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DEMONSTRATING LATERAL SYSTEM EQUIVALENCE OF A NOVEL MASS TIMBER MATERIAL THROUGH A FEMA P795 METHODOLOGY

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ABSTRACT: A test program was designed and implemented to demonstrate equivalency of a novel veneer-based mass timber material (SCP) to the cross-laminated timber (CLT) shear wall system currently in the code in the US. To characterize lateral performance, reverse cyclic tests were performed on full-scale 2.44 m by 2.44 m walls using steel connectors prescribed in the 2021 Special Design Provisions for Wind and Seismic (SDPWS). Three different materials, the novel veneer-based panel and two CLT layups with different species, and two panel aspect ratios, 2:1 and 4:1, were investigated. Additionally, the walls were tested on a steel base and load beam to better standardize the testing approach, compared to the previous research that used a CLT base and load beam. Equivalency was determined following the FEMA P795 methodology. The walls exhibited higher strength and displacement capacity at the 4:1 panel aspect ratio compared to the 2:1 panel aspect ratio for all materials. The novel material met equivalence parameters at a 2:1 panel aspect ratio with the Code prescribed nail and met equivalence at both aspect ratios with a shorter nail.

KEYWORDS: Veneer-based mass timber, Equivalency, Lateral Force-Resisting System, FEMA P795, SDPWS

1 INTRODUCTION AND BACKGROUND

As mass timber has grown in prominence in the built environment, there has been increased interest in new mass timber materials. One area that has seen a large area of growth is veneer-based mass timber materials. Veneer-based mass timber has benefits over traditional lumber-based Cross-Laminated Timber (CLT) and glued laminated timber. The use of veneer allows for more efficient use of wood material compared to lumber, as both smaller size logs and more of each log can be converted into a structural product. Additionally, the process of peeling veneer and reassembling it into a structural panel creates more consistent mechanical properties and reduces discontinuities in the material. While laminated veneer lumber (LVL) panels were used in the 2010s for mass timber structures in New Zealand [1], a separate veneer-based mass timber material, Mass Ply Panels (MPP), gained usage in the United States in the late 2010s. MPP has some veneer plies oriented in orthogonal directions, which increases properties in the weak spanning direction. This material was investigated for lateral systems, ranging from small scale testing [2], to full scale tests [3,4]. MPP has been qualified as a CLT under APA PRG 320 [5].

Within this context a new veneer-based mass timber material recently entered the market, utilizing 27 mm hot-pressed billets, each with nine total plies and one cross-ply in the center, laminated together in a cold press to thicker sections. This mass timber product is composed of Douglas-fir veneers and has been termed in the literature as Structural Composite Panel (SCP). This SCP has been qualified as a CLT under APA PRG-320 [6].

At the same time as this growth in the market of new mass timber materials, large strides have been made with lateral-force resisting systems in mass timber. While much of the attention has been paid to performance-based design and low damage systems, such as post-tensioned rocking walls [1,3,7,8,9], much has changed over the last decade with conventional wall systems. The largest change, within a North American context, has been the codification of a prescriptive CLT wall design in the

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Special Design Provisions for Wind and Seismic (SDPWS) [10] through a FEMA P695 methodology [11]. This project, from van de Lindt et al. [12], utilized two types of plate steel connectors with commodity nails, combined with testing and modeling to create design requirements.

The two connectors described in the 2021 SDPWS, a floor-to-wall connector and an inter-panel connector have been investigated for other materials and circumstances. Studies have characterized the behavior of the floor-to-wall connector under a variety of environmental conditions: including elevated temperature [13], moisture intrusion [14], and fungal decay [15]. The performance of both the floor-to-wall and inter-panel connectors using the above-mentioned SCP as the mass timber material were investigated using reverse-cyclic loading on the component scale [16]. When compared to the original study, this study found lower ductility and initial stiffness, but slightly higher strength and comparable displacement capacity for both connectors. These results suggested that a full shear wall system using the target SCP could likely have equivalent performance to the tested CLT.

2 – PROJECT DESCRIPTION

This study aimed to demonstrate the equivalency of SCP shear walls and CLT shear wall systems in the 2021 SDPWS. An additional purpose of this study was to standardize the experimental approach for equivalency within this specific context. This goal was completed through full-scale experimental testing of both SCP and CLT shear walls at two panel aspect ratios (2:1 and 4:1). Equivalency was demonstrated through the FEMA P795 methodology [17] by comparing the results of this study with the results from the original system. The objectives of this study are two-part. First, demonstrate equivalency of SCP shear walls with CLT shear walls when designed and detailed following the 2021 SDPWS [10]. Second, assist in the standardization of demonstrating equivalency to the SDPWS prescriptive wall methodology through the use and analysis of a consistent steel base and top loading beam, compared to the CLT base and load beam used in the original study that utilized FEMA P695[12].

Table 1: Wall Test Matrix

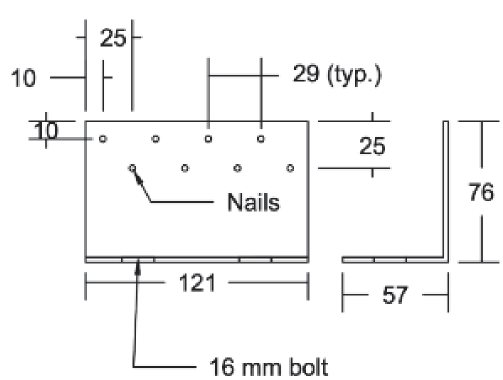
Name	Material	Panel Aspect Ratio	Nail	Replicates
SPF_2	SPF CLT	2:1	16d box[1]	2
SCP16_2	SCP	2:1	16d box	2
SCP10_2	SCP	2:1	10d box[2]	2
SPF_4	SPF CLT	4:1	16d box	2
SCP16_4	SCP	4:1	16d box	2
SCP10_4	SCP	4:1	10d box	2

1. 16d box nails are 89 mm in length, 3.4 mm diameter
2. 10d box nails are 76 mm in length, 3.3 mm diameter

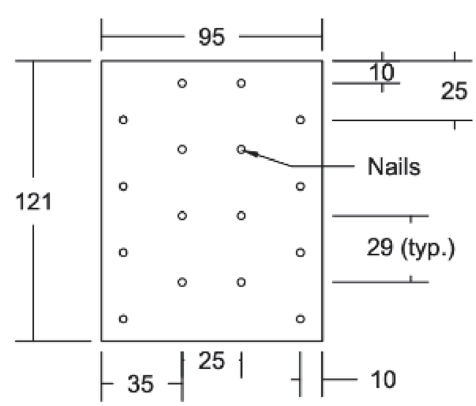
4 – EXPERIMENTAL SETUP

4.1 Experimental Methods

The experimental setup for this study involved primarily physical testing of full-scale SCP and CLT shear walls, in addition to analytical methods to allow comparison between the tests and with previous testing of the system. All wall tests used ASTM E2126 as a guide [18]. The physical testing involved 12 full-scale shear wall tests, with each tested wall having total dimensions of 2.44 m in width by 2.44 m in height (Table 1). The investigated SCP was four-ply in thickness (108 mm) with all individual plies having the same layup of Douglas-fir veneer. The CLT layup was five-ply (175 mm) spruce-pine-fir.



(a)



(b)

Figure 1: (a) A3 floor-to-wall connector front and side view and (b) IP inter-panel connector (dimensions in mm)

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All tests used the same steel connectors, the A3 floor-to-wall connector and adjoining panel edge connector (IP connector) prescribed in the 2021 SDPWS and the original P695 study. These connectors, shown in Fig. 1, are made from ASTM A663 12 Ga material (2.7 mm) [19]. The A3 connector connects the wall through 8 nails, and the floor through two 16 mm diameter bolts. The IP connector connects adjoining wall panels through a total of 16 nails, 8 in each wall panel. These connectors are designed to be the limiting fuse of the lateral system with ductility and resistance being governed by the yielding of the nails in the connection. The SDPWS prescribes the use of 16d box nails (89 mm in length, 3.4 mm diameter) for the connections. These nails were used in both A3 and IP connectors for all tests of the CLT layup, and for one set of tests each at each aspect ratio for the SCP. Additionally, for the SCP, additional testing was conducted using 10d box nails (76 mm in length, 3.3 mm diameter) for both panel aspect ratios. The purpose of these tests was to determine if the shorter length nail would allow for higher ductility and displacement capacity.

Two separate panel aspect ratios were considered for testing, defined by the limits within the 2021 SDPWS [10], 2:1 panel aspect ratio and 4:1 panel aspect ratio. The 2:1 panel aspect ratio case involved two paired panels, each measuring 1219mm wide by 2439 mm high. The two panels were adjoined by eight IP connectors. Shear was transferred into and out of the wall through 16 A3 connectors, 8 each at top and bottom of the wall, connecting the panels to the loading beam and to the base. The 4:1 panel aspect ratio case involved four wall panels per test, each measuring 610 mm in width by 2439 mm in height, adjoined along their vertical edges by eight IP connectors per wall seam. Similarly, (16) A3 connectors, 8 each at top and bottom of the wall, transferred the shear into the wall from the actuator and out of the wall at the base.

Figure 2: Shear wall test aparatus

The test apparatus, shown in Fig. 2, applied displacement to the shear wall using an 890 kN actuator with a stroke of +/- 254 mm. A built-up steel load beam allowed for connection from the actuator to the wall, while a wide-flange beam under the wall transferred shear and overturning into the strong-floor. Two pin-pin rods, spanning from the parallel strong-wall to the load beam, resisted the out-of-plane motion of the wall. To resist overturning, four (4) 25 mm Grade A307 rods [20], with two at each end of the wall, spanned from the base beam up to the load beam. These rods yielded during each test and new rods were installed for each test.

Reverse cyclic testing was conducted following the CUREE displacement protocol [21], shown in Fig. 3. A reference displacement of 25.4 mm was used for all tests, from prior testing in the related FEMA P695 study [12]. A cyclic testing rate of 0.025 Hz was used, resulting in cycles every 40 seconds. While other instrumentation was included, the primary instrumentation discussed in this study were the load-cell and integrated displacement sensor in the actuator to measure the story drift and shear. Data were recorded at a rate of 10 Hz.

4.2 Analytical Methods

The analytical methods employed in this study were primarily the extraction of the FEMA P795 parameters which were used to demonstrate equivalency following the FEMA P795 methodology [17]. These parameters were determined from the envelope of the hysteretic response, averaged between the positive and negative excursions into only the first quadrant. The FEMA P795 parameters, similar to those found in ASTM E2126 [18] that define the envelope, are defined as follows. F_{max} is the peak force of the envelope in kN. Δ_{Fmax} is the displacement at peak force in mm. Ki is the initial stiffness, defined as the secant stiffness between the origin and the point where the force is equal to 0.4 of

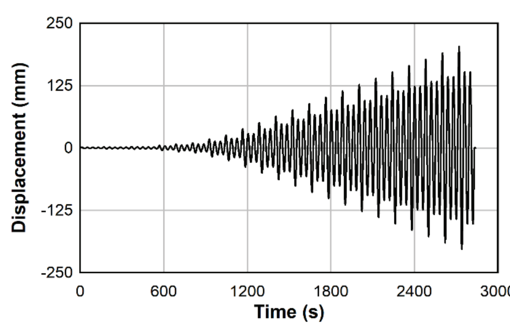

Figure 3: CUREE Protocol [21]

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F_{max}. Δ_{yeff} is the effective yield displacement, defined as F_{max} divided by K_i. Δ_u is the ultimate displacement capacity, defined as the first time the force drops below 80% of F_{max} on the descending branch of the response post-peak. Finally, μ_{eff} is the ductility, defined as the ratio between Δ_u and Δ_{yeff}.

Equivalence is then determined using the FEMA P795 parameters for the reference system (CLT shear walls made from SPF) with the parameters for the proposed system (CLT shear walls made from SCP). There are a total of four checks to be made per FEMA P795: ultimate displacement capacity, strength, stiffness, and ductility. These checks use four equations from FEMA P795 as follows.

The first check is between ultimate displacement capacity when using the proposed and reference components for the seismic force resisting system (SFRS). This performance check is shown in (1):

$$\Delta_{U,PC} \geq \Delta_{U,RC} P_U P_Q \tag{1}$$

Where $\Delta_{U,PC}$ is the ultimate displacement capacity of the proposed system, $\Delta_{U,RC}$ is the ultimate displacement capacity of the reference system, P_U is a penalty factor to account for uncertainty, and P_Q is a penalty factor to account for differences in strength between the proposed and reference system.

The second check is between the ultimate capacity of the proposed and reference systems. A penalty is applied, P_Q, if the values do not satisfy (2):

$$1.2 \geq \frac{R_{Q,PC}}{R_{Q,RC}} \geq 0.9 \tag{2}$$

Where $R_{Q,PC}$, is the strength of the proposed system and $R_{Q,RC}$, is the strength of the reference system.

The next check compares the initial stiffness of both systems to avoid any large differences in stiffness within a single lateral system and is given in (3):

$$1.33 \geq \frac{R_{K,PC}}{R_{K,RC}} \geq 0.75 \tag{3}$$

Where $R_{K,PC}$ is the stiffness of the proposed system, while $R_{K,RC}$ is the stiffness of the reference system.

The final check compared the ductility of the two systems. The proposed system must satisfy (4):

$$\mu_{eff,PC} \geq 0.5\mu_{eff,RC} \tag{4}$$

Where $\mu_{eff,PC}$ is the ductility of the proposed system and $\mu_{eff,RC}$ is the ductility of the reference system.

5 – RESULTS

The results are presented in three sections: hysteretic results from the experimental tests, FEMA P795 parameters and comparisons, and comparisons between results from this study with the original FEMA P695 study.

5.1 HYSTERETIC RESULTS

Representative hystereses for each test series are shown in Fig. 4. The 2:1 panel aspect ratio tests in general exhibited lower displacement capacity than the tests at 4:1 panel aspect ratio, which aligns with the original study from van de Lindt et al [12]. The tests of SPF CLT and the SCP with 16d box nails exhibited similar responses, both reaching peak force on the cycle leading to 64mm and exhibiting failures on the proceeding major cycle. The failure mode for these tests were nail withdrawal and fracture of the A3 connectors at the top of the wall. The SCP with 10d box nails did not exhibit this trend, with failure occurring on the negative direction of the cycle with a peak displacement at approximately 100 mm. The likely cause of this increased displacement and strength capacity was due to the 10d box nails exhibiting higher withdrawal prior to failure, including damage to the top and base of the wall. The higher displacements corresponded to larger uplifts that could have caused an additional friction force along the top and base of the wall, increasing the shear.

The 4:1 panel aspect ratio tests exhibited higher variance between test series. The SPF CLT reached peak load and showed very slow degradation of capacity, still being above 80% of maximum capacity at almost 8% story drift. It was presumed that much of this post-peak capacity can be attributed to the friction developed between the steel fixturing and the shear wall as it rocked. This would help to explain the almost asymptotic behavior of the SPF CLT, since neither the material nor the connections exhibited sudden fractures or losses in capacity. The increased rocking at higher displacements could generate large overturning forces and related friction.

The SCP shear wall tests suggested that a higher density material resulted in increased strength and reduced displacement capacity at the 4:1 panel aspect ratio, when compared to lower density SPF CLT. The tests with 16d box nails exhibited failures primarily through fracture of the nails, rather than through withdrawal and continued yielding of the nails. While the connections could resist higher forces in the SCP, the sudden fracture contributed to lower ductility and displacement capacity for the system. The 10d box nail tests with SCP exhibited more

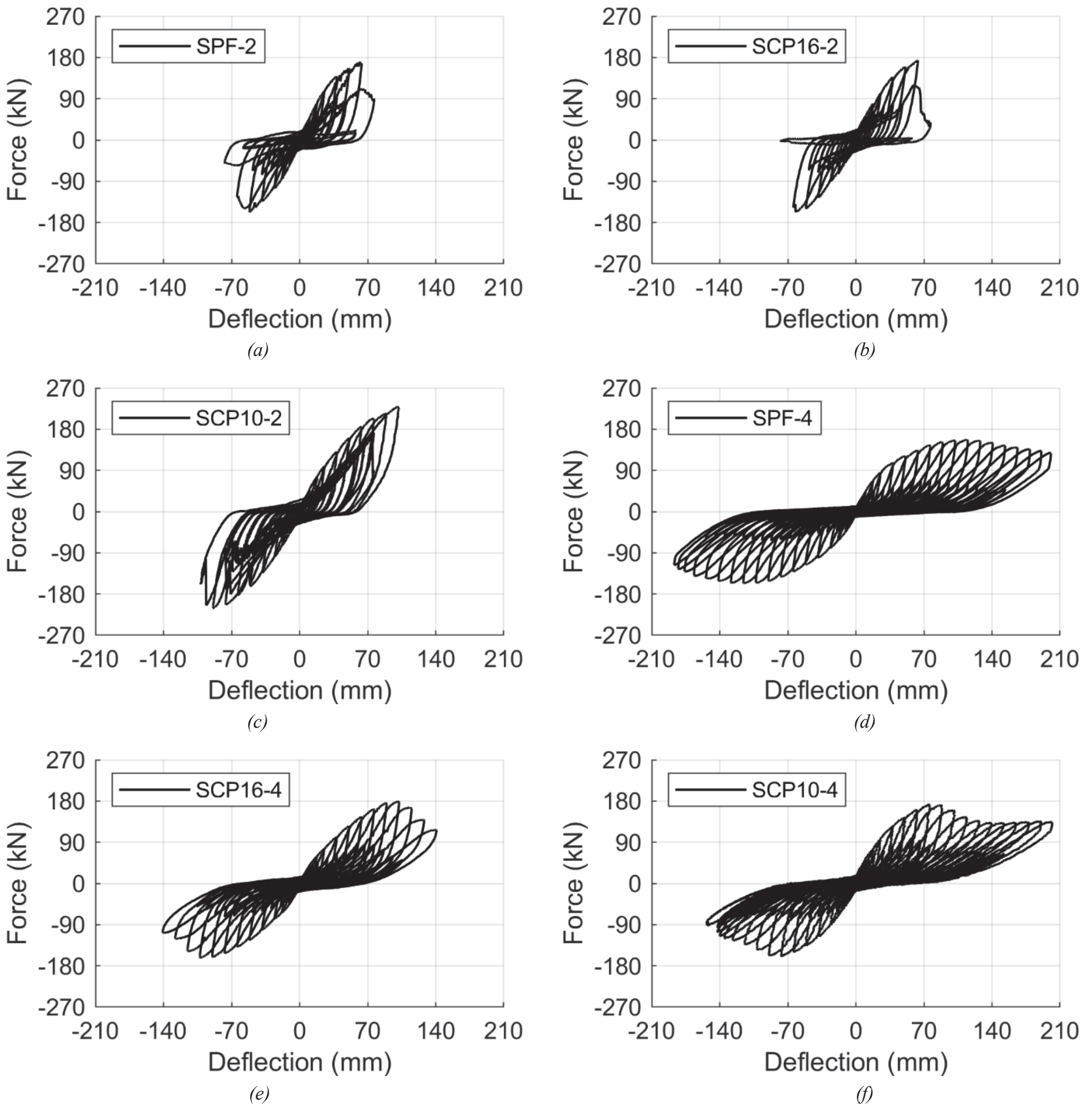

Figure 4: Representative wall test hystereses for (a) 2:1 aspect ratio SPF CLT wall, (b) 2:1 aspect ratio SCP wall with 16d box nails, (c) 2:1 aspect ratio SCP wall with 10d box nails, (d) 4:1 aspect ratio SPF CLT wall, (e) 4:1 aspect ratio SCP wall with 16d box nails, and (f) 4:1 aspect ratio SCP wall with 10d box nails.

nail withdrawal than the comparable 16d box nail tests, with higher displacement capacity and a slower loss in capacity post-peak.

5.2 FEMA P795 RESULTS

The FEMA P795 parameters were extracted from the envelope curve of each test averaged between the positive and negative excursion to be expressed purely in the first quadrant. Average plots of these envelopes for 2:1 and 4:1 panel aspect ratios can be seen in Fig. 5. These envelopes highlight the findings discussed in the previous discussion on the hysteretic results.

The median FEMA P795 parameters for all test series are shown in Table 2. These parameters highlight the similarities at the 2:1 panel aspect ratio for initial stiffness between all test series, and the similarities in both strength and displacement capacity between the SPF CLT and SCP with 16d box nails. The 4:1 panel aspect ratio parameters show the effect of specific gravity on strength and stiffness, comparing between the SPF CLT (with a specific gravity of 0.42) and the other SCP, composed of Douglas-fir (with a specific gravity of 0.5).

The four checks in FEMA P795 mentioned previously were then made between the SCP tests and the SPF CLT tests at the same aspect ratios. An example comparison table is shown in Table 3. At the 2:1 aspect SCP walls with both 16d box and 10d box nails were equivalent to

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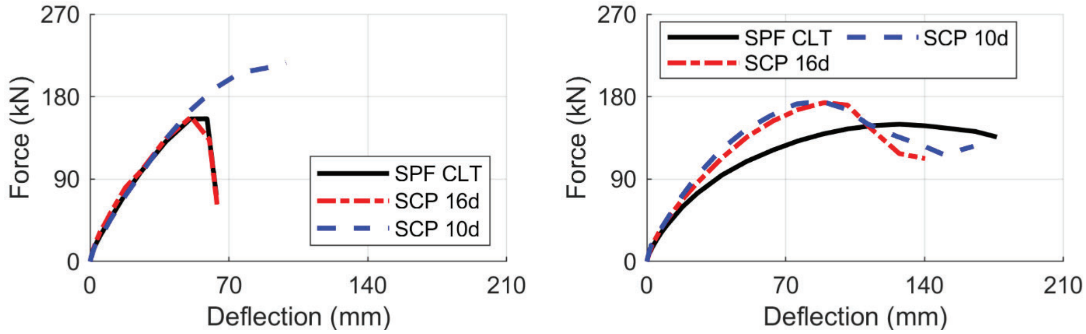

(a) *(b)*

Figure 5: Positive average envelope curves for (a) 2:1 aspect ratio wall tests and (b) 4:1 aspect ratio wall tests

Table 2: FEMA P795 Parameters

Test Series	Test	Ki (kN/mm)	Δ_{yeff} (mm)	Fmax (kN)	Δ_{Fmax} (mm)	Δ_u (mm)	μ (mm/mm)
SPF_2	1	4.74	33.8	160.1	59.4	61.2	1.82
	2	3.79	40.6	154.2	50.5	59.9	1.48
	Median	4.27	37.1	157.1	54.9	60.7	1.65
SCP16_2	1	4.42	37.6	165.6	62.5	63	1.68
	2	5.18	31	161	51.1	54.6	1.75
	Median	4.8	34.3	163.3	56.9	58.7	1.72
SCP10_2	1	3.96	54.9	217.3	98.8	98.8	1.8
	2	3.74	56.1	209.8	88.4	88.4	1.57
	Median	3.85	55.4	213.6	93.5	93.5	1.69
SPF_4	1	3.63	43.2	156.8	113.8	134.1	3.11
	2	2.9	50	145.2	153.2	134.1	2.68
	Median	3.27	46.5	151	133.4	134.1	2.89
SCP16_4	1	4.17	42.7	178.4	89.4	109.5	2.56
	2	3.19	53.6	171	100.8	123.4	2.3
	Median	3.68	48.3	174.7	95.3	116.6	2.43
SCP10_4	1	3.94	47.2	185.7	87.4	120.9	2.57
	2	4.29	38.6	165.7	75.4	123.2	3.19
	Median	4.12	42.9	175.7	81.5	121.9	2.88

SPF CLT walls. The SCP with 10d box nails exhibited higher strength, above the limitation in FEMA P795, however the difference was similar to variations seen between CLT grades in the original P695 study [12]. The 4:1 panel aspect ratio tests of the SCP with 16d box nails did not meet FEMA P795 equivalence criteria due to the lower displacement capacity. The SCP with 10d box nails also did not pass this displacement capacity check, though the wall exhibited a much slower force degradation and did not exhibit any sudden failures. Additional modeling and analyses using the FEMA P695 methodology demonstrated improved collapse performance of the SCP wall with 10d box nails compared to the SPF CLT and was used in addition to the FEMA P795 parameters to demonstrate equivalence.

5.3 ORIGINAL P695 STUDY COMPARISONS

Part of the impetus to this study was to investigate mass timber shear walls with a steel base. The original FEMA P695 study used a CLT base and load beam made from spruce-pine-fir. Moving forward with testing of a broader range of species and products, using steel top and bottom fixtures allows for a more standardized approach, focusing on the shear wall rather than the entire system. However, this change to the shear wall boundary conditions does cause some changes in the response. Table 4 compares the FEMA P795 parameters of 4:1 panel aspect ratio wall tests using SPF CLT. Both tests had the same number of connections and dimensions. The two differences between the tests are the base conditions, as mentioned above, and the rod diameter changing from

Table 3. Comparison of FEMA P795 parameters between results of this study with steel base and loading beam and previous testing of same system with CLT base and loading beam [12]

Check	Proposed System	Reference System	Ratio	Pass/ Fail
Displacement Capacity (mm)	93.5	60.7	1.54	Pass
Overstrength (kN)	213.6	157.1	1.36	Pass
Stiffness (kN/mm)	3.85	4.27	0.9	Pass
Ductility (mm/mm)	1.69	1.65	-	Pass

16 mm to 25 mm. The change from a CLT to steel base appeared to change the structural response of the wall. The steel base tests exhibited higher stiffness and strength than the test on a CLT base. The steel base also reached both yield and peak forces at larger displacements. While the table shows a disparity in the displacement capacity, this is in part due to this study evaluating the parameter at a 5.5% drift limit, which was also defined in the previous study but not applied to the parameters [12]. This change would also result in both methods exhibiting the same displacement capacity and lower the difference in the ductility. The rod change would help explain some of the difference in stiffness, as the larger rod increases the overturning resistance of the system. These comparisons suggest that, while higher capacities were noted, using a steel base would be suggested for future testing looking to demonstrate equivalence between novel systems and existing codified mass timber lateral force-resisting systems.

6 – CONCLUSION

An experimental program investigated different mass timber materials used in a shear wall system with connectors outlined in the 2021 SDPWS. This testing demonstrated the equivalence of a novel veneer-based mass timber panel (SCP) shear wall system, with the CLT shear wall system when following the SDPWS provisions, though with the SCP requiring a slightly shorter nail, a 10d box nail (64 mm) compared to a 16d box nail (89 mm). This equivalence was determined following the procedures in the FEMA P795 methodology. The following other conclusions were made:

- There appears to be a positive relationship between mass timber specific gravity and both stiffness and strength capacity of shear walls using the connection system described in the SDPWS at a 4:1 panel aspect ratio.
- Little difference was noted between a veneer-based mass timber panel (SCP) and SPF CLT at the 2:1 panel aspect ratio, suggesting that the geometry of the panel may have a larger effect than the material strength.
- The FEMA P795 methodology highlighted that the SCP was equivalent to the SPF CLT at the 2:1 panel aspect ratio for both fasteners in the SCP, and equivalent at the 4:1 panel aspect ratio when the SCP panel used 10d box nails for the connectors in the SDPWS.
- Comparisons between tests of SPF CLT using CLT bases and steel bases show higher strength and stiffness for the case with the steel base, without any meaningful reductions in displacement capacity. This suggests that consistent testing on steel base is a valid option to demonstrate equivalence of other existing and emerging mass timber materials or novel connection systems.

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Table 4. Comparison of FEMA P795 parameters between results of this study with steel base and loading beam and previous testing of same system with CLT base and loading beam [12]

Test Series	Ki (kN/mm)	Δ_{yeff} (mm)	Fmax (kN)	Δ_{Fmax} (mm)	Δ_u (mm)	μ (mm/mm)
SPF_4	3.27	46.5	151.0	133.4	134.1	2.89
van de Lindt et al. (2022) [12]	2.84	37.6	106.9	113.5	165.1	4.39

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