Design and Evaluation of a Shear Analogy Tool for Custom Cross-Laminated Timber (CLT) Panels Made from Various Wood Species

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Abstract

A user-friendly cross-laminated timber (CLT) design tool called SAM-CLT was developed to calculate the minimum design values for custom CLT panels. Custom panels are those made from different species not currently included in APA PRG 320 and include the use of multiple species in a panel. The tool uses the design value of hardwood and softwood lumber published in the national design specification book to design custom CLTs and the standard CLT grade lumber specification values published in PRG 320 standard. SAM-CLT was designed based on the shear analogy model and is intended to assist CLT manufacturers, construction and design companies, and researchers in designing and evaluating CLTs' deformation when using different lumber types and thicknesses. This project included the calibration and validation of the tool, followed by examples of its use by computing the design value of the softwood, hardwood, and softwood–hardwood hybrid CLTs. The SAM-CLT tool was adjusted to match the published standard design values on PRG 320 and validated by comparing output for standard CLT layups. In the next step, SAM-CLT tool was used to calculate the minimum design value of custom CLTs made from hardwood–yellow poplar lumber and softwood–southern yellow pine lumber. Based on observed validation results of the tool and its application results to determine the design values for various CLT layups, this project concludes that SAM-CLT can be a valuable tool for designing custom CLTs, evaluating CLTs' strength properties, and promoting heterogeneous lumber types in CLT manufacturing.

The positioning and types of lumber used in the cross-laminated timber (CLT) layers determine the performance across their cross-section. Different values of shear moduli over the cross-section of the CLT layers also result in behavioral changes—its performance under applied load—in the out-of-plane shear (Niederwestberg et al. 2018, APA 2019); thus, arrangements of the layers have significant importance in maintaining the structural integrity of the structure when designing CLT (Buka-Vaivade et al. 2017). The orientations of different layers of the panel affect the stiffness and stresses within the cross-section of the CLT. The shear properties of CLT are due to the perpendicular layers and act perpendicular to the grain of the lumber (Niederwestberg et al. 2018). The shear force perpendicular to the grain is also known as rolling shear, and when CLT is exposed to out-of-plane bending, one of the most common failure modes is the rolling shear (Brandner et al. 2016).

As designers and builders continuously increase the use of CLTs in mid- and high-rise structures, consumers are also interested in having different species of lumber on CLTs. For the successful design of a CLT structure, it is significant to know the impact of lumber variation on CLT layers on the performance of the CLT panels under applied load and guarantee that it does not compromise the structural integrity.

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Using various species of lumber in CLT manufacturing requires a detailed analysis of the CLT elements and specific performance value of CLTs for all kinds of forces applied on the structure that translated into the panels based on expected load types and load intensity. There are four different analytical design methods for the CLT elements, which are Mechanically Jointed Beams Theory (Gamma Method), Composite Theory (k Method), Shear Analogy (Kreuzinger), and Simplified Design Methods (FPInnovations 2011).

The latest version of the North American CLT standard PRG 320-2019 (ANSI/APA 2019) uses shear analogy methods to estimate the design value for shear deformation of the CLT panels. The shear analogy method states that the middle slab's maximum deflection under a uniformly distributed load can be calculated as a sum of the deflection contribution due to the shear and bending (Kreuzinger 1999). The shear analogy method considers the different moduli of elasticity and shear moduli of the individual layers (Kreuzinger 1999, Niederwestberg et al. 2018). Thus, the shear analogy method is regarded as one of the most precise methods for analyzing the shear deformation of the CLT panels (Buka-Vaivade et al. 2017).

PRG 320 permits using different lumber species in a single panel for different layers of CLT as long as they have similar mechanical and strength properties. Thus, manufacturers can use a mixture of species in a single CLT panel (ANSI/APA 2012). However, this standard excludes lumber from hardwood species. The revised PRG 320 in 2019 (ANSI/APA 2019) also does not recognize hardwood lumber as raw material. With the rise in interest in using lumber from different species and the need for an adequate and sustainable supply of raw materials, CLTs from hardwood lumber could be substituted for softwood lumber (Grasser 2015). In the United States, hardwood has been used to manufacture custom CLTs for nonstructural applications using various species of lumber, including red oak (*Quercus rubra*), white oak (*Q. alba*), beech (*Fagus* spp.), soft maple, and hard maple (Adhikari et al. 2020). Yellow-poplar (*Liriodendron tulipifera*) is the only hardwood species used to produce CLTs for structural application in Europe (AHEC 2019). A train observatory constructed in Radford, Virginia, was the first structural application of hardwood CLT made from yellow-poplar lumber in the United States (Adhikari 2020). Maggie's Centre, a specialist cancer center in the north of England, was completed as the first hardwood CLT building globally and was constructed using yellow-poplar lumber (Adhikari et al. 2021). It was registered as the first application of hardwood CLTs in engineering construction (AHEC 2019). CLTs used for these structures were manufactured as custom CLTs, and individual companies or organizations produced the design values for their structure and got approval from local authorities. These structures indicate the feasibility of producing hardwood CLTs for structural use, but there is no information on the minimum design values for custom CLTs using hardwood species.

CLT manufacturers could use hardwood and softwood and their mix to manufacture structural-rated CLT panels, which ultimately add variation to the product and presumably its strength and helps to attract more consumers if hardwood is accepted by PRG 320 standard. Hardwood lumber can be used to manufacture custom CLTs (even though it is not included in the PRG320 standard) by getting approval from local building code authorities. There are no published data to help design these custom CLTs using hardwood and hybrid CLTs using softwood and hardwood species. Developing design specifications for multiple combinations of lumber needs rigorous calculation and is time-consuming. Thus, this project aimed to create an Excel-based user-friendly tool called SAM-CLT, which is based on the shear analogy model and can be used to determine the minimum design values (ANSI/APA 2012) for custom CLT made from various wood species, as published in the national design specification (NDS). The Engineered Wood Association (APA) has published design values only for homogeneous lumber combinations for softwood CLTs, but there is no information for the heterogeneous combination, although it recognizes the use of heterogeneous combinations. SAM-CLT is intended to assist CLT industries, construction and design companies, researchers, and other interested public in evaluating different types of custom CLTs: softwood-only, softwood–softwood hybrid, hardwood-only, hardwood–hardwood hybrid, and hardwood–softwood hybrid CLTs and make it publicly available to facilitate its widespread use. Thus, the objectives of the project were (a) to design an Excel-based shear analogy tool that can accommodate different lumber types and thicknesses to publish minimum design values and make it publicly available; and (b) to evaluate the strength properties of the yellow-poplar (YP) CLT and its hybrid using southern yellow pine (*Pinus echinata*; SYP) lumber as an example species.

Methodology

This project was completed in three major steps: the SAM-CLT tool was first designed, then calibrated and validated, and finally, the design value of the SYP-CLTs, YP-CLTs, and YP-SYP hybrid CLTs was evaluated.

Design of the SAM-CLT tool

SAM-CLT tool was designed to calculate the various design values for shear deformation of a custom CLT panel. It utilizes the strength properties of the lumber as input for lumber types selected by users for both strength directions of the CLT panel. VLOOKUP command in Excel was utilized to extract the strength value of the user-selected lumber species from the NDS database attached to this tool. The strength value from the NDS for the lumber was used to calculate shear deformation and populated into the "Result Tab." Thus, obtained design values were plotted against published PRG 320 values of various CLT grades and updated in the "Comparison Graph." The overall workflow of the tool is presented in Figure 1.

The configuration layups and orientation of the lumber for the major and minor directions for the custom CLT as an example, are shown in Figure 2. The design layups and calculation parameters for CLT and lumber thickness from the centroid of the custom CLTs are shown in Figure 3.

Engineering formulas used to determine the CLT design values are based on the shear-analogy model and were adopted from the 2019 revised version of the PRG 320 standard and were listed below.

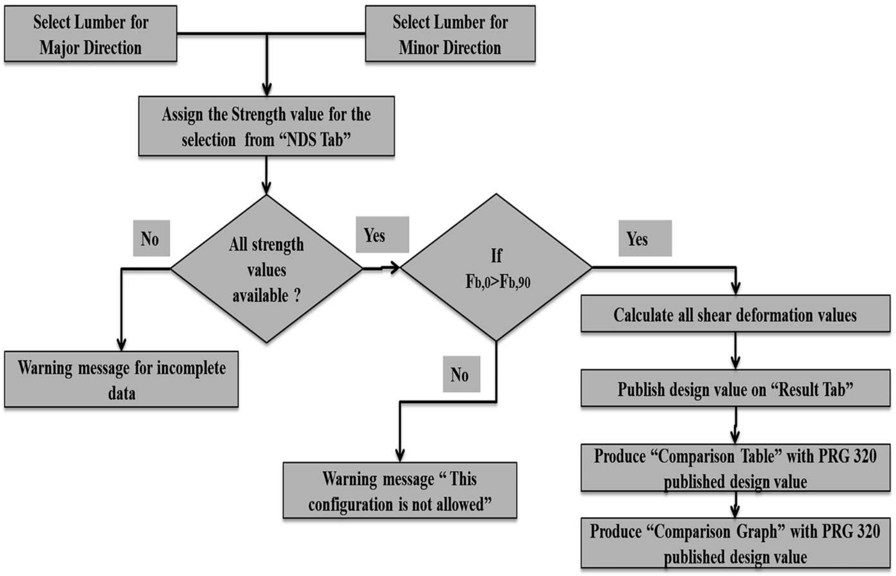

Figure 1.—Overall workflow of the SAM-CLT tool.

Flatwise bending moment of the CLT panel

For the major strength direction.—

$$(F_b, S)_{eff,f,0} = \frac{0.85 \times F_{b,\mathrm{major}} \times S_{eff,f,0}}{12} \tag{1}$$

where,

$$S_{eff,f,0} = \frac{(EI)_{eff,0}}{E_{\mathrm{major}}} \times \frac{2}{h} \tag{2}$$

where

$(F_b,S)_{eff,f,0}$ = effective flatwise bending moment of CLT, expressed in pounds-feet of width, in the major strength direction;

$F_{b,\mathrm{major}}$ = bending stress of the lumber in the major strength direction, expressed in psi;

$(EI)_{eff,f,0}$ = effective flatwise bending stiffness of the CLT expressed pounds-feet/foot of width in the major strength direction;

E_{major} = modulus of elasticity of the lamination, in psi in the major strength direction; and

h = Gross thickness of CLT, in inches.

For the minor strength direction.—

$$\frac{(F_b, S)_{eff,f,90} = \frac{F_{b,\mathrm{minor}} \times S_{eff,f,90}}{12}}{12} \tag{3}$$

where

$$S_{eff,f,90} = \frac{(EI)_{eff,90}}{E_{\mathrm{minor}}} \times \frac{2}{(h - h_1 - h_n)} \tag{4}$$

where

$(F_b,S)_{eff,f,90}$ = effective flatwise bending moment of CLT, in pounds-feet/foot of width, in the minor strength direction;

$F_{b,\mathrm{minor}}$ = bending stress of the lumber in the minor strength direction, expressed in psi;

$(EI)_{eff,f,90}$ = effective flatwise bending stiffness of the CLT expressed pounds-feet/foot of width in the minor strength direction;

E_{minor} = modulus of elasticity of the lamination, in psi in the major strength direction;

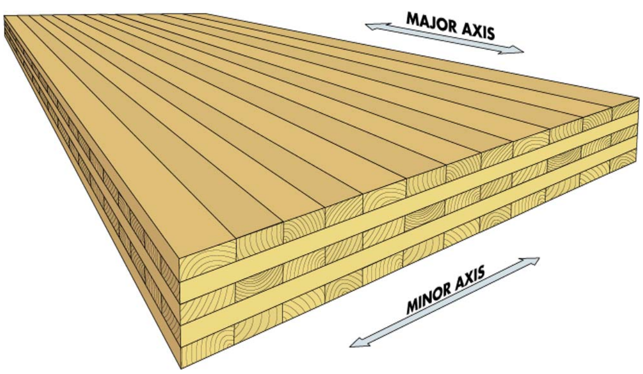

Figure 2.—5-layers CLT configuration assumed for this project (Breneman 2016).

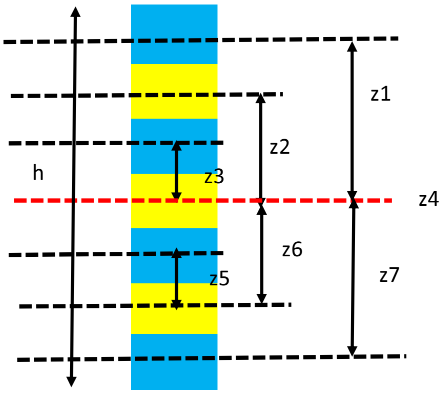

Figure 3.—Design layups of the seven-layer CLT panel with an indication of distance from the centroid.

h_1 = thickness of the bottom layer of the lamination in inches; and

h_n = thickness of the top layer of the lamination in inches.

Flatwise bending stiffness of the CLT panel

For the major strength direction.—

$$(EI)_{eff,0} = \sum_{i=1}^{n} E_i w_0 \frac{h_i^3}{12} + \sum_{i=1}^{n} E_i w_0 h_i z_i^2 \tag{5}$$

where

E_i = modulus of elasticity of the lamination in the *i*th layer, in psi;

w_0 = CLT width in the CLT major strength direction, expressed in inches of width;

h_i = thickness of laminations in the *i*th layer, expressed in inches;

z_i = distance between the center point of the *i*th layer and the neutral strength direction, expressed in inches; and

n = number of layers in the CLT.

For the minor strength direction.—

$$(EI)_{eff,90} = \sum_{i=2}^{n-1} E_i w_{90} \frac{h_i^3}{12} + \sum_{i=2}^{n-1} E_i w_{90} h_i z_i^2 \tag{6}$$

where

$(EI)_{eff,f,90}$ = effective flatwise bending stiffness of CLT, expressed in pound-squared inches/foot of width in the CLT minor strength direction;

w_{90} = CLT width in the CLT major strength direction, expressed in inches of width; and

h_i = thickness of laminations in the *i*th layer, expressed in inches.

Flatwise shear rigidity of the CLT panel

For the major strength direction.—

$$GA_{eff,f,0} = \frac{a^2}{\left[\left(\frac{h_1}{2G_1 w_0}\right) + \left(\sum_{i=2}^{n-1} \frac{h_i}{G_i w_0}\right) + \left(\frac{h_n}{2G_n w_0}\right)\right]} \tag{7}$$

where

$$a = \sum_{i=1}^{n} h - \frac{h_1}{2} - \frac{h_n}{2} \tag{8}$$

where

$GA_{eff,f,0}$ = effective flatwise shear rigidity of CLT, expressed in pounds/foot of width, in the major strength direction;

G_i = modulus of rigidity (shear modulus) of the lamination in the *i*th layer, in psi;

G_1 = modulus of rigidity of the first layer of CLT expressed in psi; and

G_n = modulus of rigidity of *n*th layer of CLT expressed in psi.

Table 1.—CLT layups evaluated using the SAM-CLT tool.

Layers	Lumber combination[a]	Remark
3	PPP	Hardwood CLT
	SSS	Softwood CLT
	PSP	Hybrid
	SPS	Hybrid
5	PPPPP	Hardwood CLT
	SSSSS	Softwood CLT
	PSPSP	Hybrid
	SPSPS	Hybrid
	PSSSP	Hybrid
	SPPPS	Hybrid
	PPSPP	Hybrid
	SSPSS	Hybrid
7	PPPPPPP	Hardwood CLT
	SSSSSSS	Softwood CLT
	PSSSSSP	Hybrid
	SPPPPPS	Hybrid
	PSPSPSP	Hybrid
	SPSPSPS	Hybrid
	SSPPPSS	Hybrid
	PPSSSPP	Hybrid
	PPSPSPP	Hybrid
	SSPSPSS	Hybrid
	PPPSPPP	Hybrid
	SSSPSSS	Hybrid

[a] P = yellow-poplar lumber; S = SYP lumber.

For the minor strength direction.—

$$GA_{eff,f,90} = \frac{a^2}{\left[\left(\frac{h_1}{2G_1 w_{90}}\right) + \left(\sum_{i=2}^{n-1} \frac{h_1}{G_1 w_{90}}\right) + \left(\frac{h_n}{2G_n w_{90}}\right)\right]} \tag{9}$$

where

$$a = \sum_{i=1}^{n} h - \frac{h_1}{2} - \frac{h_n}{2} \tag{10}$$

where

$GA_{eff,f,90}$ = effective flatwise shear rigidity of CLT, in pounds/foot of width, in the CLT minor strength direction.

Flatwise (rolling) shear capacity

For the major strength direction.—

$$V_{s.0} = F_{s,\mathrm{minor}} \frac{2A_{\mathrm{gross},0}}{3} \tag{11}$$

where

$$F_{s,\mathrm{minor}} = \frac{F_{V,\mathrm{minor}}}{3} \tag{12}$$

where

$V_{s,0}$ = flatwise shear capacity, expressed in pounds/foot of width in major strength direction;

$F_{s,\mathrm{minor}}$ = planar rolling shear stress of lamination in the minor strength direction; and

$A_{\mathrm{gross},0}$ = gross cross-sectional area of CLT, expressed in square inches of width in major strength direction ($h \times w_0$).

Table 2.—Observed design values for all standard CLT types derived from the SAM-CLT tool.

		Major strength direction				Minor strength direction			
CLT grade	Categories	$F_bS_{eff,0}$	$EI_{eff,0}$	$GA_{eff,0}$	$V_{s,0}$	$F_bS_{eff,90}$	$EI_{eff,90}$	$GA_{eff,90}$	$V_{s,90}$
E1	3 layers	4,530	115	0.46	1,490	160	3.12	0.61	495
	5 layers	10,405	440	0.92	2,480	1,365	81.21	1.23	1,490
	7 layers	18,380	1,089	1.39	3,475	3,145	311.54	1.84	2,480
E2	3 layers	3,835	102	0.53	1,985	165	3.64	0.56	660
	5 layers	8,820	389	1.06	3,310	1,435	94.75	1.12	1,980
	7 layers	15,600	963	1.58	4,635	3,305	363.46	1.68	3,300
E3	3 layers	2,790	81	0.35	1,155	110	2.34	0.44	385
	5 layers	6,405	311	0.69	1,930	955	60.91	0.87	1,160
	7 layers	11,315	769	1.04	2,705	2,205	233.65	1.31	1,930
E4	3 layers	4,530	115	0.5	1,820	140	3.38	0.62	605
	5 layers	10,410	440	1.0	3,030	1,230	87.98	1.24	1,820
	7 layers	18,395	1,089	1.49	4,250	2,830	337.5	1.86	3,030
E5	3 layers	3,835	101	0.46	1,655	160	3.12	0.55	550
	5 layers	8,810	389	0.92	2,755	1,365	81.21	1.10	1,650
	7 layers	15,570	962	1.38	3,865	3,145	311.54	1.65	2,750
V1	3 layers	2,090	108	0.53	1,985	165	3.64	0.59	660
	5 layers	4,810	415	1.06	3,310	1,435	94.75	1.18	1,980
	7 layers	8,500	1,027	1.59	4,635	3,305	363.46	1.78	3,300
V2	3 layers	2,035	95	0.46	1,490	160	3.12	0.52	495
	5 layers	4,675	363	0.91	2,480	1,365	81.21	1.03	1,490
	7 layers	8,265	898	1.37	3,475	3,145	311.54	1.55	2,480
V3	3 layers	1,745	95	0.49	1,820	140	3.38	0.52	605
	5 layers	4,010	363	0.98	3,030	1,230	87.98	1.04	1,820
	7 layers	7,090	899	1.47	4,250	2,830	337.5	1.56	3,030
V4	3 layers	1,800	74	0.38	1,490	140	2.6	0.41	495
	5 layers	4,145	285	0.76	2,480	1,230	67.68	0.82	1,490
	7 layers	7,325	706	1.13	3,475	2,830	259.61	1.23	2,480
V5	3 layers	1,975	88	0.45	1,655	160	3.12	0.48	550
	5 layers	4,545	337	0.91	2,755	1,365	81.21	0.97	1,650
	7 layers	8,035	835	1.36	3,865	3,145	311.54	1.45	2,750

For the minor strength direction.—

$$V_{s,90} = F_{s,\mathrm{major}} \times \frac{2 \times A_{\mathrm{gross},90}}{3} \qquad (13)$$

where

$$F_{s,\mathrm{minor}} \frac{F_{V,\mathrm{minor}}}{3} \qquad (14)$$

where

$V_{s,90}$ = flatwise shear capacity, expressed in pounds/foot of width in minor strength direction;

$F_{s,\mathrm{major}}$ = planar rolling shear stress of lamination in the major strength direction; and

$A_{\mathrm{gross},90}$ = gross cross-sectional area of CLT, expressed in square inches of width in minor strength direction after excluding the outermost layer in both directions $[(h - h_1 - h_n) \times w_{90}]$.

The following assumptions were made when designing the SAM-CLT tool by referencing the PRG-320 standard:

1. Each layer of the CLT has a thickness equal to lumber thickness.
2. Each CLT layer is perpendicular to the other, and none has multiple layers.
3. Similar types of lumber are used in single layers and are from single species.

Assumptions for both the major and minor direction of the CLT are as follows:

For major direction design value calculation,

- The elasticity modulus (E) for the lumber in the parallel layer is E.
- The elasticity modulus (E) for the lumber in the perpendicular layer is E/30.
- Shear rigidity (G) of the lumber in the parallel layer is assumed to be E/16, and
- The lumber's shear rigidity (G) in the perpendicular layer is assumed to be E/16/10.

For minor direction design value calculation,

- The elasticity modulus (E) for the lumber in the parallel layer is E = 0
- The elasticity modulus (E) for the lumber in the perpendicular layer is E/30.
- The shear rigidity (G) of the lumber in the parallel layer is assumed to be E/16/10,
- The lumber's shear rigidity (G) in the perpendicular layer is assumed to be E/16.

Accuracy and validation of the SAM-CLT tool

The first step of the SAM-CLT tool design was to adjust the calculation parameter to increase the tool's accuracy.

Table 3.—Error percentage of the design values for all standard CLT types using SAM-CLT.

		Error percentage calculated between observed and published data							
		Major strength direction				Minor strength direction			
CLT grade	Categories	$F_bS_{eff,0}$	$EI_{eff,0}$	$GA_{eff,0}$	$V_{s,0}$	$F_bS_{eff,90}$	$EI_{eff,90}$	$GA_{eff,90}$	$V_{s,90}$
E1	3 layers	0%	0%	0%	0%	0%	1%	0%	0%
	5 layers	0%	0%	0%	0%	0%	0%	3%	0%
	7 layers	0%	0%	−1%	0%	0%	0%	2%	0%
E2	3 layers	0%	0%	0%	0%	0%	1%	0%	0%
	5 layers	0%	0%	−4%	0%	0%	0%	2%	0%
	7 layers	0%	0%	−1%	0%	0%	0%	−1%	0%
E3	3 layers	0%	0%	0%	0%	0%	2%	0%	0%
	5 layers	0%	0%	0%	0%	0%	0%	0%	0%
	7 layers	0%	0%	4%	0%	0%	0%	1%	0%
E4	3 layers	0%	0%	0%	0%	0%	−1%	0%	0%
	5 layers	0%	0%	0%	0%	0%	0%	3%	0%
	7 layers	0%	0%	−1%	1%	−1%	0%	−2%	0%
E5	3 layers	0%	0%	0%	0%	0%	1%	0%	0%
	5 layers	0%	0%	0%	0%	0%	0%	0%	0%
	7 layers	0%	0%	−1%	0%	0%	0%	−3%	0%
V1	3 layers	0%	0%	0%	0%	0%	1%	0%	0%
	5 layers	0%	0%	−4%	0%	0%	0%	−2%	0%
	7 layers	0%	0%	−1%	0%	0%	0%	−1%	0%
V2	3 layers	0%	0%	0%	0%	0%	1%	0%	0%
	5 layers	0%	0%	0%	0%	0%	0%	3%	0%
	7 layers	0%	0%	−2%	0%	0%	0%	−3%	0%
V3	3 layers	0%	0%	0%	0%	0%	−1%	0%	0%
	5 layers	0%	0%	0%	0%	0%	0%	4%	0%
	7 layers	0%	0%	−2%	1%	0%	0%	−3%	0%
V4	3 layers	0%	0%	0%	0%	0%	0%	0%	0%
	5 layers	0%	0%	0%	0%	0%	0%	0%	0%
	7 layers	0%	0%	3%	0%	0%	0%	3%	0%
V5	3 layers	0%	0%	0%	0%	0%	1%	0%	0%
	5 layers	0%	0%	0%	0%	0%	0%	0%	0%
	7 layers	0%	0%	−3%	0%	0%	0%	−3%	0%

The tool was adjusted on rounding and truncating the values to increase the accuracy of the design value referenced with E1 grade CLT as explained in PRG320 standard. Error percentage was calculated by subtracting the published data from the observed data and dividing it by the published data to optimize the tool. Necessary amendments and correction measures on rounding and truncating were taken to minimize the error percentage value below ±5 percent for all design values for the E1 grade. After the required adjustment, the tool was validated in two steps. First, major and minor strength directions design values for all standard CLT types published in PRG 320 were computed on SAM-CLT. Then the observed design value was compared with the published design values of each CLT type.

Evaluation of design value for custom CLTs

After validating the tool, the minimum design value of a custom 3-, 5-, and 7-layer CLT using YP lumber and SYP lumber was computed first. Later, 3-, 5-, and 7-layer hybrid CLT combinations were computed using YP and SYP lumber mix. The custom CLT layups computed using the SAM-CLT tool were presented in Table 1. For this project, only symmetrical CLT layups were considered for computing the design values. For all combinations of YP and SYP lumber types, NO. 2-grade lumber in the major direction and NO. 3-grade lumber in the minor direction were considered.

Observation and Results

The SAM-CLT tool was constructed in the Excel sheet and made available on the Department of Sustainable Biomaterials website (https://cfpb.vt.edu/). The tool includes 5 hardwood species (yellow-poplar, mixed-maple, white oaks, red oak, and red maple (*Acer rubrum*), 7 softwood species, and standard CLT grade lumber specification values to design custom CLTs. The tool was designed so users can only vary lumber species and thickness. Variation in the lumber width is out of the scope of this tool because PRG 320 has not explicitly explained how to incorporate the variation in lumber width in CLT layups. For a mixed lumber combination to manufacture hybrid CLTs, the minimum strength value among the used lumber species was selected to determine the design value, assuming the CLT will fail at the weakest part.

The results from the SAM-CLT use are presented in two sections. The first section discusses the Validation of the SAM-CLT, and the second section discusses the application of the tool to evaluate the design value of YP-CLTs and YP-SYP hybrid CLTs.

Validation of the SAM-CLT

Validation of the tool was completed as discussed in the methodology. At first, the design value for the standard E1 grade CLT published in PRG 320 standard was determined

Table 4.—Custom CLTs minimum design values observed with SAM-CLT tool.

		Major strength direction				Minor strength direction			
CLT layup[a]	Layers	$F_bS_{eff,0}$	$EI_{eff,0}$	$GA_{eff,0}$	$V_{s,0}$	$F_bS_{eff,90}$	$EI_{eff,90}$	$GA_{eff,90}$	$V_{s,90}$
PPP	3	1,625	88	0.45	1,490	125	3.12	0.48	495
PSP	3	1,625	88	0.49	1,820	140	3.38	0.49	605
SSS	3	1,745	95	0.49	1,820	140	3.38	0.52	605
SPS	3	1,745	95	0.46	1,490	125	3.12	0.52	495
PPPPP	5	3,740	337	0.91	2,480	1,095	81.22	0.97	1,490
PSPSP	5	3,745	337	0.98	3,030	1,230	87.98	0.98	1,820
PPSPP	5	3,745	338	0.91	2,480	1,095	81.23	1.00	1,490
PSSSP	5	3,750	338	0.98	3,030	1,230	87.99	1.01	1,820
SPSPS	5	4,005	363	0.91	2,480	1,095	81.23	1.03	1,490
SSSSS	5	4,010	363	0.98	3,030	1,230	87.99	1.04	1,820
SPPPS	5	4,025	363	0.91	2,480	1,095	81.22	1.00	1,490
SSPSS	5	4,025	363	0.98	3,030	1,230	87.98	1.01	1,820
PPPPPPP	7	6,615	835	1.36	3,475	2,520	311.76	1.45	2,480
PPPSPPP	7	6,615	835	1.39	3,475	2,520	312.02	1.46	2,480
PSPSPSP	7	6,625	836	1.46	4,250	2,830	337.5	1.46	3,030
PPSSSPP	7	6,670	842	1.4	3,475	2,525	312.25	1.52	2,480
PPSPSPP	7	6,670	842	1.37	3,475	2,520	311.99	1.52	2,480
PSSSSSP	7	6,675	843	1.47	4,250	2,835	337.72	1.53	3,030
SPPPPPS	7	7,065	892	1.36	3,475	2,520	311.76	1.48	2,480
SSPPPSS	7	7,075	892	1.43	3,475	2,725	337.24	1.49	2,480
SSPSPSS	7	7,075	892	1.47	4,250	2,830	337.5	1.49	3,030
SPSPSPS	7	7,085	898	1.37	3,475	2,520	311.99	1.55	2,480
SSSSSSS	7	7,090	899	1.47	4,250	2,835	337.72	1.56	3,030
SSSPSSS	7	7,090	899	1.44	3,475	2,725	337.46	1.56	2,480

[a] P = yellow-poplar lumber; S = SYP lumber.

using the SAM-CLT tool, and the tool was readjusted on rounding and truncating the values to ensure a minimal difference between observed and published design values of E1 grade CLT. After the tool was optimized to obtain minimum differences for all design values of E1 grade CLT, the design value for all standard CLT types was computed using the SAM-CLT tool. The observed design value is presented in Table 2. Table 3 presents the error percentage between evaluated and published design values for all standard CLT types. The result had an error below ±4 percent, validating the tool's accuracy and the tool itself.

Application of the tool

After validating the tool, design values for SYP, YP, and SYP-YP hybrid custom CLTs were evaluated by considering only NO. 2-grade lumber in the major strength direction and NO. 3-grade lumber in the minor strength direction for all lumber combinations. The observed results of the various combination of the custom CLTs are presented in Table 4. These data can be used as the minimum design values for the lumber combination indicated in the table. In this example, the authors only used the SYP and YP NO 2- and NO. 3-grade lumber to demonstrate the tool's applicability; however, this tool can be used for all lumber combination types and thicknesses as presented in the NDS database of the Excel sheet.

Discussion and Summary

In this project, the SAM-CLT tool was developed and evaluated for its ability to calculate design values for custom CLT panels made from various wood species. Thus developed tool, presented the design layups and calculation parameters for the custom CLTs based on the shear-analogy model adopted from the 2019 revised version of the PRG 320 standard. The results indicated that the SAM-CLT tool effectively calculated the design values for all standard CLT grades published in PRG 320. The calculated design values for all published CLT grades matched the calculated design values for a similar configuration of the CLT with a maximum deviation of <4 percent. Thus, the results from the SAM-CLT tool can be used with confidence.

The SAM-CLT tool provides a user-friendly and efficient approach to evaluating the minimum design value of custom CLTs using different lumber species and thicknesses. However, the tool's accuracy depends on the accuracy of the input parameters, such as the strength value of the different wood species, rounding, and truncating consistency used in the calculation, because it included multiplication and division of large numbers in most calculations.

In summary, SAM-CLT was developed as a simple tool for calculating custom CLT panels' design value. The tool successfully provides a method to calculate the minimum design values when different lumber types and thicknesses are used. This tool was validated and corrected to minimize error, and it effectively calculated the design values for all standard CLT grades published in PRG 320 with less than ±4 percent error. The tool is available to the public so that anyone can estimate the minimum design value of CLTs with custom layups. This project also calculated the strength properties of the YP CLT and its hybrid using SYP lumber as an example species.

SAM-CLT allows the user to evaluate the various shear deformation of the CLT panel and compare it against the design values of the published CLT grade listed in PRG 320, so this tool is useful in four aspects:

1. To determine the design values of the custom CLT with the standard dimension;
2. To determine the design values of the CLTs with the various layer thickness;
3. To estimate the design value of CLT constructed using all types of dimensional grade lumber whose strength value was published in the NDS; and
4. To determine the design value of the softwood–softwood, hardwood–hardwood, or softwood–hardwood hybrid CLTs.

The model has been validated by comparing the design value of the SAM-CLT tool with the published design value on PRG 320; however, future work will include comparing the design values calculated to actual test data on YP-SYP hybrid CLTs in the next step of our continuous project.

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Literature Cited

Adhikari, S. 2020. Assessment of cross laminated timber markets for hardwood lumber. Doctoral dissertation 2020-09-25. Virginia Tech, Blacksburg. 250 pp.

Adhikari, S., H. Quesada, B. Bond, and T. Hammett. 2020. Potential of hardwood lumber in cross laminated timber in North America: A CLT manufacturer's perspective. *Mass Timber Construct. J.* 3(1):1–9. http://www.journalmtc.com/index.php/mtcj/article/view/20

Adhikari, S., H. Quesada, B. Bond, and T. Hammett. 2021. Current status of the United States hardwood sawmills to produce structural grade hardwood lumber. *Mass Timber Construct. J.* 4(1):10–18.

American Hardwood Export Council [AHEC]. 2019. Tulipwood CLTs properties and manufacturing requirements. American Hardwood Export Council. 40 pp. https://www.americanhardwood.org/en/library/publications/tulipwood-clt-properties-and-manufacturing-requirements. Accessed September 13, 2020.

American National Standards Institute/The Engineered Wood Association [ANSI/APA]. 2012. ANSI/APA PRG 320-2012 Standards for performance-rated cross-laminated timber. ANSI/APA, Tacoma, Washington. 23 pp. https://www.apawood.org/ansi-apa-PRG 320. Accessed September 19, 2020.

American National Standards Institute/The Engineered Wood Association [ANSI/APA]. 2019. ANSI/APA PRG 320-2019 Standards for performance-rated cross-laminated timber. ANSI/APA, Tacoma, Washington. https://www.apawood.org/ansi-apa-PRG 320. Accessed September 13, 2020.

Brandner, R., G. Flatscher, A. Ringhofer, G. Schickhofer, and A. Thiel. 2016. Cross-laminated timber (CLT): Overview and development. *Eur. J. Wood Wood Prod*. 74(3):331–351.

Breneman, S. 2016. Cross-laminated timber structural floor and roof design. https://www.structuremag.org/?p=10054. Accessed September 21, 2023.

Buka-Vaivade, K., D. Serdjuks, V. Goremikins, A. Vilguts, and L. Pakrastins. 2017. Experimental verification of design procedure for elements from cross-laminated timber. *Proc. Eng*. 172:1212–1219.

FPInnovations. 2011. Introduction to cross-laminated timber. CLTs Handbook - Canadian Edition. [online] FPInnovations. https://library.fpinnovations.ca/en/viewer?file=%2fmedia%2fWP%2fE4840.pdf#phrase=false&pagemode=bookmarks. Accessed May 25, 2020.

Grasser, K. K. 2015. Development of cross-laminated timber in the United States of America. Master's thesis. University of Tennessee, Knoxville. 129 pp. http://trace.tennessee.edu/utk_gradthes/3479. Accessed September 23, 2020.

Kreuzinger, H. 1999. Platten, Scheiben und Schalen–ein Berechnungsmodell für gängige static program. *Bauen Mit Holz* 1:34–39.

Niederwestberg, J., J. Zhou, and Y. H. Chui. 2018. Comparison of theoretical and laboratory out-of-plane shear stiffness values of cross laminated timber panels. *Buildings* 8(10):146.

The Engineered Wood Association [APA]. 2019. Cross-laminated timber (CLTs), innovative solid wood panels offer new large-scale design options. APA – The Engineered Wood Association. https://www.apawood.org/cross-laminated-timber. Accessed July 25, 2018.