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Summary

An investigation into the methods of potentially improving the performance of light-frame shear walls was undertaken as part of a larger project for the United States Office of Naval Research. The goals of the project were to increase the durability, strength, and stiffness performance of light-frame shear walls by directly substituting wood-plastic composite members for the traditional dimensional lumber sill plate. The study included connection design as well as proof of concept cyclic racking tests of full-scale wall specimens. The results were that changing the sill plate form and the connections between the studs and the sill plate, increases the lateral capacity of the wall by a factor of 3, increases the “toughness” of the wall, and minimizes the potential for decay.

1. Introduction

1.1 Background

Wood-frame buildings incurred damage that outweighed loss by any other building type during the 1994 Northridge earthquake, in Northridge, California. Wood shear wall and lateral force resisting systems were particularly susceptible to damage, exhibiting cracking at sill-foundation connections, significant deformation at wall boundaries, sliding of walls along the foundations, and longitudinal splitting of sill plates (Day, 1996). This damage, at the location where shear and overturning forces concentrate, reduces the lateral force capacity of the structure (Hamburger, 1994). Subsequent damage from failed sill-to-foundation connections under extreme loading events creates a need to understand and improve the performance of this connection.

The Consortium of Universities for Research in Earthquake Engineering (CUREE)-Caltech Wood-frame Project, Task 1.4.1.1 Anchorage of Wood-Frame Buildings, performed extensive testing on variables affecting sill plate performance. This work completed by Mahaney and Kehoe (2002) included the following variables: sill width, sill thickness, sill species, anchor bolt size, amount of dead load, shear connection type, bolt washer size and type, anchor bolt location, anchor bolt hole size, and hold-down type. A force-controlled loading protocol based on developments in CUREE Task 1.3.2, Cyclic Response of Wood-frame Shearwalls: Loading Protocol and Rate of Loading Effects (Gatto and Uang, 2002), was utilized in testing specimens.

Results from CUREE anchorage tests provide insight on shear wall failure modes and ductility response. Out of sixty-three valid tests, thirty-four failed in the sill plate. Of those tests lacking hold-down connectors, where failures in the sill plate occurred, lower load capacities and lower number of cycles were achieved—compared to walls having other failure mechanisms (Mahaney and Kehoe, 2002).

Specific failures observed in sill plates occurred due to combined bending and twisting, coupled with stress concentrators along the grain from sheathing nails. By limiting sill plate bending and twisting, failure of shear walls can be shifted from brittle sill-to-foundation connection damage to a
more ductile failure associated with plywood/framing connections yielding. Testing has shown that when failure modes occur in the plywood rather than in sill plates, ductility and wall performance are improved.

Final design recommendations from CUREE Task 1.4.1.1 suggest increasing sill plate thicknesses to nominal 76 mm and using square plate washers—both design recommendations parallel code changes after Northridge earthquake. In addition, it was recommended that end studs be 102 mm nominal posts connected to stiff hold-downs, and 76 mm nominal framing be provided at plywood panel joints.

The effectiveness of square plate washers to counteract cross-grain bending and subsequent sill splitting has been further investigated. The International Residential Building Code requires the use of plate washers with minimum dimensions of 50 mm x 50 mm x 5 mm, as opposed to round, cut washers (ICBO, 2000a). The American Plywood Association (APA) reported no splitting failures and a shear wall strength of 12.7 kN/m in tests on walls with 38 mm x 89 mm sill plates restrained with large, 76 mm x 102 mm x 19 mm plate washers (Martin, 2004). Oregon State University prepared reports for the American Forest and Paper Association (AF&PA) considering different plate washer sizes for engineered shear walls (Rosowsky et al, 2004). In this testing, walls with standard round washers were shown to carry higher maximum loads with smaller deflections, resulting in lower energy dissipation than square plate washers.

### 1.2 Objective

For this study, development of a prototype wall-to-foundation connector system for wood-frame walls under dynamic loading will apply specifically to slab-on-grade construction. This project utilized durable wood plastic composite (WPC) material to replace pressure-treated lumber in sill plates. Three different WPC sill prototypes were installed in full scale shear walls in order to evaluate and compare system performance of these wood-frame walls under full-scale shear wall testing. The intent of this study is to identify specific improvements in the prototypes’ structural shape, and to demonstrate a conceptual use of the durable wood-plastic material in a shear wall system versus walls constructed with traditional pressure-treated wood sills.

### 2. Methods and Materials

#### 2.1 Sill Plate Materials

Wood plastic composite material was extruded and machined into three different section profiles, shown with nominal dimensions, along with a traditional solid wood sill in Figure 1. Sections in Figure 1 all have approximately nominal 15 cm widths. Therefore, sections will be referred to by material type and nominal depth in centimeters (e.g. WOOD4 is a wood sill plate with nominal depth of 4 cm). Section and material properties are found in Table 1.

The solid deck board (PE3) is intended as a direct substitution for prescriptive wood sill plates. The hollow three-box (PP5) is also intended as a direct substitution, only using a more efficient section shape. The deeper hollow section (PP10) is intended to improve upon prescriptive shear wall design, incorporating hold-down behavior between end studs and sills, without the use of commercial hold-down fasteners. This section was developed and modified to most significantly improve traditional end-grained nailing and reduce sill plate splitting in shear walls.

#### 2.2 Prototype WPC Sill Plate PP10

The designed WPC prototype sill is based on a conceptual L-shaped cross section as illustrated in Figure 2. Ideally, the bottom sill surface would be 38-mm thickness and the side section would stand 152-mm to replicate the thickness of traditional wood sills and provide additional clearance for the bottom sheathing edge, respectively. The section also provides additional connection...
options between studs and sills to obtain higher performance levels than rectangular sill sections. The prototype sill plate incorporates the hold-down resistance necessary for engineered design within the stud-to-sill connections.

PP10 members were machined to create slots at stud locations providing the necessary space for traditional length studs and an ability to fasten through sill side walls into stud edges. The conceptual L-section is located at stud locations and does not have dimensions exactly equal to the intended design, as the tested prototype used previously developed cross-sections. Uplift resistance was provided by the lateral resistance of fasteners installed through the sill side into the studs, perpendicular to stud lengths, improving upon traditional end nailed connections which have negligible withdrawal/uplift resistance. Calculations based on simple mechanics’ assumptions
indicated that the highest stresses induced in typical sill plate loading will occur in tension perpendicular-to-extrusion direction at these connections.

The PP10 sill plate design used in shear wall tests shown in Figure 3 was based on previous component testing by DuChateau (2005) that identified highest capacities resulting from:

- Connections having maximum edge distances,
- Connections having minimal sidewall penetrations,
- Shifted end stud configurations with dowel attachment between studs and sills, and
- Reinforcement installed between flanges and webs of WPC sections.

Figure 3 Component design: a) Full section, b) End stud detail

2.3 Specimen Fabrication

Framing for each wall specimen consisted of 50 mm x 152 mm nominal Douglas-Fir, graded No. 2, No. 1, or machine rated to 1950 Fy 1.7 E or 2100 Fy 1.8 E. All lumber was purchased at the local building supply. Each wall configuration was named a different test group based on its unique sill plate. Four different sill plate types were used for walls, each having different thicknesses due to using previously produced sections. Details of the one-sided sheathed specimen construction are available in DuChateau’s thesis (2005). The dimensions for sill plates, studs, and sheathing for each wall type, as well as for end stud and anchor bolt locations, are listed in Table 1.2.

2.2 Testing Procedure

Monotonic tests followed ASTM E564 (2000), loading walls at 15 mm/min. One monotonic test was performed for each test group to determine the reference displacement for following cyclic test
methods. Test methods were altered to apply a constant displacement rate until failure (80% peak load capacity), eliminating sequences of loading and unloading as directly specified in the standard.

Cyclic tests followed ASTM E2126-02a Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Framed Walls for Buildings (2002), following the CUREE-Caltech Standard Protocol (CUREE). Two cyclic tests were completed for each test group, and the details of the test fixture and boundary conditions are presented in DuChateau (2005).

3. Results

3.1 Monotonic Results

Monotonic results for all test groups are located in Figure 4. WOOD4-M, PE3, and PP5 all exhibited rigid body rotation with sheathing and studs “unzipping” from the sill plate. The sill plate developed a longitudinal split along the length for WOOD4-M, where as PE3 and PP5 failed in flexure at the anchor bolt locations. PP5 exhibited brittle behavior and developed a longitudinal split along its processing strands in addition to the flexural failure. PP10 exhibited more racking behavior than the previous three shear wall types and failed in flexural at the end stud location. Dowels used to transfer the uplift force from the end stud to the sill plate yielded before sill failure. All shear walls with WPC sill plates had sheathing fasteners that either bent (PE3) or tore through the sheathing or sill (PE3, PP5, PP10). The shear wall with the wood sill was unable to stress the sheathing connectors as the sill plate failure occurred first.

Based on the monotonic performance parameters summarized in Table 2, composite sill plates prove to be competitive with traditional treated-wood sill plate behavior. Compared to traditional wood walls, load capacities at peak and failure increased for Tests PP5-M and PP10-M. Consequently, peak shear capacities increased, upon which wall design values are established. Test PP10-M reaches an ultimate shear capacity of 9.7 kN/m, while a traditional wood wall without hold-down restraint reaches only 5.2 kN/m. For Test PP10-M, this equates to an ASD design capacity of 3.2 kN/m when assuming a factor of safety of three between ultimate and design. This would place the performance on the lower end of engineered wall unit shear capacities from the NDS, but it also is almost double the value observed for the prescriptive configuration for light-frame construction. Comparing to previous shear wall testing using the information in Table 2, the capacity attained in wall PP10-M is close in value to those walls with full anchorage tested by Salenikovich (2000) but with lower deflection capacities and stiffness.
Table 2 Monotonic test summary of performance parameters

| Test ID   | Load (kN) | Yield | Peak | Failure | Yield | Peak | Failure | Deflection (mm) | $D_o$ (mm/mm) | $k_e$ (kN/mm) | $E$ (kN-mm) | $V_{peak}$ (kN/m) | $\Delta_{ref}$ (mm) |
|-----------|-----------|-------|------|---------|-------|------|---------|----------------|----------------|----------------|-------------|--------------|--------------|--------------|
| WOOD4-M   | 11.2      | 12.7  | 10.1 | 11      | 32    | 63   |         |                | 5.98           | 1.07           | 643.2       | 5.2          | 41           |
| PE3-M     | 10.4      | 11.7  | 9.4  | 7       | 21    | 56   |         |                | 8.39           | 1.57           | 548.4       | 4.8          | 35           |
| PP5-M     | 13.3      | 15.8  | 12.7 | 8       | 17    | 24   |         |                | 2.92           | 1.59           | 268.4       | 6.5          | 18           |
| PP10-M    | 21.1      | 23.5  | 18.8 | 23      | 54    | 55   |         |                | 2.42           | 0.93           | 923.7       | 9.7          | 36           |
| Salenikovich (2000) | 24.2 |       |      |         | 73    | 107  |         |                |                | 1.6            |             |              |

Top wall displacement measures account for lateral displacement due to uplift and lateral displacement due to racking. The latter may be estimated by subtracting the tension chord uplift measure from total wall top displacement to remove the rigid body motion deflection. Comparing this measure versus wall displacement in Figure 5, it can be concluded that Test PP10-M exhibits substantially more racking movement, which increases at a linear rate. This is consistent with damage observations unique to Test PP10-M, having more sheathing fasteners yielded and visible sheathing movement relative to studs. The majority of top wall displacement for Tests WOOD4-M, PE3-M, and PP5-M are contributed to uplift of wall ends from rigid body rotation. The deformation pattern of Specimen PP10-M is more desirable as it results in a more distributed damage pattern by activating more of the structure and increases the damping effects of the system when cyclic loading occurs.

3.2 Cyclic Results

A summary of average cyclic test parameters is presented in Table 3. Similar to monotonic tests, the first three wall types (WOOD4-M, PE3, PP5) exhibited primarily rigid body motion under cyclic loading. WOOD4 failed when the sill split along the grain. Nail withdrawal was contained to the bottom row of fasteners. PE3 failed in flexural as the sill was lifted at each stud connection and restrained at the anchor bolts. The amount of nail withdrawal was greater than WOOD4, but still contained to the bottom row of fasteners. PP5 exhibited brittle failure from longitudinal splitting, followed by flexural failure at the anchor bolt locations. Cross-grain bending was still apparent in this composite sill behavior. PP10 exhibited the most racking deformation, as represented by the increase in sheathing fastener damage. Nails withdrew for the bottom 25% of the side row of fasteners. Instances of nail fatigue and fracture were observed. Dowels connecting the end studs to the sill yielded substantially and preceded flexural failure at the end stud slots.
### 3.3 Sill Type Comparison

Use of a WPC material as a sill plate can improve the shear wall performance under lateral loads. The following discussion compares the performance of various wall configurations based upon observed failure mechanisms and calculated performance parameters.

Cyclic test results of walls with a solid polyethylene sill may be compared to that of traditional walls with treated-wood sill plates in WOOD4. Similar loads, and therefore shear strengths (10% increase), were achieved. Though with a combination of increased yield displacement (40%), decreased maximum and ultimate displacements, and decreased elastic shear stiffness, the wall ductility was reduced as compared to wood sill walls. Attributable to lowered displacement capacities, energy dissipation from cycles up to failure decreased by almost 40% for walls with a polyethylene WPC sill. This section, if having equivalent thickness to 38-mm (nominal 2x) wood sill plates could potentially have a larger improvement in performance, due to increased flexural resistance of the sill plate.

PP5 test results show improved load capacities--50% over that of WOOD4 walls. Similar to PE3 improvements, yield displacements of PP5 walls increased by at least 50%. With a decrease in maximum and ultimate displacements due to more brittle failures, the ductility was reduced tremendously. As expected from such brittle failure, energy dissipation decreased by 40%. Despite these disadvantages, walls with the three-box polypropylene section were able to provide over 50% more shear strength than the traditional wood sill plate. To capitalize on this wall configuration’s improved shear strength, weaknesses in the perpendicular-to-extrusion direction in the section must be addressed to provide desirable earthquake performance. Surface reinforcement, section profile changes, or elimination of die stranding all might improve behavior.

### 4. Conclusions

Tests have demonstrated the effect of using durable wood plastic composites as a structural member in a full-scale wood shear walls. By achieving results comparable to fully restrained walls, WPC material can be utilized effectively in structural applications under dynamic loading. The following conclusions highlight each section’s distinguishing behavior and performance implications.

- Solid polyethylene sill plates prove to be feasible as substitutes for walls with traditional wood sill plates without hold-downs.
- A polypropylene three-box section requires section improvement to avoid brittle behavior and widespread damage before being fully utilized as a sill plate in cyclic applications.

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**Table 3 Cyclic Wall Performance parameters**

<table>
<thead>
<tr>
<th></th>
<th>WOOD4</th>
<th>PE3</th>
<th>PP5</th>
<th>PP10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum absolute load, P_{peak}</strong></td>
<td>10.8</td>
<td>11.9</td>
<td>16.9</td>
<td>28.6</td>
</tr>
<tr>
<td><strong>Maximum absolute displacement, Δ_{peak}</strong></td>
<td>29</td>
<td>20</td>
<td>20</td>
<td>44</td>
</tr>
<tr>
<td><strong>Failure Load, 0.80*P_{peak}</strong></td>
<td>8.6</td>
<td>9.5</td>
<td>13.5</td>
<td>22.9</td>
</tr>
<tr>
<td><strong>Ultimate Displacement, cyclic, Δ_u</strong></td>
<td>45</td>
<td>35</td>
<td>25</td>
<td>77</td>
</tr>
<tr>
<td><strong>P_{yield}</strong></td>
<td>10.0</td>
<td>10.9</td>
<td>14.7</td>
<td>26.2</td>
</tr>
<tr>
<td><strong>Yield Displacement, cyclic, Δ_{yield}</strong></td>
<td>5</td>
<td>7</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td><strong>Shear Strength, v_{peak}</strong></td>
<td>4.4</td>
<td>4.9</td>
<td>6.9</td>
<td>11.7</td>
</tr>
<tr>
<td><strong>Secant Shear Modulus, G' @ 0.4P_{peak}</strong></td>
<td>1.8</td>
<td>1.5</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>D, Δ_{peak}/Δ_{yield}</strong></td>
<td>5.3</td>
<td>2.7</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>D_{ur}, Δ_{failure}/Δ_{yield}</strong></td>
<td>8.1</td>
<td>4.7</td>
<td>2.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>

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• A polypropylene 102-mm x 152-mm (4x6) hollow section (PP10) engaged full wall elements, exhibiting racking behavior and achieving a design shear capacity of 3.2 kN/m (220 plf) from monotonic loading, which makes the load capacity equal to the lower strength walls designed according to the NDS. This load capacity essentially doubles the strength of prescriptive construction. (load capacity increased by 160% over current prescriptive construction) This configuration resulted in load capacities in the lower range of engineered wood-framed walls.

• Walls having WPC sill plates show improved capacities when loaded under cyclic loading versus monotonic (up to 20% increase in peak capacity for PP10), contributable to different load distribution among sheathing fasteners as compared to walls with solid wood sill plates.

Acknowledgments

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References


