PE represented 89% of the industry’s production; PP was 7%; and PVC was 4%

- Decking represented 70% of the industry's sales; railing was 15%, window lineals 6.5%, and "other" was 3.5%
- Key new products, not currently available, that will be produced in the next 2 years include fencing and siding; in the next 5 years = siding and structural components
- Key threats affecting the growth of the WPC industry include competitive market issues, raw material costs and supplies, product performance issues, and litigation issues
- Approx. 84% of WPC products were sold through wholesalers; and 14% direct to retailers.
- Key communication methods used by WPC firms include trade shows, product samples, websites & brochures, printed ads, and point-of-purchase displays

Brand Name Development and Architectures in the North American Woodfiber Plastic Composite Industry

Compared to 2006 data on the WPC industry (Smith and Tichy 2007), the WPC industry has shrunk from 26 to 23 extruders as consolidation of a mature market has taken form. Decking and railing products continue to dominate the industry which is evident by the number firms manufacturing each product line (21 for decking, and 17 for railing), and in the total number of brand names that define the industry (68 decking and 50 railing brands). Fencing is a becoming a growing product line as 10 firms were extruding in the Fall of 2008, marketing 11 masterbrands, compared to four firms and four masterbrands in 2006.

It was found that WPC firms utilized an array of internal and external sources to develop their most recent brand name in the brand name development process. The data indicates that the brand name development is an important undertaking as 10/ 14 respondents indicated that the CEO/president/owner was involved in the development of their firm's most recent brand. It was found that 10/14 firms utilized an external advertising agency and 9 /14 firms utilized trademark agencies/attorneys. The results also illustrate that large firms utilize an average of 8.3 sources per firm, while small firms utilize 3.75 sources per firm.

A total of 95 brand names were identified to exist in WPC industry in the Fall of 2008. Due to the fact that masterbrands are defined as those brands that drive the purchase decision it can be hypothesized that the 34 masterbrands that were identified across all WPC product lines are the brands that are most widely identified by WPC consumers. Decking dominated the total number of brands, followed by railing, and fencing. It was found that although manufacturers are producing a multitude of "other" products which include fenestration, trim, exterior coverings and landscaping products, only 8 masterbrands existed in 2008. Only one WPC firm who sold OEM had a brand name to identify their product offering.

The fact that masterbrands in decking (28), railing (27), fencing (11) and other products (8) add up to more then a total of 34 masterbrands indicates that WPC producers are taking advantage of the benefits of subbrands and endorsed brand strategies (re-categorized mixed brands in this study). When brand portfolios were categorized by brand architecture, significant differences were uncovered in WPC firm's agreement on the benefits of brand names. For branded house firms "the efficiency of marketing communication" was rated the #1 benefit. For mixed house firms "product identification" was ranked as the #1 benefit. And for house of brands producers "creates differentiation among our firm's brands" was ranked as the #1 benefit. However, overall it was found that regardless of architecture, brand strategy is an important marketing tool for WPC firms. Product identification was the highest perceived benefit, followed by differentiation, and product positioning.

Regardless of firm size "product identification" was ranked as the #1 benefit of employing a brand strategy, which is consistent with the overall industry findings. This finding is consistent with the fact that manufacturers perceive the proliferation of brand names in the WPC industry is a result of the proliferation of manufactures. This leads the researcher to believe that the number of brand names in the industry is a function of the number of manufactures. All means scores related to brand strategy benefits were ranked higher by large firms then small firms except for "provides legal protection".

Although this study is a snapshot look at the WPC industry, the qualitative exploratory research methods and findings provide a sound foundation for further research into brand development and brand architectures within and beyond the WPC industry.

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Figures

Please indicate your estimated sales of all WPC products in 2006:

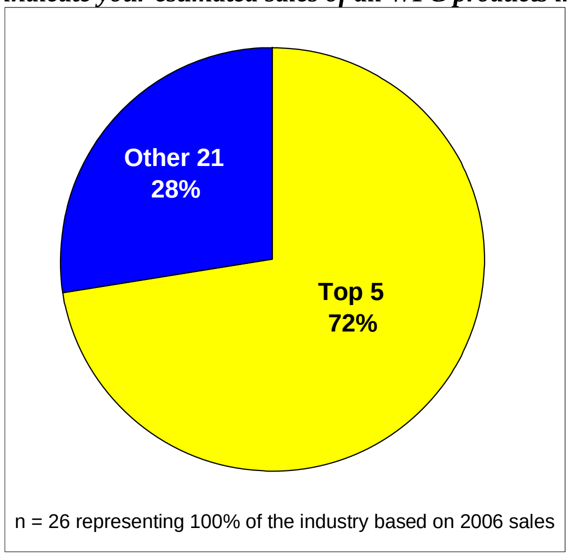


Figure 1 – Breakdown of 2006 Industry Sales

Please indicate the date your firm starting producing WPC products:

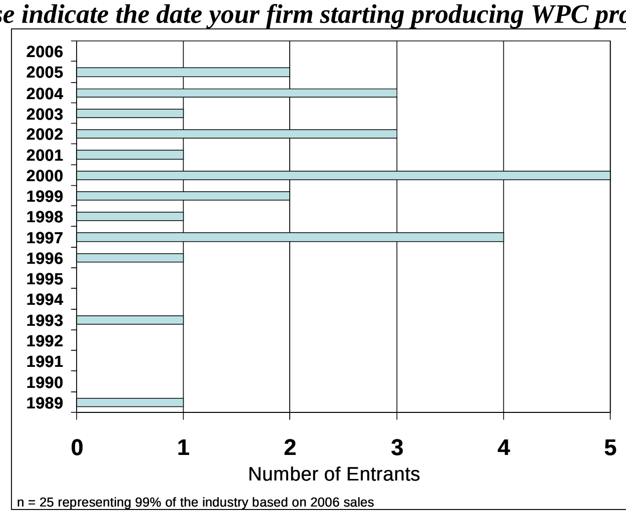


Figure 2 – Number of Entrants into the WPC Industry by Year

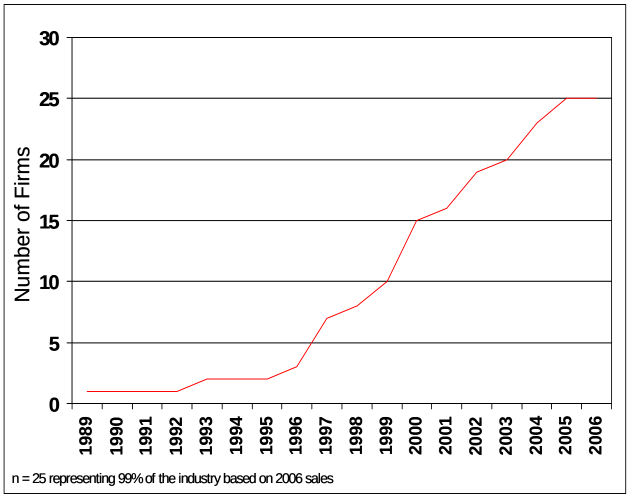


Figure 3 – Number of Firms in The WPC Industry by Year

Please indicate the type and number of extruders your firm used to produce WPCs in 2006:
Manufacturer/Brand Name Model No. #

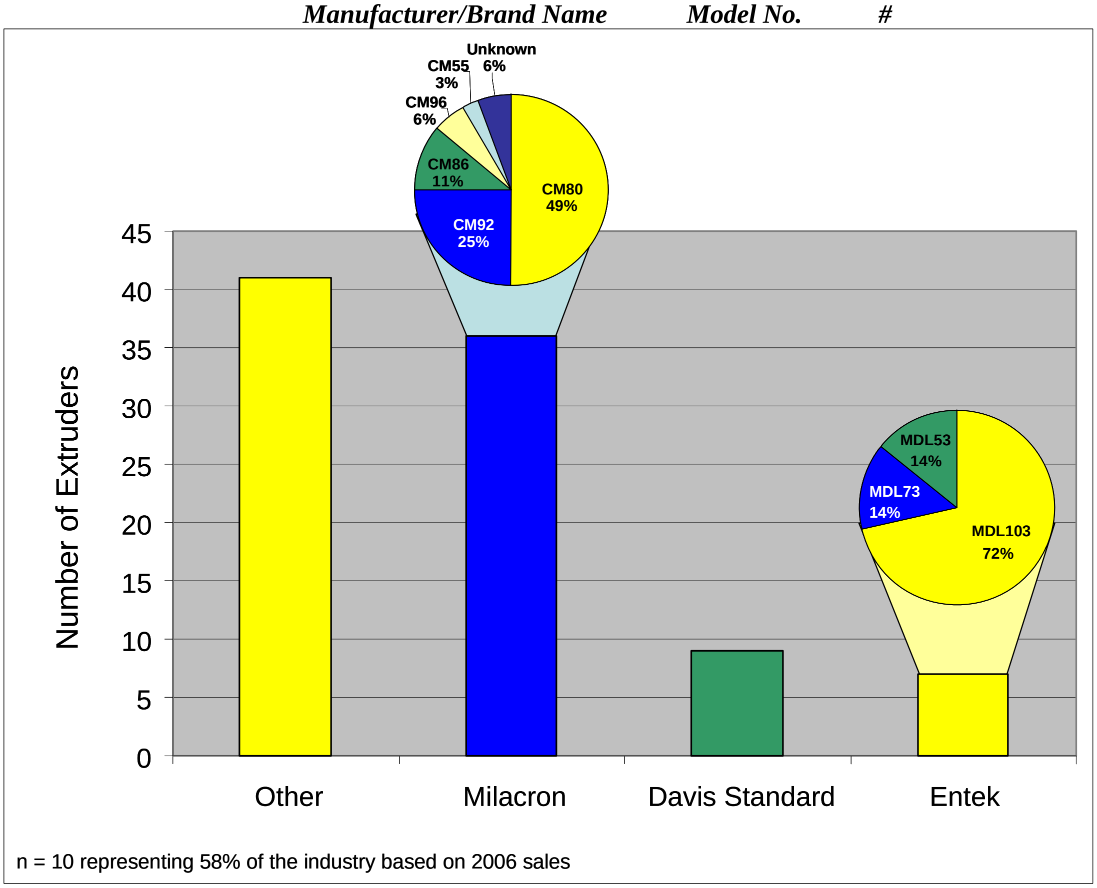


Figure 4 – Brand & Model of Extruders Used in WPC Production for 2006

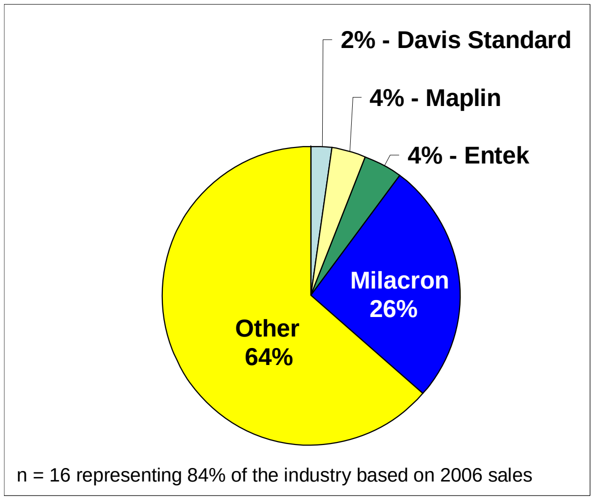


Figure 5 – Brand of Extruders Used in WPC Production for 2006 Weighted by Percent Sales

Please estimate the percent of wood flour that your firm obtained from each of the following sources in 2006:

Source		***% Wood Flour***
	Make in-house:	
Buy:	***Outside source(s) of wood flour in 2006:***	

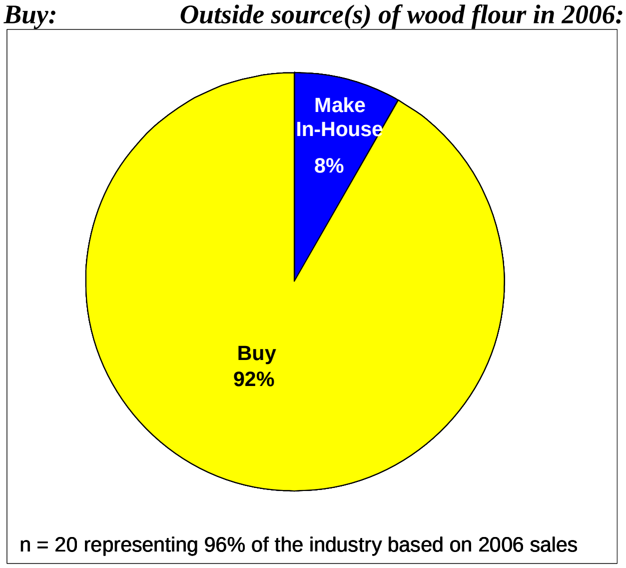


Figure 6 – Percent of Wood Flour Made In-house vs. Bought in 2006 Weighted by 2006 Sales

Please estimate the percent of each of the following thermoplastics, both virgin and recycled, that your firm used in its WPC products in 2006:

Thermoplastic	*% Virgin*	*% Recycled*	
PP:			
PVC:			
PE:			
Other:			***Please Specify:***

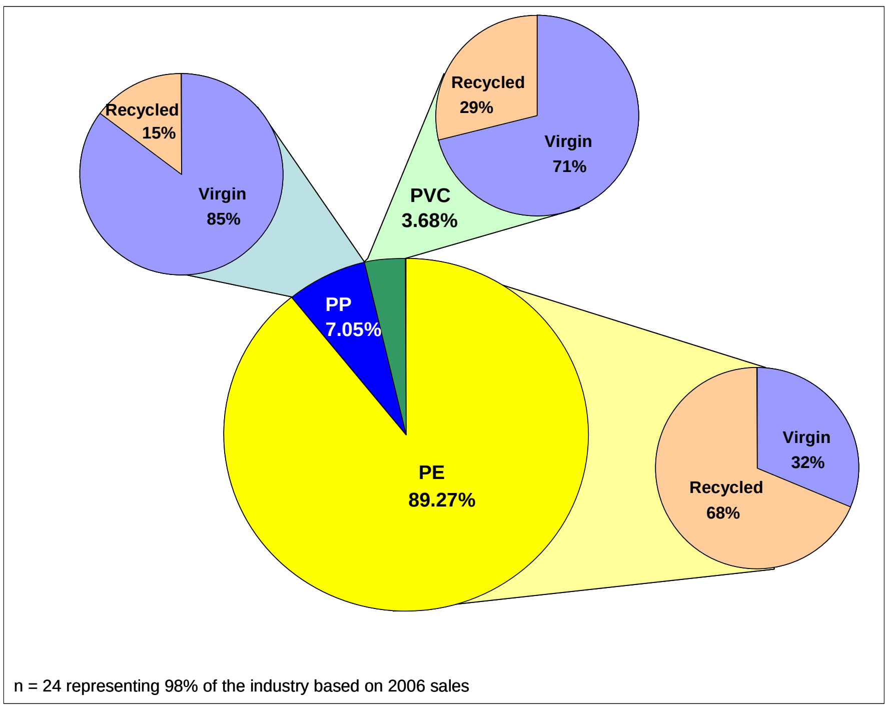


Figure 7 – Ave. % Usage of Thermoplastics & % Recycled vs. Virgin in 2006 Weighted by 2006 Sales

Please indicate which of the following products your firm produced in 2006 (please check all that apply). Also, please provide your best estimate of the percent of total WPC sales that each product accounted for in 2006.

Product	***% of Sales***	
Decking		
Railing		
Fencing		
Window Lineals		
Door Sills/Rails		
Trim/Molding		
Other		***Please Specify:***
Other		***Please Specify:***
Other		***Please Specify:***

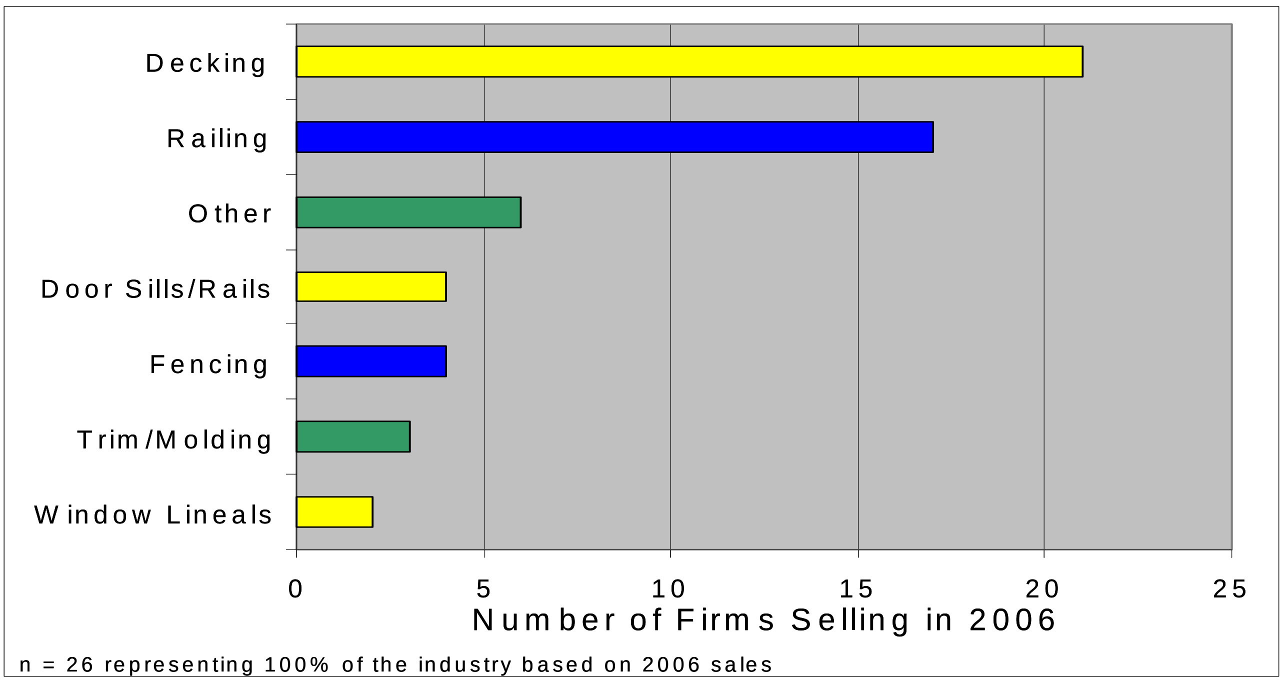


Figure 8 – Number of Firms Producing Each WPC Product in 2006

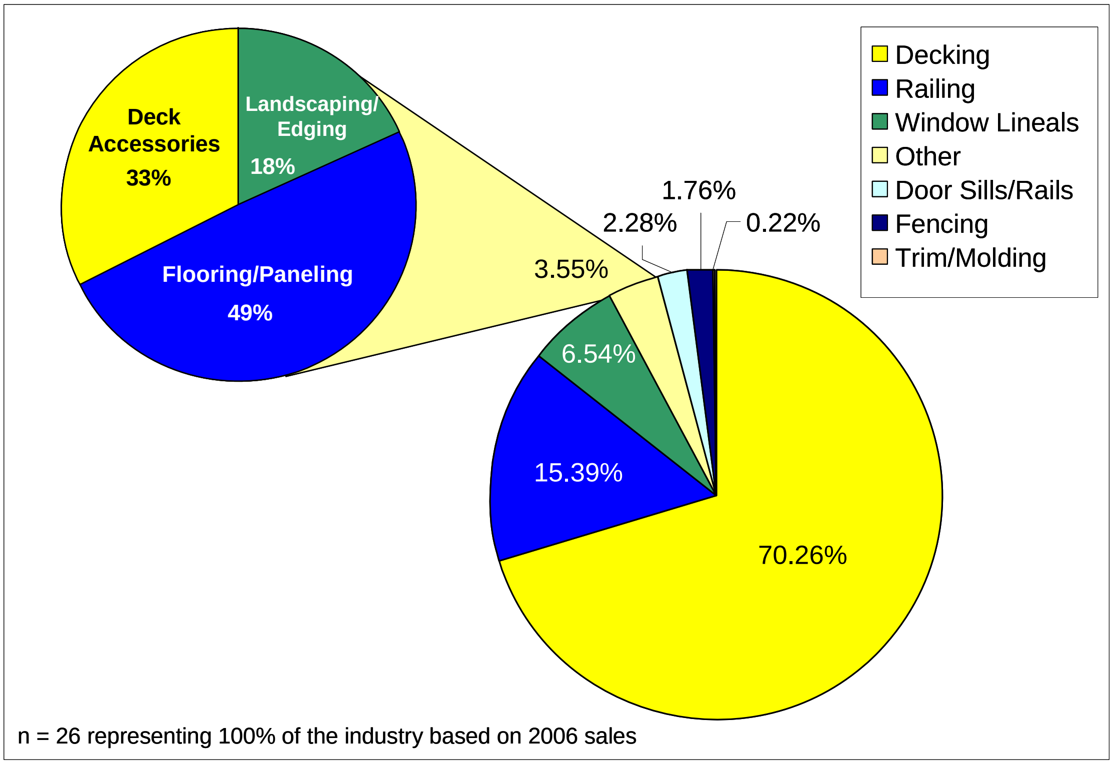


Figure 9 – Average Percent of Sales Made up by Each WPC Product in 2006 Weighted by 2006 Sales

What new products, currently not available commercially, do you think the WPC industry will be producing within:

the Next 2 Years:
the Next 5 Years:

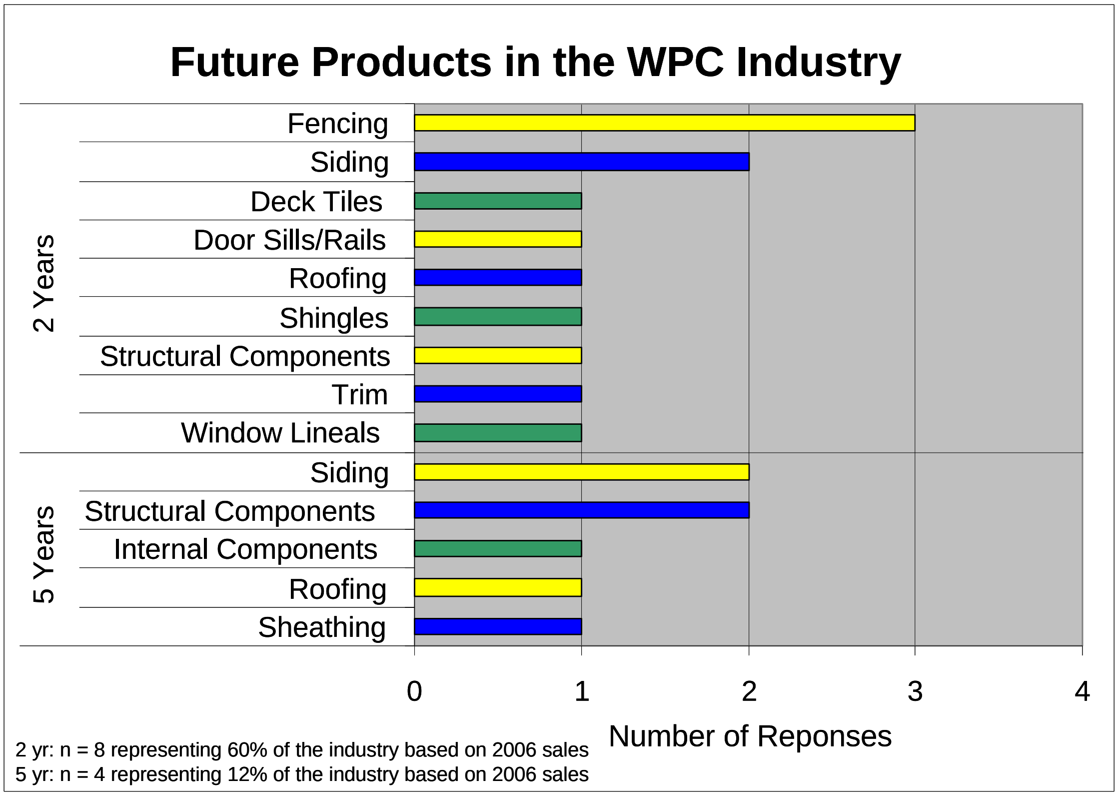


Figure 10 – Future Products in the Next 2 & 5 Years Indicated by Number of Respondents

What threats, if any, do you think will affect the continued growth of the WPC industry:

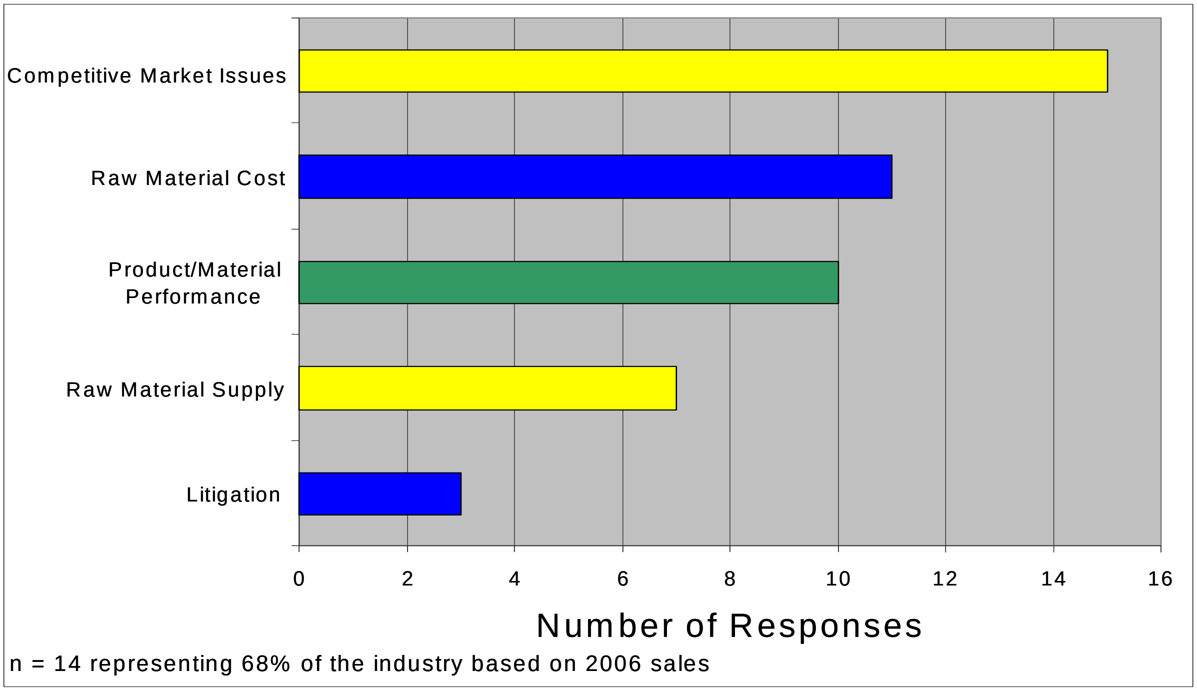


Figure 11 – Threats to the Continued Growth of the WPC Industry by Major Categories

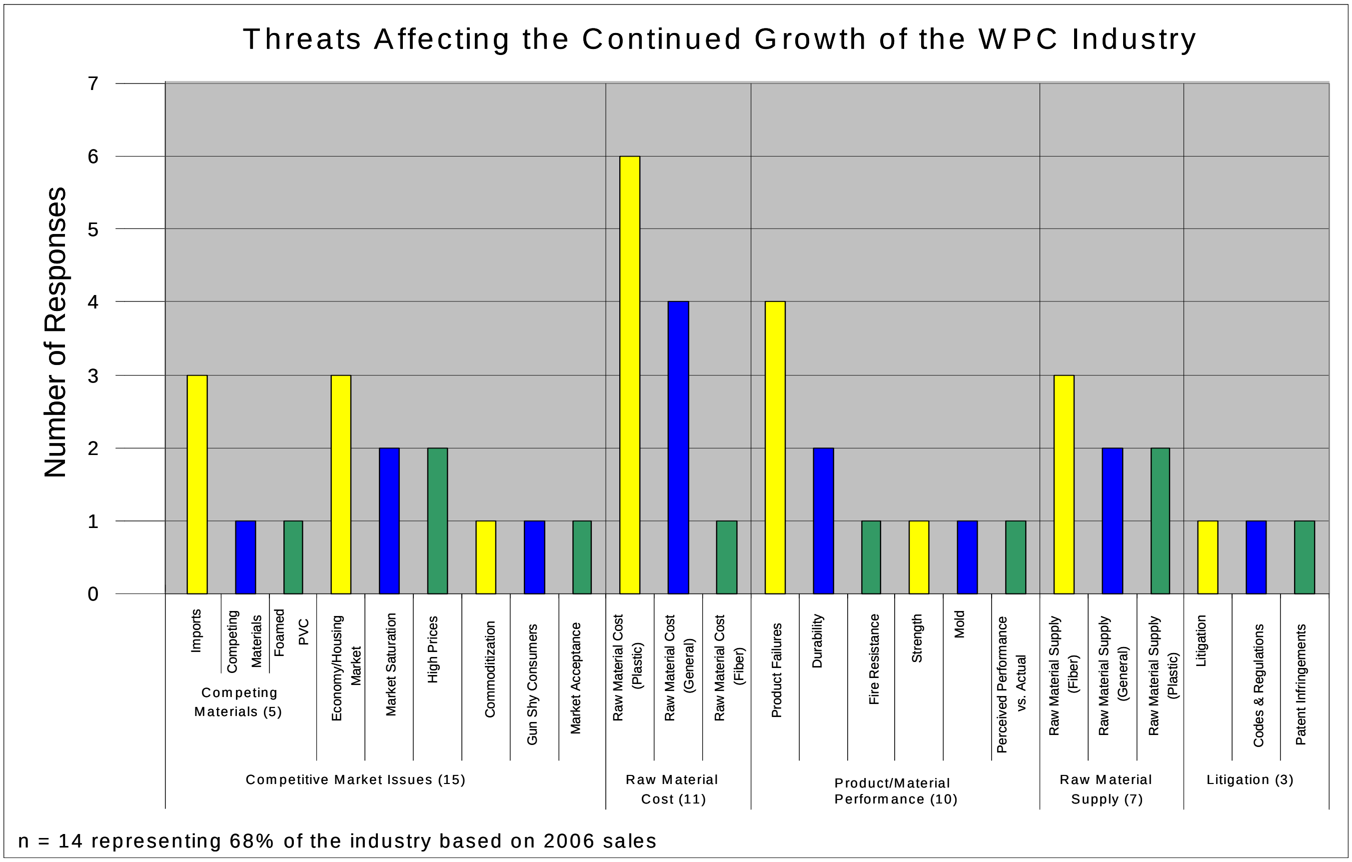


Figure 12 – Breakdown of Threats to the Continued Growth of the WPC Industry

Please provide your best estimate of the percent of your 2006 WPC sales that were sold directly to each of the following customer types:

Customer	***% of Sales***
Direct to Wholesalers	
Direct to Retailers	
Direct to Builders/Contractors	
Direct to DIYs/Homeowners	
Direct to Other	

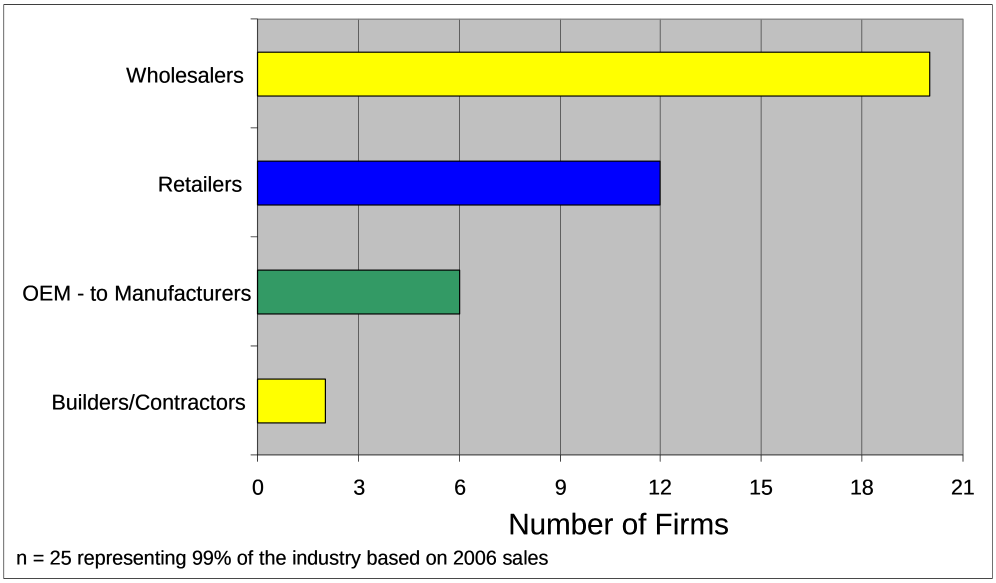


Figure 13 – Number of Firms Selling to the Various Customer Types in 2006

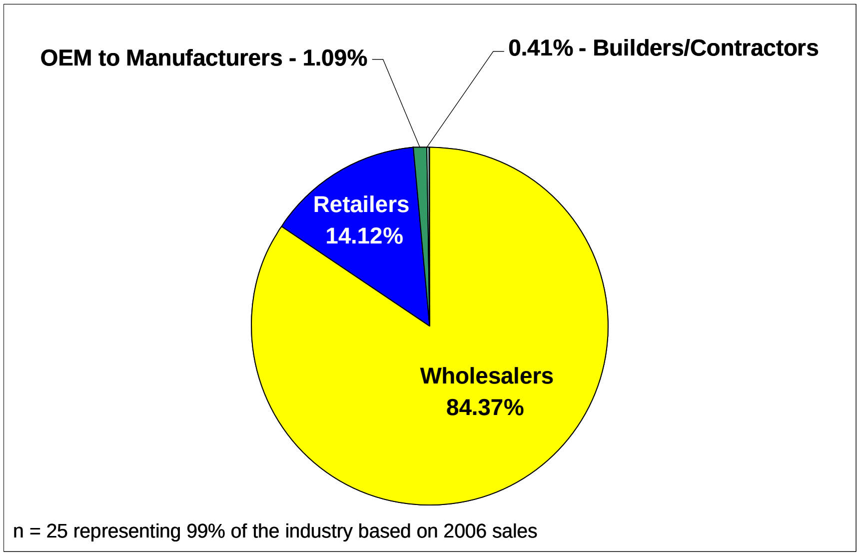
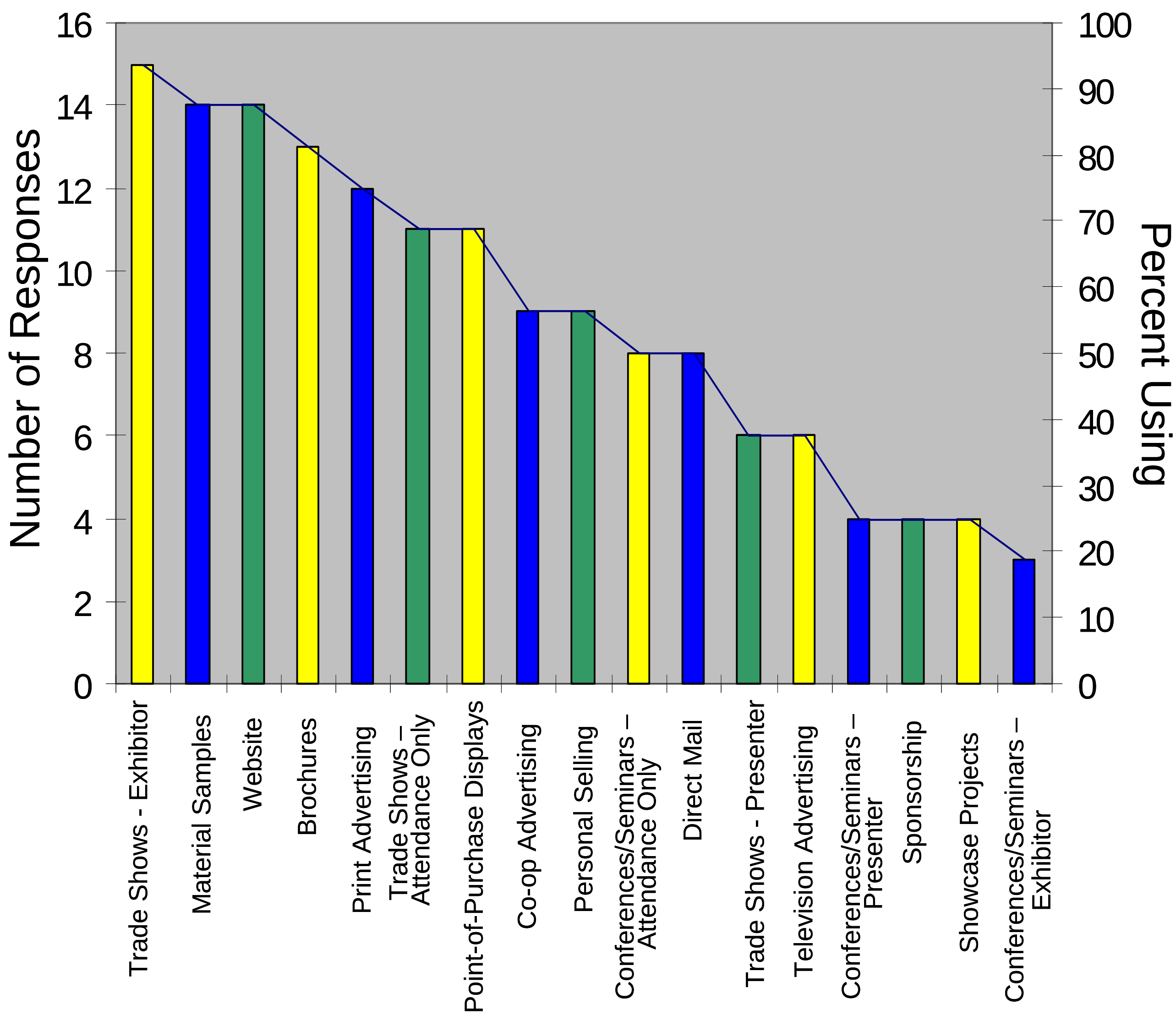


Figure 14 –Average Percent of Sales to Each Customer Type in 2006 Weighted by 2006 Sales

Please indicate which of the following communication methods your firm employed to promote its WPC products in 2006 (please check all that apply).

Conferences/Seminars (Attendance Only)	*Direct Mail*	
Conferences/Seminars (Exhibitor)	*Point-of-Purchase Displays*	
Conferences/Seminars (Presenter)	*Material Samples*	
Trade Shows (Attendance Only)	*Website*	
Trade Shows (Exhibitor)	*Sponsorship*	
Trade Shows (Presenter)	*Showcase Projects*	
Print Advertising	*Co-op Advertising*	
Television Advertising	*Personal Selling*	
Brochures	*Other*	*Please Specify:*
	Other	*Please Specify:*



n = 16 representing 74% of the industry based on 2006 sales

Figure 15 -

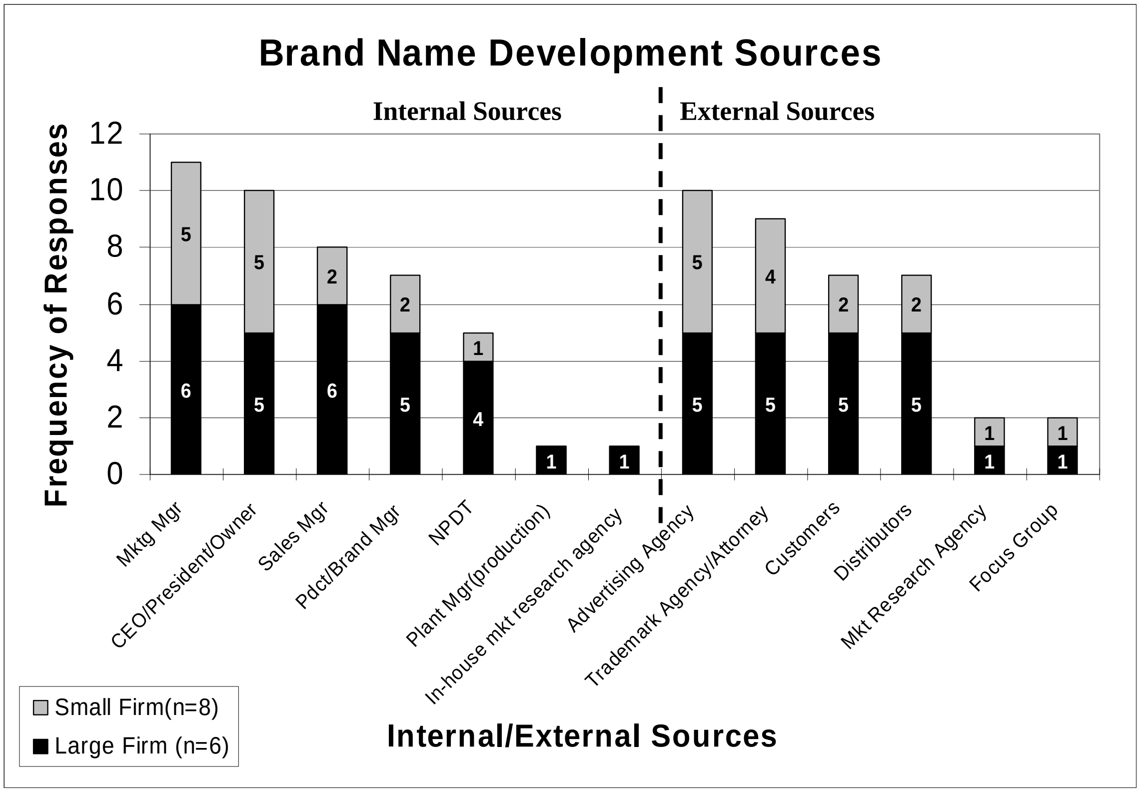
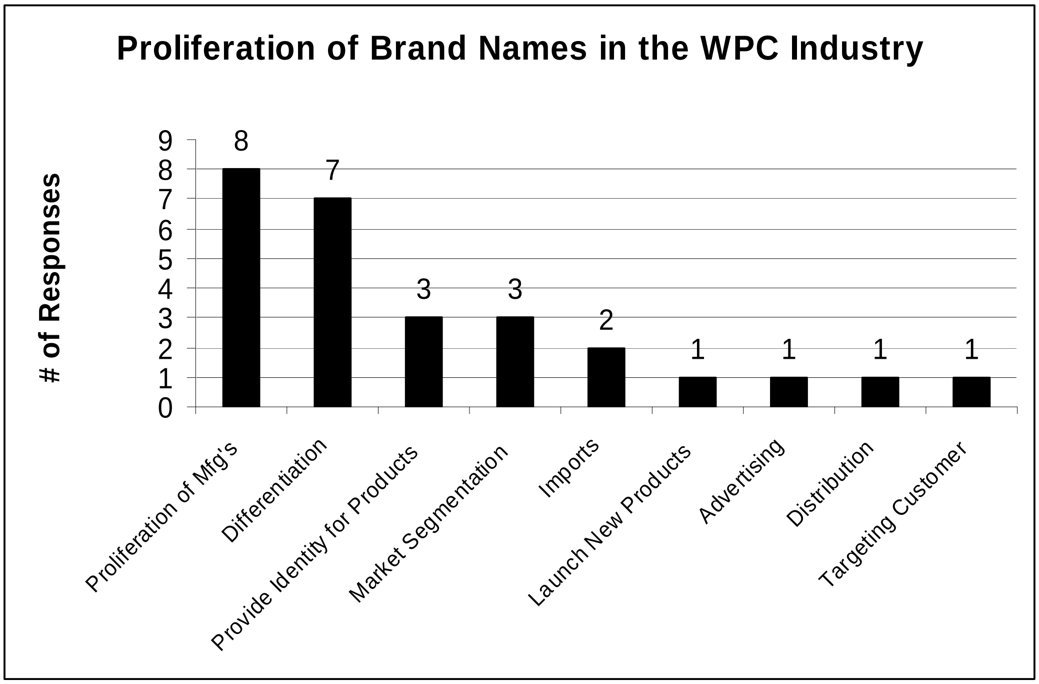
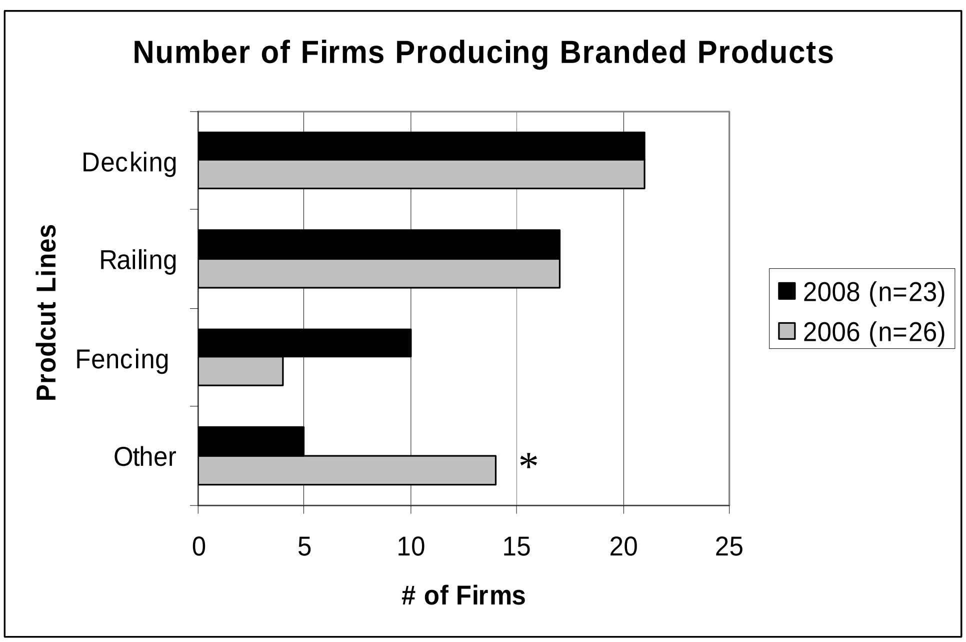


Figure 16 - Sources of Brand Name Development



* Respondents could provide more then one answer

Figure 17 - Proliferation of Brand Names in the WPC Industry



(Source: 2006 data from Smith & Tichy, 2007)
*For 2006 brands were not examined in the "Other" category

Figure 18 - Number of Firms Extruding Products in 2006 & 2008

Appendix A

Semi-Structured Telephone Scripts

Branded House Script

PENNSTATE

Wood Products Marketing
College of Agricultural Sciences

Jonathan J. Stank
Graduate Research Assistant
226 Forest Resources Building
University Park, PA 16802

Cell Phone: 814.404.7410
Fax: 814.865.3725
E-mail: jjs359@psu.edu

Brand Name Management & Strategies: Wood-Plastic Composites (WPCs)

The discussion will focus exclusively on your firm's **wood-plastic composite brands**. The discussion is intended to be informal, and your thoughts and opinions will be highly valued.

--Start of Interview---

1) What is your job title? ________________________________

2) What are your day-to-day responsibilities?

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3) Is there anyone else within your firm responsible for the day-to-day management of your brand portfolio?

1) Name ______________________________ Job Title ______________________________

2) Name ______________________________ Job Title ______________________________

3a) If yes, what are their day-to-day responsibilities?

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4) The following list of brand names has been generated to confirm your firm's brand portfolio. Please indicate the year in which each brand entered the market.

Please add any brands that may be missing and indicate the year the brand entered the market. Please indicate any discontinued brands.

Deck Brand:	**Market Entry Year:**	**Check if discontinued**
Brand X		
Other_______________________		

Railing Brand:	**Market Entry Year:**	**Check if discontinued**
Brand X		
Other_______________________		

Other Brands:	**Market Entry Year:**	**Check if discontinued**
Other_______________________		
Other_______________________		
Other_______________________		

5) When your firm developed your most recent WPC brand name (please specify :___________________) which of the following internal and/or external sources were utilized? (Check all that apply)

Internal Sources:

□ Marketing Manager: □ CEO/President:
□ Product/Brand Manager: □ New Product Development Team:
□ Sales Manager: □ Other: ____________________________

External Sources:

□ Trademark Agency/Attorney □ Customers
□ Advertising Agency □ Distributors
□ Market Research Agency □ Focus Group
□ Other: __________________________

6a) What are the objectives and thought process behind your firm's brand strategy when using the single brand name *Brand X to* brand all of your firm's WPC products?

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6b) Is it a goal of your firm's brand strategy to associate the company name *Company X* with *Brand X ?* Please Explain.

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7) Please indicate your level of **AGREEMENT** with the following statements related to your firm's **brand name strategy** for your firm's **WPC products**. (*Please circle one number fore each statement.*)

Our brand strategy provides the following <u>benefits</u> to our firm:	Strongly Disagree			Neither Agree or Disagree			Strongly Agree
1. Provides product identification.	`1	22	33	44	55	66	77
2. Creates differentiation among our firm's brands:	11	22	33	44	55	66	77
3. Creates differentiation from competing brands:	11	32	33	44	55	66	77
4. Helps in product positioning	11	22	43	44	55	66	77
5. Increases the efficiency of marketing communication:	11	22	43	44	55	66	77
6. Generates a price premium:	11	22	43	44	55	66	77
7. Provides legal protection:	11	22	43	44	55	66	77
8. Promotes repeat purchasing (customer loyalty):	11	22	43	44	55	66	77
9. Increases customer purchase confidence:	11	22	43	44	55	66	77
10. Affords no benefits:	11	22	43	44	55	66	77

8) In your opinion what has led to the proliferation of brand names within the WPC industry?

House of Brands Script

PENNSTATE

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College of Agricultural Sciences

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Graduate Research Assistant
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Brand Name Management & Strategies:
Wood-Plastic Composites (WPCs)

The discussion will focus exclusively on your firm's **wood-plastic composite brands**. The discussion is intended to be informal, and your thoughts and opinions will be highly valued.

--Start of Interview---

1) What is your job title? _________________________________

2) What are your day-to-day responsibilities?

____

____

____

3) Is there anyone else within your firm responsible for the day-to-day management of your brand portfolio?

1) Name ______________________________ Job Title ______________________________

2) Name ______________________________ Job Title ______________________________

3a) If yes, what are their day-to-day responsibilities?

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4) The following list of brand names has been generated to confirm your firm's brand portfolio. Please indicate the year in which each brand entered the market.

Please add any brands that may be missing and indicate the year the brand entered the market. Please indicate any discontinued brands.

Deck Brand:	**Market Entry Year:**	**Check if discontinued**
Brand X		
Brand Y		
Other______________________		

Railing Brand:	**Market Entry Year:**	**Check if discontinued**
Brand X		
Brand Y		
Other______________________		

Other Brands:	**Market Entry Year:**	**Check if discontinued**
Other______________________		
Other______________________		
Other______________________		

5) When your firm developed your most recent WPC brand name (please specify :___________________) which of the following internal and/or external sources were utilized? (Check all that apply)

Internal Sources:

□ Marketing Manager:
□ Product/Brand Manager:
□ Sales Manager:
□ CEO/President:
□ New Product Development Team:
□ Other: ____________________________

External Sources:

□ Trademark Agency/Attorney
□ Advertising Agency
□ Market Research Agency
□ Other: __________________________
□ Customers
□ Distributors
□ Focus Group

6a) What are the objectives and thought process behind your firm's brand strategy when using *Brand X* to brand some of your firm's WPC products and *Brand Y* to brand some of your firm's WPC products?

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6b) Is it a goal of your firm's brand strategy to associate the company name *Company X* with your firm's brands*?* Please Explain.

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7) Please indicate your level of **AGREEMENT** with the following statements related to your firm's **brand name strategy** for your firm's **WPC products**. (*Please circle one number fore each statement.*)

Our brand strategy provides the following <u>benefits</u> to our firm:	Strongly Disagree			Neither Agree or Disagree			Strongly Agree
1. Provides product identification.	`1	22	33	44	55	66	77
2. Creates differentiation among our firm's brands:	11	22	33	44	55	66	77
3. Creates differentiation from competing brands:	11	32	33	44	55	66	77
4. Helps in product positioning	11	22	43	44	55	66	77
5. Increases the efficiency of marketing communication:	11	22	43	44	55	66	77
6. Generates a price premium:	11	22	43	44	55	66	77
7. Provides legal protection:	11	22	43	44	55	66	77
8. Promotes repeat purchasing (customer loyalty):	11	22	43	44	55	66	77
9. Increases customer purchase confidence:	11	22	43	44	55	66	77
10. Affords no benefits:	11	22	43	44	55	66	77

8) In your opinion what has led to the proliferation of brand names within the WPC industry?

____
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Mixed Strategy Script (Endorsed and/or Subbrand)

PENNSTATE

Wood Products Marketing
College of Agricultural Sciences

Jonathan J. Stank
Graduate Research Assistant
226 Forest Resources Building
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Cell Phone: 814.404.7410
Fax: 814.865.3725
E-mail: jjs359@psu.edu

Brand Name Management & Strategies: Wood-Plastic Composites (WPCs)

The discussion will focus exclusively on your firm's **wood-plastic composite brands**. The discussion is intended to be informal, and your thoughts and opinions will be highly valued.

--Start of Interview--

1) What is your job title? ________________________________

2) What are your day-to-day responsibilities?

____

____

____

3) Is there anyone else within your firm responsible for the day-to-day management of your brand portfolio?

1) Name ____________________________ Job Title ____________________________

2) Name ____________________________ Job Title ____________________________

3a) If yes, what are their day-to-day responsibilities?

____

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4) The following list of brand names has been generated to confirm your firm's brand portfolio. Please indicate the year in which each brand entered the market.

Please add any brands that may be missing and indicate the year the brand entered the market. Please indicate any discontinued brands.

Deck Brand:	**Market Entry Year:**	**Check if discontinued**
Brand X Brand Y		
Brand X Brand Z		
Other_______________________		

Railing Brand:	**Market Entry Year:**	**Check if discontinued**
Brand X Brand Y		
Brand X Brand Z		
Other_______________________		

Other Brands:	**Market Entry Year:**	**Check if discontinued**
Other_______________________		
Other_______________________		
Other_______________________		

5) When your firm developed your most recent WPC brand name (please specify :___________________) which of the following internal and/or external sources were utilized? (Check all that apply)

Internal Sources:
□ Marketing Manager: □ CEO/President:
□ Product/Brand Manager: □ New Product Development Team:
□ Sales Manager: □ Other: ____________________________

External Sources:
□ Trademark Agency/Attorney □ Customers
□ Advertising Agency □ Distributors
□ Market Research Agency □ Focus Group
□ Other: __________________________

6a) What are the objectives and thought process behind your firm's brand strategy when using *Brand X* in conjunction to Brand Y and *Brand Z* to brand your firm's WPC products?

____
____
____
____
____
____

6b) Is it a goal of your firm's brand strategy to associate the company name *Company X* with your firm's brands*?* Please Explain.

____
____
____
____
____
____

7) Please indicate your level of **AGREEMENT** with the following statements related to your firm's **brand name strategy** for your firm's **WPC products**. (*Please circle one number fore each statement.*)

Our brand strategy provides the following <u>benefits</u> to our firm:	Strongly Disagree			Neither Agree or Disagree			Strongly Agree
1. Provides product identification.	`1	22	33	44	55	66	77
2. Creates differentiation among our firm's brands:	11	22	33	44	55	66	77
3. Creates differentiation from competing brands:	11	32	33	44	55	66	77
4. Helps in product positioning	11	22	43	44	55	66	77
5. Increases the efficiency of marketing communication:	11	22	43	44	55	66	77
6. Generates a price premium:	11	22	43	44	55	66	77
7. Provides legal protection:	11	22	43	44	55	66	77
8. Promotes repeat purchasing (customer loyalty):	11	22	43	44	55	66	77
9. Increases customer purchase confidence:	11	22	43	44	55	66	77
10. Affords no benefits:	11	22	43	44	55	66	77

8) In your opinion what has led to the proliferation of brand names within the WPC industry?

____
____
____
____
____
____
____

Appendix B

Initial Email

Dear Mr or Mrs. ___________________,

My name is Jonathan Stank and in conjunction with the Wood Products program in School of Forest Resources at Penn State University, I am conducting a study that examines individual brand strategies that exist in today's North American wood-plastic composite (WPC) industry. In order to complete this study, which is part of my efforts to complete my M.S. degree at Penn State, I am respectfully asking *Company X* to participate in a telephone interview.

Please find attached a Microsoft Word document containing a short cover letter that outlines the details of the study and the questionnaire that will be used during the telephone interview. If you have any technical problems opening the attachment please reply to this email and I will send the document via an alternative format. Thank you very much for your time and help. I look forward to speaking to you soon!

Sincerely,

Jonathan J Stank
Graduate Research Assistant
226 Forest Resource Building
University Park, PA 16802
Phone: 814.404.7410
Email: jjs359@psu.edu

Attachment

Appendix C

Cover Letter (Sent in Attachment)

PENNSTATE

Wood Products Marketing
College of Agricultural Sciences

Jonathan J. Stank
Graduate Research Assistant
226 Forest Resources Building
University Park, PA 16802

Cell Phone: 814.404.7410
Fax: 814.865.3725
E-mail: jjs359@psu.edu

Date_______, 2008

Dear Mr. or Mrs. ______________,

The purpose of this study is to gain an industry-wide understanding on how brand names are developed and subsequently managed by WPC manufacturing firms. The results of this study will provide your firm with an up-to-date snapshot of the WPC industry in terms of brand management, brand portfolios and brand strategies. Also, industry-specific benefits of brand strategies will be reported, and implications of brand strategies and brand architectures will be examined.

As an industry leader, we respect and value your expertise and therefore are requesting your participation in this interview. The interview is intended to be brief and will only take a few minutes of your valuable time. This interview is **voluntary and completely confidential** and your answers will be used only in combination with other responses for analysis and reporting. Your responses will never be associated with you or your firm. As a token of our appreciation for completing the survey, we will provide a complete summary of the results to all responding firms.

If you are the person **most responsible for managing your firm's brands**, please let me know (email) when you are available to participate in the telephone interview with a date and time at your earliest convenience. Please make sure to include **your phone number**. If you are not the person most responsible for managing your firm's brand(s), please forward this correspondence to the appropriate person with a request to have him/her follow-up with me accordingly.

The questionnaire that will be used during the telephone interview follows. If you have any questions and/or concerns please do not hesitate to contact me (or Dr. Smith). Thank you very much for your cooperation and help and I look forward to speaking with you soon.

Sincerely,

Jonathan J. Stank
Graduate Research Assistant
Phone: 814.404.7410
E-mail: jjs359@psu.edu

Paul Smith
Professor of Wood Products Marketing
Phone: 814-865-8841
E-mail: pms6@psu.edu

Appendix D

Follow-up Request for Participation (email)

Mr. or Mrs. ________________,

I contacted you on July 16th concerning our WPC Brand Strategy study for the North American WPC extrusion industry. I have not yet received a response from your firm concerning your participation in the telephone interview. I understand that the summer months are a busy time of the year making it difficult to find extra time. However the completion of the telephone interview should only take 5-10 minutes of your valuable time. Due to the limited number of WPC manufacturers completion of every interview is important to achieve results that are meaningful and truly representative the industry.

To expedite the data collection process, and consequently help me graduate, I am respectfully requesting that I call you on Date_____ at Time_____? If this date and time is inconvenient for you, please respond to this email with an alternate date that better fits your schedule. The telephone number I have for your firm is #_______, if there is an alternate number in which you would prefer me to call please let m know by responding to this email.

For your convenience I have attached a cover letter and copy of the questionnaire that will be used during the telephone interview.
Thank you in advance for your participation. I look forward to speaking with you soon.

Sincerely,

Jonathan J Stank
Graduate Research Assistant
226 Forest Resource Building
University Park, PA 16802
Phone: 814.404.7410
Email: jjs359@psu.edu

Enclosure

Foundation Elements for Naval Low-Rise Buildings

Market Research of the WPC Extrusion Industry

Demonstration and Markets

Task D4 – Qualitative textual analysis of WPC promotional literature

Paul M. Smith *Pennsylvania State University*

Prepared for
Office of Naval Research
under Grant N00014-06-1-0874

Project End Report

Pennsylvania State University
210 Forest Resources Building
University Park, PA 16802
Tel: 814-854-8841
Fax: 814-863-7193

Summary of Important Results:

Content analysis of WPC decking advertisements

Table 8 provides a spreadsheet summarizing the product and service attributes found in the 86 identified WPC decking advertisements in the January/February issues of Professional Deck Builder from 2002 – 2009.

Highlights include:

- The number of WPC decking advertisements in Professional Deck Builder followed a predominantly increasing trend with 6 advertisements in 2002 peaking with 19 advertisements in 2006 and then decreasing steadily to 3 advertisements in 2009.
- The majority of WPC decking ads were full page advertisements (n = 65/86) followed by 1/2 Page ads (n = 9/86), and 1/2 Page Island ads (n = 5/86).
- There was total of $238,770 spent on WPC decking advertising in the January/February issues of Professional Deck Builder from 2002 – 2009 based on the 2009 advertising rates accounting for 77 7/12 pages of ad space.
- The mean cost per WPC decking advertisement was $2,776 with an average size of 9/10 of a page.
- Full page WPC decking advertisements accounted for the majority (68%) of ad expenditures and advertising space (72%) followed outside back cover ads accounting for 10% of total expenditures and 8% of ad space.
- “Aesthetics” was contained in 59/86 WPC decking advertisements followed by “Color Options” (n = 42/86), “Low Maintenance” (n = 32/86), and “Ease of Installation” (n = 31/86).
- The attributes mentioned at least once in the fewest number of WPC decking ads were “Little Material Waste” (n = 1/86), “Ease of Sawing” (n = 1/86), “Resistance to Damage” (n = 2/86), and “Chemical Free” (n = 2/86).
- Aesthetics was the most mentioned WPC decking ad attribute overall with a total of 105 mentions in the 86 advertisements followed by Color Options (n = 54), Low Maintenance (n = 54), Ease of Installation (n = 42), Warranty (n = 35), and Resistance to Decay (n = 30).
- The least mentioned WPC decking ad attributes were Little Material Waste (n = 1), Ease of Sawing (n = 1), Resistance to Damage (n = 2), Recommendation of Others (n = 3), and Initial Cost (n = 3).

Review the websites of all WPC producers for content

Table 9 provides a spreadsheet summarizing the content review of all 26 WPC producers’ websites. Each website was reviewed for content regarding 14 pre-defined categories.

Highlights include:

- “Contact Info” was found on virtually all (25 of the 26 reviewed websites) WPC producer sites, followed by “Installation Info” (n = 23), “Warranty Info” (n = 23), “Separate Product Pages” (n = 20), and “Photo Gallery” (n = 20)
- “Design Software” was the category included least often (n = 8 of the 26 reviewed websites), followed by “Contractor Info” (n = 10), “Literature Available” (n = 14), and “Separate Pro & DIY Pages” (n = 14)
- Four company websites included all 14 of the content categories – Certainteed, Elk, TimberTech, and Trex
- Andersen’s website did not include information concerning their WPC products
- Of the companies with websites including information on their WPC products OnSpec’s, TeelGRT, and Royal Group Technologies included the fewest of the pre-defined content categories with 2, 3, and 5, respectively

Literature Review

Advertising

Business to business (B2B) advertising plays an important role in B2B marketing and is used to perform the following communication functions for a firm: (1) informing, (2) persuading, (3) reminding, (4) adding value, and (5) assisting other company efforts (Shimp 1997). Advertising can be seen as a way to help consumers make informed decisions by providing them with information, while others see advertising as being persuasive and suggestive by trying to sell something to the consumer (Stern et al. 1981). B2B advertising spending in trade/industry journals exceeds $1 billion annually in more than 2,700 business publications (Hutt and Speh 2004). Within the forest products industry, advertising has long been successfully used by firms with prime examples being Weyerhaeuser 4-Square Lumber efforts dating to the late 1920s to the current advertising efforts of Trex (Tokarczyk and Hansen 2006).

A major component of B2B advertising is the advertising copy. Advertising copy refers to the written portion of the advertising including the headline, subheads, logo or signature, and the body copy (Bellizzi and Hite 1986). Ad copy is exceptionally important not only to the advertising itself, but also marketing of a firms products in general as it must effectively convey the message that the firm wants to portray concerning its product (Bellizzi and Hite 1986). One methodology to assess the messages that are contained within ad copy is content analysis.

Previous Content Analysis Research in Advertising

Content analysis is a qualitative method that can be utilized to analyze the media messages used by firms. Content analysis is utilized to understand "any text which constitutes a relevant and necessary source material for answering the questions one is interested in" (Alexa 1997). Content analysis can be used to organize the attributes included in a document, such as advertising, through the use of coding to be later used to combine this qualitative analysis with further quantitative analysis (Sinkovics et al. 2005). These qualitative research tools can be a valuable tool in evaluating and refining promotional items such as printed advertising to make sure that they reflect the message that the company wants to communicate to their customers (McNeil 2005, Block and Block 2005).

Earlier studies of printed advertising have utilized content analysis methods to understand and predict meaning and effectiveness of advertisements. Naccarato and Neuendorf (1998) employed content analysis to study recall, readership, and evaluation of B2B advertisements in trade magazines. They examined printed form (e.g., headline size, use of color, illustration placement) and content (e.g., subject matter, use of humor). Stern (1996) used textual analysis to deconstruct the meaning of an advertisement by reviewing advertisement copy in conjunction with identification of variables such as rhythm, character, and plot. Turley and Kelley (1997) evaluated several elements (message appeal, headlines, price information, quality claims, and Internet address inclusion) to compare advertising for B2B services to advertising for consumer services. They concluded, for example, that headlines in printed advertisements are closely connected to advertising message appeal.

In another application of content analysis in advertising research, Stern et al. (1981) examined the amount of information included in print advertisements and concluded that advertisements for more durable or expensive products tended to be more informative. Seitz and Razzouk (2005) examined 214 printed advertisements in Romanian magazines, and concluded that Romanian print advertising is in its infancy compared to western advertising and that the use of comparative advertising is a rarity in Romania.

Although not a common method in the forest products industry, it is one that is gaining in use. Wagner and Hansen (2002) used content analysis as a way to measure the level of "greenness" of advertisements within the forest products industry from 1995 – 2000. Peters et al. (2006) used content analysis to characterize innovations in particleboard and composite materials as found in the International Particleboard/ Composite Materials Symposium Proceedings. Content analysis was also utilized the product and service attributes used by siding manufacturers in their builder-focused advertising (McGraw et al. 2008). Lastly, in a follow-up to the previous research by Wagner and Hansen (2002), Grillo et al. (2008) extended the study of "green" advertising in the forest products industry from 2001 – 2005 to add to the previous research and make additional comparisons over time.

Decking Industry

The decking industry is approximately a $4 billion (2005 estimate) industry mainly comprised of six competing materials, treated lumber, wood-plastic composites, redwood, cedar, imported woods (i.e. ipe), and plastic lumber (Smith & Wolcott 2006). The decking market is expected to grow to an estimated $5.6 billion industry by 2011 (Freedonia 2007). Deck builders are a key target market in this industry and often play an important role in the selection of decking material (Eastin et al. 2005). Treated lumber is the most popular decking material with approximately 64% market share, followed by WPCs (18%), redwood (6%), imported woods (5%), cedar (3%), and plastic lumber (2%) (Smith and Wolcott 2006). The decking industry has seen the market share of WPCs grow rapidly from approximately 2% in 1997 to an estimated 18% in 2005 (Smith and Wolcott 2006).

Wood-Plastic Composites

Wood-plastic composites (WPCs) are a material that combines the favorable performance and cost attributes of wood with the processablity of thermoplastic composites (Smith and Wolcott 2006). Commercially available WPCs utilize various formulations that include wood flour and thermoplastic composites along with an assortment of additives including lubricants, inorganic fillers, coupling agents, stabilizers, and biocides (Smith and Wolcott 2006).

Though WPCs have been used for some time in applications such as automobile parts and interior door skins, extruded WPCs have recently found success in the building materials industry resulting in a $1 billion industry with two-thirds of this being decking and railing (Smith and Wolcott 2006). These extruded WPCs are now also being utilized in applications such as window lineals, door stiles and rails, mouldings, fencing, siding and trim (Smith and Wolcott 2006). In addition to these residential markets, industrial infrastructure applications such as waterfront infrastructure and recreational bridge decking have been studied (Bright and Smith 2002, Smith and Bright 2002, McGraw and Smith 2006, McGraw and Smith 2007).

WPC extruders have used a combination of push-pull marketing communications to help in the diffusion of WPC products (Smith and Wolcott 2006). Push communications aimed at channel partners include favorable credit terms, co-op advertising, sales contests, trade show assistance, training programs, and point-of-purchase (POP) displays (Smith and Wolcott 2006). Company's pull marketing efforts are aimed at builders and homeowners and include television home-improvement shows, trade/home shows, web-based information, NASCAR racing endorsements, showcase product demonstration projects, company brochures, and print advertisements in trade/industry journals and home and garden magazines (Smith and Wolcott 2006).

Methodology

A content analysis methodology as defined by Neundorf (2002) in her book "The Content Analysis Guidebook" was used as the starting point for this research study. This research project focuses on advertisements used by the siding and decking industries to specifically target builders. Content analysis was used to identify key advertisement attributes as well as identify material attributes that are highlighted in the advertising copy. The methods of content analysis, data collection procedures including magazine identification and justification, advertisement identification, and attribute identification, and data analysis are detailed in the following sections.

Content Analysis

Content analysis can be briefly defined as "the systematic, objective, quantitative analysis of message characteristics" (Neuendorf 2002). Content analysis research typically follows the following nine steps (Neuendorf 2002):

(1) Theory and Rationale – what will be examined and why;
(2) Conceptualization Decisions – what variables will be studied;
(3) Operationalization Measures – what unit of data collection will be used;
(4) Coding Schemes – either human or computer coding scheme must be established;
(5) Sampling – sampling method must be determined;
(6) Training and Initial Reliability – coders must be trained and it must be assessed on whether they can agree on coding the variables;
(7) Coding – coding schemes are applied either by human or computer coding;
(8) Final Reliability – with human coding final reliability must be calculated;
(9) Tabulation and Reporting – results are analyzed and reported.

It is important to note that since content analysis is a qualitative method the data collected is subject to the interpretation by the researchers (Mariampolski, 2001).

Content analysis is a qualitative method that can be utilized to analyze the media messages used by firms. Content analysis is utilized to understand "any text which constitutes a relevant and necessary source material for answering the questions one is interested in" (Alexa 1997). Content analysis can be used to organize the attributes included in a document such as advertising through the use of coding to be later used to combine this qualitative analysis with further quantitative analysis (Sinkovics et al. 2005).

Though not a common method traditionally used in the forest products industry, it is gaining in utilization as recognized by the recent publications involving research employing content analysis. Wagner and Hansen (2002) used content analysis as a way to measure the level of "greenness" of ads within the forest products industry and Grillo et al. (2008) repeated this study as a follow-up. In addition, Peters et al. (2006) and McGraw et al. (2008) used content analysis to characterize innovations in particleboard and composite materials and product and service attributes found in builder-focused siding material advertisements, respectively. These qualitative research tools can be a valuable tool in evaluating and refining promotional items such as printed advertising to make sure that they reflect the message that the company wants to communicate to their customers (McNeil 2005, Block and Block 2005).

Data Collection

Magazine Identification

The first step in the data collection process was to identify the most relevant trade magazines to the target market segment. McGraw et al. (2008) identified the most relevant trade magazines to builders based upon circulation. In addition to these seven magazines, Professional Deck Builder (PDB) was identified as extremely important in reaching deck builders even though its circulation (approximately 20,000) was not as great as the other seven magazines.

Through personal communications with Maura Jacob (2008), managing editor of PDB from 2002-2006, we learned that there are no other trade magazines specifically targeting the decking industry and prior to the launch of PDB in 2002, decking materials were primarily advertised to consumer markets. In addition, Jacob (2008) pointed out that any advertisement found in other builder-focused magazines would be identical to those found in PDB. Moreover, Jacob (2008) indicated that decking advertising varies little throughout the year, so the January issue (preceding the #1 trade show for the decking industry – the Deck Expo) would be a good barometer of the advertising for each year. Therefore, the January 2005 issue of PDB was obtained and compared to the January 2005 issues of the seven magazines used in the siding study by McGraw et al. (2008).

A comparison of these eight magazines confirmed that PDB was the most relevant magazine for reaching deck builders with advertisements. Professional Deck Builder contained 72 percent of all of the advertisements aimed at deck builders by count and 70 percent based on actual ad space (Table 1). Advertisements in the seven builder-focused magazines were compared to those in PDB to explore duplicate advertisements. Of the 32 advertisements found in the other seven builder-focused magazines only 19 were not found in PDB resulting in 83% of all advertisements being in PDB. In addition, of these 19 advertisements only 10 were not accounted for by a similar advertisement in PDB. This would result in PDB representing 91% of all advertisements aimed at builders in some form. Therefore, it was determined that PDB alone provides the coverage we are seeking for advertising targeting builders and will be utilized for the collection of advertisements within the decking industry. The January issue for every year of publication (2002 – 2009) was obtained for analysis of the decking industry advertisements.

Table 1. Comparison of Decking Ads in Builder-Focused Magazines

		January 2005 Issue	
Magazine	**Circulation**	**Total Number of Ads**	**Total Ad Space**
Professional Builder	145,365	5	3.5
Qualified Remodeler	141,399	0	0
Professional Remodeler	127,000	3	4
Journal of Light Construction	82,489	7	5.1
Fine Homebuilding	80,523	6	1.9
Remodeling	74,738	1	1
Builder	63,400	10	8.3
Professional Deck Builder	23,292	82	55.1
TOTAL	**738,206**	**114**	**78.9**
% PDB	**3%**	**72%**	**70%**

Advertisement Identification

All WPC decking advertisements targeted to deck builders were identified in each January issue of Professional Deck Builder and marked. Once all of the advertisements were identified each one was scanned into an electronic format which was then used to complete the content analysis. In the case of identical advertisements found in multiple years, each one was treated as a separate case and used in the data analysis.

Advertisement Attributes

All scanned advertisements contained in Professional Deck Builder were analyzed for various attributes of the advertisement. First, for identification purposes the years, page number, company, and product was recorded. Besides helping to identify specific advertisements, the location (inside front cover, page number, inside back cover, back cover, double page spread) has been shown to have a significant effect on recognition readership scores (Finn 1988). The use of color was also recorded because it has been shown to have a significant effect on the effectiveness of advertisements (Chamblee & Sandler 1992). Finally the size of the advertisement was recorded. Finn (1988) found that advertisement size affects the audience readership of print ads.

Decking Attribute Identification

In addition to the aforementioned advertisement attributes, the ad copy of WPC decking material advertisements was analyzed using content analysis. This analysis identified the major product and service attributes of decking materials that were being conveyed in the ad copy. Through extensive secondary research a comprehensive list of decking attributes was compiled as seen in Table 2. This list was condensed to group similar attributes such as “aesthetics” and “appearance” as one attribute “aesthetics” resulting in a final list of 52 decking attributes (Table 4) representing all attributes in Table 2. Additional attributes that appear in decking advertisements were added throughout the content analysis process.

Table 2. Decking Attributes

Smith and Bright (2002) – Decking Material Attributes for Port Authorities & Engineering Firms		
Bright and Smith (2002) – Decking Material Attributes for Marinas		
Reliable strength	High-energy absorption	Non-conductive
Resistance to impact	Resistance to U.V.	Low initial cost
Resistance to decay	Resistance to fire	Less aquatic biofouling
Low life cycle cost	Easy installation	Attractive appearance
Low maintenance cost	Low replacement cost	Low disposability cost
Structural design flexibility	Low expansion/contraction	Use of recycled materials
Resistance to marine borers	Toxic chemical free	
McGraw and Smith (2007) – Importance of recreational bridge decking material attributes		
Low maintenance	Availability	High strength
Decay resistance	Proven track record	Fire resistance
Initial cost	Wear resistance	Low weight
Slip resistance	Aesthetics	Thermal expansion
Life-cycle cost	UV resistance	Chemical free
Shook and Eastin (2001) – Importance of deck material attributes for deck surface or accessories		
Long life	Easy to maintain	Little material waste
Beautiful & aesthetically pleasing	High workability	Low material cost
Durability	Price stability	
Availability	High strength properties	
Smith and Carter (1999) – Importance of deck board attributes		
Smith, Wolcott, and Smith (1998) – Importance & satisfaction Home center deck board attributes & builders		
Cost	Straightness	Environmental friendliness of preservatives
Resistance to decay	Resistance to wear	
Quality	Ease of handling	Ease of storage
Comparison of WPC decking & wood decking by builders & home centers		
Resistance to decay	Environmental friendliness	Ease of sawing
Resistance to wear	Ease of storage	Ease of nailing
Recyclability	Appearance	Availability
Straightness	Feel	Cost
Damery (2001) – architects, contractors, & homeowners – Importance of factors on deck purchase		
Better performance	Better appearance	
Lower cost	Recommendation of others	
Importance of performance problems		
Poor durability	Poor environmental record	Installed stability
Easily damaged	Short service life	Inconsistent quality
Material not available	Difficult to install	Not long enough
Importance of appearance characteristics		
Able to change colors	Fits style of house	Fits neighborhood
Up-close appearance	Fits the landscape	Fits desired status

Decking Attribute Identification in Advertisements

Researchers used content analysis to assign attributes to the ad copy. Table 3 shows an example of advertising copy and assigned decking attributes.

Table 3. Example of attribute assignment to advertising copy.

Advertising Copy	Attribute
“for stronger, easier-to-install composite decking”	high strength, ease of installation
“a more beautiful, easily maintained and safe deck”	low maintenance
“is resistant to rotting, splitting, and warping”	resistance to decay
“Available in a variety of colors”	color options

Codebook

The following (Table 4) is the codebook that was used when analyzing the advertisements in Professional Deck Builder. Coders had a copy of this and marked information for each advertisement on the codebook. Once each advertisement was analyzed, the information was entered into a spreadsheet for data analysis.

Data Analysis

Once all advertisements were analyzed for advertisement and decking material attributes and entered into a database, various statistical methods were used to complete data analysis. Methods employed included basic descriptive statistics to present the results of the attribute counts and expenditures for the WPC decking advertisements.

Website Content Analysis

The content of all 26 WPC manufacturers’ websites were analyzed for content. Each website was examined for the inclusion of 14 pre-defined categories. The 14 pre-defined categories are: (1) Separate Pro & DIY Pages, (2) Technical Info, (3) Separate Product Pages, (4) Distribution Info, (5) Warranty Info, (6) Contractor Info, (7) Design Software, (8) Literature Available, (9) Care/Cleaning Info, (10) Installation Info, (11) FAQ, (12) Contact Info, (13) Photo Gallery, and (14) Press Releases.

Table 4. Codebook for Content Analysis

Content Analysis Codebook – Builder-Focused Decking Industry Advertisements

Advertisement Identifying Attributes

1. Year
2. Page Number
3. Company
4. Product
5. Use of Color
6. Ad Size

Decking Attributes

7. Aesthetics
8. Availability
9. Chemical Free
10. Color options
11. Cost
12. Durability
13. Ease of handling
14. Ease of installation
15. Ease of maintenance
16. Ease of nailing
17. Ease of sawing
18. Ease of storage
19. Environmental friendliness
20. Feel
21. Fits desired status
22. Fits neighborhood
23. Fits style of house
24. Fits the landscape
25. High energy absorption
26. High workability
27. Initial cost
28. Length
29. Life-cycle cost
30. Little material waste
31. Long life
32. Low disposability cost
33. Low maintenance
34. Low maintenance cost
35. Low material cost
36. Low replacement cost
37. Low weight
38. Non-conductive
39. Performance
40. Price stability
41. Proven track record
42. Quality
43. Recommendation of others
44. Recyclability
45. Resistance to damage
46. Resistance to decay
47. Resistance to fire
48. Resistance to impact
49. Resistance to marine borers
50. Resistance to U.V.
51. Resistance to wear
52. Slip resistance
53. Straightness
54. Strength
55. Structural design flexibility
56. Thermal expansion
57. Use of recycled materials
58. Warranty

Results and Discussion

Of the 52 pre-defined WPC decking product and service attributes, 20 were not contained in any of the PDB advertisements. These 20 attributes are listed in Table 5 below and were not included in any of the analysis.

Table 5. Attributes not Contained in any WPC Decking Advertisements

Ease of Handling	High Workability	Price Stability
Ease of Nailing	Length	Recyclability
Ease of Storage	Life-cycle Cost	Resistance to Impact
Fits Desired Style	Low Disposability Cost	Resistance to Marine Borers
Fits Neighborhood	Low Material Cost	Straightness
Fits the Landscape	Low Replacement Cost	Structural Design Flexibility
High Energy Absorption	Non-conductive	

A total of 86 WPC decking advertisements were found in the January/February 2002 – 2009 issues of Professional Deck Builder (PDB). The 2002 issue contained 6 WPC decking ads and the number of ads continued to climb until it peaked with 19 WPC decking ads in the 2006 issue. The number of WPC decking ads then declined with only 3 WPC decking ads appearing in the 2009 issue. This can be seen in Figure 1 below.

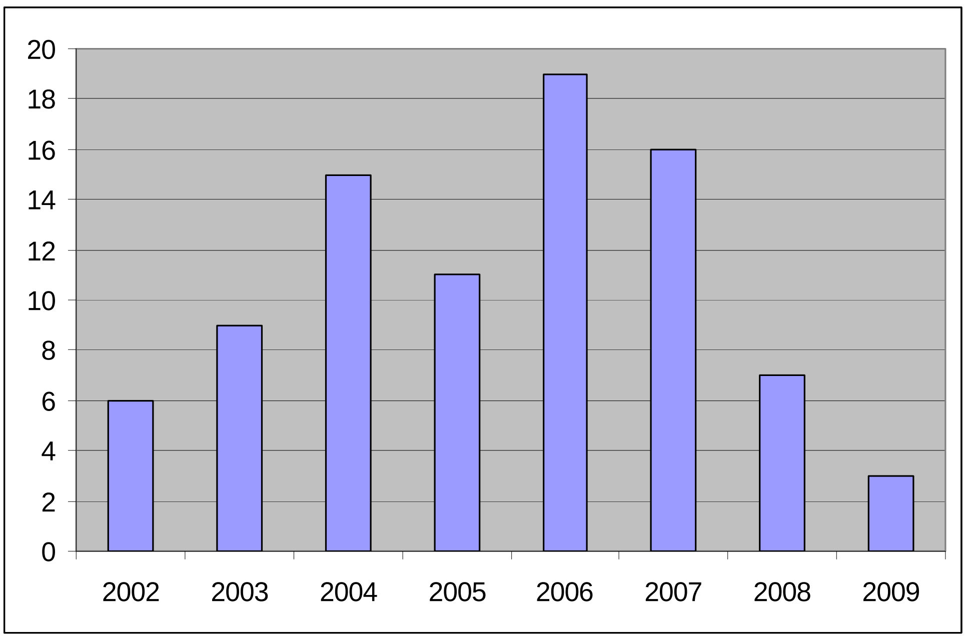

Figure 1. Number of WPC Decking Advertisements in PDB by Year

The majority (n = 65/86) of WPC decking advertisements found in the January/February 2002 – 2009 issues of Professional Deck Builder were full page advertisements followed by 1/2 Page ads (n = 9/86), and 1/2 Page Island ads (n = 5/86).

Table 6. WPC Decking Advertisements by Advertisement Size in PDB (2002-2009)

Size	Number of Ads (n = 86)	Percent of Ads
1/4 Page	1	1.16%
1/3 Page	4	4.65%
1/2 Page	9	10.47%
1/2 Page Island	5	5.81%
1 Page	65	75.58%
2 Pages	2	2.33%
Total	**86**	**100.00%**

Advertisement expenditures were recorded based on the 2009 rate chart for Professional Deck Builder. The cost of the various sizes and placements for the advertisements can be seen in Table 7. Advertising costs increase as the size of the ad increases, and there is also a premium for placement on the inside of the front and back covers as well as on the outside of the back cover. The outside back cover contained a WPC decking advertisement in 6 out of the 8 years that PDB has been published. There was total of $238,770 spent on WPC decking advertising in the January/February issues of PDB from 2002 – 2009 based on the 2009 advertising rates accounting for 77 7/12 pages. The mean cost per advertisement was $2,776 with an average size of 9/10 of a page. Full page advertisements accounted for the majority (68%) of ad expenditures and advertising space (72%) followed outside back cover ads accounting for 10% of total expenditures and 8% of ad space.

Table 7. Summary of WPC Decking Ad Size, Placement, and Cost in PDB (2002 – 2009)

Ad Size/ Placement	Ad Cost	Number of Ads (n = 86)	Percent of Ads	Expenditures	Percent of Expenditures	Number of Pages	Percent of Pages
1/4 Page	$1,015	1	1.16%	$1,015	0.43%	1/4	0.32%
1/3 Page	$1,325	4	4.65%	$5,300	2.22%	1 1/3	1.72%
1/2 Page	$1,725	9	10.47%	$15,525	6.50%	4 1/2	5.80%
1/2 Page Island	$1,785	5	5.81%	$8,925	3.74%	2 1/2	3.22%
1 Page	$2,900	56	65.12%	$162,400	68.02%	56	72.18%
Inside Back Cover	$3,575	3	3.49%	$10,725	4.49%	3	3.87%
Outside Back Cover	$3,980	6	6.98%	$23,880	10.00%	6	7.73%
2 Pages	$5,500	2	2.33%	$11,000	4.61%	4	5.16%
Total	**-**	**86**	**100.00%**	**$238,770**	**100.00%**	**77 7/12**	**100.00%**
Mean	**-**	**-**	**-**	**$2,776**	**-**	**9/10**	**-**

The attribute most mentioned as least once in WPC decking advertisements in PDB was Aesthetics contained in 59/86 advertisements followed by Color Options (n = 42/86), Low Maintenance (n = 32/86), and Ease of Installation (n = 31/86). The WPC decking ad attributes mentioned at least once in the fewest number of PDB ads were Little Material Waste (n = 1/86), Ease of Sawing (n = 1/86), Resistance to Damage (n = 2/86), and Chemical Free (n = 2/86). Aesthetics was the most mentioned WPC decking ad attribute overall with a total of 105 mentions in the 86 advertisements followed by Color Options (n = 54), Low Maintenance (n =

54), Ease of Installation (n = 42), Warranty (n = 35), and Resistance to Decay (n = 30). The least mentioned WPC decking ad attributes were Little Material Waste (n = 1), Ease of Sawing (n = 1), Resistance to Damage (n = 2), Recommendation of Others (n = 3), and Initial Cost (n = 3).

Table 8. Summary of Product and Service Attributes Found in WPC Decking Advertisements in PDB (2002-2009)

Attribute	Number of Ads Containing Attribute at Least Once (n = 86)	Percent of Ads Containing Attribute at Least Once	Total Number of Mentions	Average Number of Mentions per Ad
Aesthetics	59	68.60%	105	1.22
Color options	42	48.84%	54	0.63
Low maintenance	32	37.21%	54	0.63
Ease of installation	31	36.05%	42	0.49
Warranty	28	32.56%	35	0.41
Resistance to decay	25	29.07%	30	0.35
Proven track record	18	20.93%	22	0.26
Long life	15	17.44%	20	0.23
Thermal expansion	19	22.09%	20	0.23
Quality	17	19.77%	19	0.22
Resistance to wear	13	15.12%	19	0.22
Strength	14	16.28%	17	0.20
Durability	15	17.44%	16	0.19
Resistance to U.V.	10	11.63%	12	0.14
Environmental friendliness	10	11.63%	11	0.13
Performance	9	10.47%	10	0.12
Feel	6	6.98%	8	0.09
Low weight	6	6.98%	8	0.09
Cost	4	4.65%	7	0.08
Resistance to fire	7	8.14%	7	0.08
Slip resistance	7	8.14%	7	0.08
Use of recycled materials	7	8.14%	7	0.08
Ease of maintenance	6	6.98%	6	0.07
Availability	5	5.81%	5	0.06
Chemical Free	2	2.33%	4	0.05
Fits style of house	4	4.65%	4	0.05
Low maintenance cost	4	4.65%	4	0.05
Initial cost	3	3.49%	3	0.03
Recommendation of others	3	3.49%	3	0.03
Resistance to damage	2	2.33%	2	0.02
Ease of sawing	1	1.16%	1	0.01
Little material waste	1	1.16%	1	0.01

Table 9 summarizes the findings for the review of WPC producers' website content. "Contact Info" was found on virtually all (25 of the 26 reviewed websites) sites, followed by

“Installation Info” (n = 23), “Warranty Info” (n = 23), “Separate Product Pages” (n = 20), and “Photo Gallery” (n = 20). “Design Software” was the category included least often (n = 8 of the 26 reviewed websites), followed by “Contractor Info” (n = 10), “Literature Available” (n = 14), and “Separate Pro & DIY Pages” (n = 14). Four company websites included all 14 of the content categories – Certainteed, Elk, TimberTech, and Trex. Andersen’s website did not include information concerning their WPC products. Of the companies with websites including information on their WPC products OnSpec’s, TeelGRT, and Royal Group Technologies included the fewest of the pre-defined content categories with 2, 3, and 5, respectively

Company	Website	Separate Pro & DIY Pages	Technical Info	Separate Product Pages	Distribution Info	Warranty Info	Contractor Info	Design Software	Literature Available	Care/ Cleaning Info	Installation Info	FAQ	Contact Info	Photo Gallery	Press Releases	N
AERT	http://www.aertinc.com http://www.choicedek.com http://www.moistureshield.com		X	X	X	X		X	X	X	X	X	X	X	X	12
Andersen Windows	http://www.andersenwindows.com http://www.renewalbyandersen.com															0
Brite Manufacturing, Inc.	http://www.britemfg.ca			X	X	X	X		X	X	X		X	X		9
Carney Timber Company owned by McFarland Cascade	http://www.xtendex.com		X	X	X	X	X	X	X	X	X	X	X	X		12
Certainteed Corp.	http://www.certainteed.com	X	X	X	X	X	X	X	X	X	X	X	X	X	X	14
Composatron Manufacturing Inc.	http://www.composatron.com/	X	X	X	X	X		X	X	X	X	X	X	X	X	13
Correct Building Products	http://www.correctdeck.com	X	X	X	X	X	X			X	X	X	X	X	X	12
Deceuninck Distributed by Alcoa	http://www.decna.biz http://www.alcoa.com/alcoahomes/brands/oasis.aspx	X	X	X	X	X	X		X		X		X		X	10
Elk Composite Building Products, Inc.	http://www.elkcorp.com	X	X	X	X	X	X	X	X	X	X	X	X	X	X	14
Epoch Composite Products, Inc. (Western Woods Inc.)	http://www.epoch.com http://www.evergrain.com http://www.elementsdecking.com	X	X	X	X	X				X	X	X	X	X	X	11
Fiber Composites, LLC	http://www.fiberondecking.com	X	X	X	X	X		X	X	X	X	X	X	X	X	13
FiberTech Polymers, Inc.	http://www.fibertechpolymers.com http://www.timberwolfcomposites.com			X	X	X					X	X	X			6
Greenland Composites	http://www.greenlandcomposites.com		X	X		X					X	X	X	X		7
Kroy Building Products	http://www.kroybp.com/index.htm			X	X	X				X	X	X	X	X	X	9
LDI Composites Company	http://www.geodeck.com	X	X	X	X	X			X	X	X	X	X	X	X	12
Louisiana-Pacific Corp.	http://www.lpcorp.com	X	X	X	X	X	X		X	X	X	X	X	X	X	13
Master Mark Plastics	http://www.mastermark.com http://www.rhinodeck.com		X	X	X	X	X			X	X		X	X	X	10
Millennium Decking Inc. (Wood Composite Technologies)	http://www.mdecking.com		X		X	X				X	X	X	X	X	X	9
OnSpec Composites	http://home.fuse.net/match/onspec.htm				X								X			2
Premium Composites, LLC	http://www.premiumcomposites.com/			X		X			X	X	X	X	X	X		8
Royal Group Technologies	http://www.royalgrouptech.com	X				X					X		X		X	5
TeelGRT (and Teton West Composites)	http://www.teel-grt.com		X										X		X	3
Tendura, Inc.	http://www.tendura.com	X	X		X	X				X	X	X	X	X		9
TimberTech, Ltd. (Crane Plastics)	http://www.timbertech.com	X	X	X	X	X	X	X	X	X	X	X	X	X	X	14
Trex Company, LLC	http://www.trex.com	X	X	X	X	X	X	X	X	X	X	X	X	X	X	14
Universal Forest Products, Inc.	http://www.ufpi.com/product/decking.htm	X	X	X	X	X			X	X	X	X	X	X		11
TOTAL (n)		**14**	**19**	**20**	**21**	**23**	**10**	**8**	**14**	**19**	**23**	**19**	**25**	**20**	**17**	**-**

Table 9. Summary of WPC Producer Website (n=26) Content Analysis

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