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BALLISTIC TESTING OF CROSS-LAMINATED TIMBER LAYUPS TO FURTHER DEVELOP PROTECTIVE PANELS

Marco T. Lo Ricco[1], Mark K. Weaver[2], C. Adam Senalik[3], Jim Henjum[4], Jason Cattelino[5]

ABSTRACT: Though ballistic projectile penetration of wood has been studied for centuries, standard models overestimate the thickness of wood required to stop projectiles, often by a large margin. Adhesive lamination via contemporary manufacturing methods can produce mass timber panels of unprecedented thickness, yet industry standard layups of softwood cross-laminated timber (CLT) cannot stop projectiles traveling at velocities specified by current protective design requirements. To develop mass timber panels that comprehensively mitigate blast, ballistic, and forced entry threats, seven reinforced or hardened CLT layups were manufactured to compare their ballistic performance with that of a baseline 7-ply softwood CLT layup. Three calibers of ammunition were fired at each panel specimen, and entry and exit velocities were recorded with high-speed cameras. For projectiles that did not fully perforate the panel, the depth of penetration was determined by radiography. Four of the eight tested layups stopped all projectiles. Among the successful layups, three included embedded steel reinforcements. The other successful layup was made entirely of hardwood laminations. Steel-plate-reinforced softwood CLT proved the most cost-effective option.

KEY WORDS: cross-laminated timber, ballistic penetration, protective structures, reinforced CLT, hardwood CLT

1 INTRODUCTION

Blast and ballistic threats are two primary concerns in protective design. Past testing has demonstrated that mass timber can resist blast threats [1]. Although the ballistic performance of wood has been studied over the course of three centuries [2, 3], satisfactory resistance to ballistic threats remains unresolved. Approximately two decades ago, Smrž et al. [4] tested 55 mm (2-⅛ in.) thick wood plates under ballistic impacts from 7.62-mm bullet, spherical, and simulated fragment projectiles. The model developed from these experiments, however, is limited to 100 mm (3-⅞ in.) of thickness and adapted a unified theory of penetration that has proven accurate for metal alloys [5]. Whether this unified theory of penetration simulates perforation of wood materials as well remains an open question.

Two classic models of ballistic penetration, the Robins-Euler and Poncelet equations, originated during the eighteenth century when wood materials were common targets, and remain relevant in the mechanics of terminal ballistics [6]. Koene and Broekhius [7] applied these classic models to the penetration of 9-mm ammunition into solid wood blocks of various species and showed that the models reasonably fit the penetration depth data for metal-tipped bullets. The models, however, did not apply to polyethylene tipped bullets used in the tests. To ensure that bullets would be stopped by the wood blocks, impact velocities were limited, so whether the models need parameters for projectiles hitting the targets at much higher velocities remains unknown.

Protective design of U.S. government facilities commonly uses an empirically based model that correlates hardness, density, and thickness of wood to calculate the dimension required to stop a bullet or the residual velocity of a perforating bullet. According to equations and tabulated data in UFC 4-023-07 [8], an unrealistic 4.55 m (179 in.) thick panel of pine or 1.5 m (59 in.) thick panel of hickory would be required to stop a NATO M80 round fired at a velocity of 853 m/s (2800 ft/s). However, test programs that form the basis of these UFC 4-23-07 estimates predate innovations like cross-laminated timber (CLT).

Sanborn et al. [9] conducted one of the first published ballistics tests on CLT targets and found that UFC equations, among other models, overpredicted both (a) the thickness required to prevent perforation and (b) the exit velocities of spherical projectiles. Although the tested specimens outperformed conventional ballistic model estimates, Sanborn [10] anticipated that softwood CLT would need reinforcement to stop more realistic ballistic threats and tested several enhanced "eCLT" layups using steel, fiberglass, aramid, and ultra-high molecular weight polyethylene reinforcement layers. While several reinforcing options reduced penetration depth of spherical projectiles, mild steel was the least costly reinforcement.

[1] Marco T. Lo Ricco, USDA Forest Products Laboratory, USA, marco.loricco@usda.gov
[2] Mark K. Weaver, Karagozian & Case, Inc., USA, weaver@kcse.com
[3] C. Adam Senalik, USDA Forest Products Laboratory, USA, christopher.a.senalik@usda.gov
[4] Jim Henjum, SmartLam North America, USA, jim.henjum@smartlam.com
[5] Jason Cattelino, Rotho Blaas USA, Inc. jason.cattelino@rothoblaas.com

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2 OBJECTIVE

Wood's ballistic performance must be proven before governmental agencies and other institutions implementing protective design requirements can realize the sustainable and architectural benefits of mass timber construction. A feasibility study, therefore, was undertaken to investigate whether a CLT layup measuring 254 mm (10 in.) or less in thickness could stop ogive-nose bullets. To increase the ballistic resistance of softwood CLT layups and avoid the cost of exotic armoring materials, conventional steel sheets were incorporated into several layups. Other layups incorporated dense hardwoods, instead of steel reinforcement, to determine if wood panels without metal reinforcement could prevent ballistic perforation. The objective of the study was to demonstrate that CLT could meet ballistic protection requirements at a layup thickness and cost comparable to conventional reinforced concrete and steel protective options.

3 TESTING

3.1 SPECIMENS

The layups assessed in this study are schematically shown in Figure 1. All eight layups utilize seven layers of wood, with some layups utilizing up to four additional layers of embedded steel reinforcement. The layups are comprised of: (a) all softwood [to represent the control], (b) all hardwood, (c) alternating hardwood and softwood, (d) alternating interlocked grain hardwood and softwood, (e) thin steel plate reinforcement, (f) fine steel mesh reinforcement, (g) coarse steel mesh reinforcement, and (h) thick steel plate reinforcement.

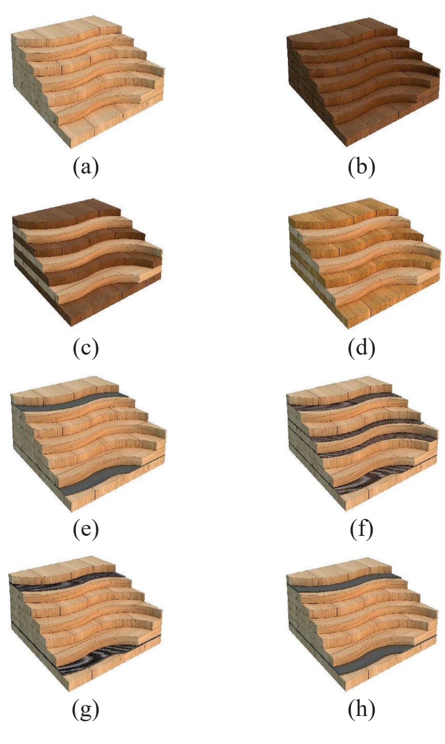

Figure 1: *Renderings of specimen layups.*

Layup (a) utilized Spruce-Pine-Fir, South (SPF-s), No. 2 Grade laminations of 35 mm (1.375 in.) nominal thickness, conforming to North American standards [11]. As the only standard CLT layup, this panel acted as a control that is representative of the ballistic resistance of unreinforced softwood CLT. Because Layup (a) had no hardwoods nor steel reinforcement, all other layups were compared and expected to outperform this control.

Layup (b) utilized laminations of shagbark hickory (Carya ovata) in select and better grades of 32 mm (1.250 in.) thickness. Shagbark hickory is selected as it is among the hardest and densest North American species, which is theorized to provide increased ballistic resistance when compared to softer and less-dense alternatives.

Layup (c) alternated hardwood (hickory) and softwood (SPF-s) layers, of respective 32- and 35-mm thickness, to assess whether contrasting combinations of hardness and density might outperform layups composed of a single species classification.

Layup (d) was similar to Layup (c) but substituted hickory with American sycamore (platanus occidentalis) to assess whether a hardwood with an interlocked grain microstructure might provide additional resistance. Previous tests indicated that sycamore has relatively high ballistic resistance relative to other woods [12].

Steel reinforcement is utilized in the four remaining layups, along with No. 2 SPF-s wood layers of 35-mm thickness. It was hypothesized that the hardness, density, and ductility of steel may sufficiently reinforce softwoods to prevent ballistic perforation. Past testing has shown that mild, low-carbon steel plates of 12.5 mm (0.5 in.) thickness are adequate in stopping the ammunition used in this study [13], so Layups (e) through (h) were limited to an embedded steel content equivalent to this thickness of steel plate or less. Two of the four layups utilize woven steel wire cloth while the other two layups utilize solid steel plates. Steel plates conform to ASTM A36 [14] with a minimum specified yield strength of 250 MPa (36 ksi), while the woven steel wire cloth conforms to ASTM E2016 [15]. The cold-drawn steel wires used in the woven steel cloth are uncoated and conform to the 1042 grade designation.

Layup (e) utilized steel plates of 3 mm (1/8 in.) thickness at the bond lines of the panel face laminations.

Layup (f) utilized finely woven steel wire cloth, with 47% open area and 1.6 mm (1/16 in.) wire diameter, at all bond-line interfaces except two. Although solid steel plates offer continuous coverage throughout the panel, woven steel cloth provides openings for adhesive contact between wood laminations, which may provide improved bond characteristics.

Layup (g) utilizes a coarsely woven steel wire cloth, with 27% open area and 3 mm (1/8 in.) wire diameter, at the bond lines of the panel face laminations.

Layup (h) utilizes 6 mm (1/4 in.) steel plates at the bond lines of the panel face laminations.

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The thicknesses of the eight layups are similar but are all slightly different. Because softwoods and hardwoods are typically milled to different dimensions, Layup (b) made entirely of hardwoods results in the thinnest panel. The embedment of steel elements thickens Layups (e) through (h). While the eight layup thicknesses could have been held constant, practical considerations of lamella thickness are more representative of what the CLT industry would eventually produce. For each of the eight layups, a panel measuring approximately 915 mm (36 inches) square was pressed and subsequently cut into four 457 mm (18 in.) tiles. For the steel-reinforced panels, hardboard spacers are placed along the edges of embedded steel plates to make a path for saws to cut only through wood-based materials.

Of the four tiles produced from each panel layup, only three tiles were used as specimens for ballistics testing, so Table 1 provides panel thickness for each of the eight layups and three tiles used in ballistics tests. The resulting range of thickness is minus 22 mm (0.866 in.) and plus 14 mm (0.551 in.) relative to the baseline Layup (a) of 248 mm (9.75 in.) tile thickness.

Table 1: Panel thickness in mm

	Tile			
Layup	**1**	**2**	**3**	**Average**
(a)	248	248	248	248
(b)	227	225	225	226
(c)	235	235	233	234
(d)	232	232	232	232
(e)	252	251	254	252
(f)	259	259	260	259
(g)	262	262	262	262
(h)	257	257	257	257

25.4 mm = 1 inch.

Figure 2 plots the measured densities of the layups. Layup (b), the thinnest panel of Table 1 and made of shagbark hickory with a specific gravity reported as 0.72 [16], ranks as the densest panel. At the opposite end of the range, softwood Layup (a), made with a SPF-s of reported specific gravity of 0.36 [17], ranks as least dense.

Figure 3 plots the measured areal densities of the layups, calculated as the mass of each tile divided by the surface area. By this measure, Layup (h) has the highest areal density, while Layup (a) remains least dense. In other words, Layup (h) is the heaviest wall component among the tested layups because it has highest mass per square meter of exterior wall area. From a ballistics perspective, areal density provides the more useful measure, so both effective and areal density are reported here to highlight the distinction.

3.2 PROJECTILES

The test ammunition of Table 2 lists specified properties of the three NATO cartridges used is this ballistic study. A complete *round of ammunition* or *cartridge*, according to ballistics terminology [18], includes a bullet and cartridge case containing propellant and primer for ignition. The *bullet* is the only portion of the cartridge that is the *projectile* and has mass specified in units of *grains*. For enhanced aerodynamics and penetration of the projectile, the front end of bullets was ogive shaped. While levels of protection may vary for different facilities, the standard [13] used to evaluate this test program requires zero perforation for the projectiles impacting targets within the range of velocities specified in Table 2.

Table 2: *Test Ammunition*

	Velocity (m/s)	
Cartridge	**Min.**	**Max.**
7.62 mm, M80, ball 147 gr.	823	853
5.56 mm, M193, ball, 55 gr.	955	986
5.56 mm, M855, ball, 63 gr.	899	930

1 m ≈ 3.28 ft; 1 grain ≈ 0.0647989 gram ≈ 0.00228571 oz.

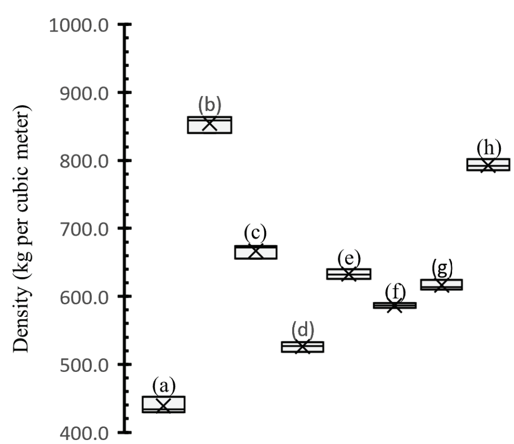

Figure 2: *Effective density of layups used in ballistic testing.*
1kg ≈ 2.2 pounds mass; 1 m ≈ 3.28 ft.

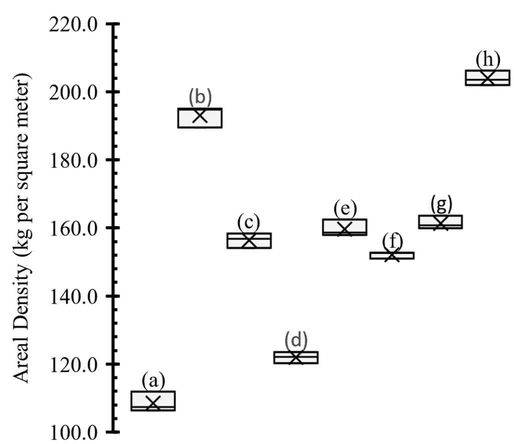

Figure 3: *Areal density of layups used in ballistic testing.*
1kg ≈ 2.2 pounds; 1 m ≈ 3.28 ft.

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Based on previous softwood CLT tests which utilized spherical projectiles [9], it was expected that a softwood 7-ply CLT layup will not be able to stop ogive-nosed cartridges fired at standard rifle speeds as the ogive-nose typically penetrates materials more efficiently than spherical projectiles, because of simultaneous driving and drilling actions.

3.3 PROCEDURE

Of the four tiles produced for each layup, one tile underwent bond integrity testing while three underwent ballistic testing. The tiles undergoing bond integrity assessments were subjected to AITC T110 cyclic delamination tests [19] and physical prying with a weighted hammer and crowbar to qualitatively assess bond integrity. Ballistic resistance testing was conducted by a qualified laboratory (H.P. White Laboratory, Inc., Street, MD) during the spring of 2020 [20]. The cartridges listed in Table 2 were fired into each tile from a muzzle 6.1 m (20 ft) away from the strike face of the tile target. The shots were oriented in a triangular pattern to minimize the influence of previous shots. Velocity screens positioned relative to the muzzle at distances of 1.52 m (5 ft) and 4.57 m (15 ft) recorded the times projectiles passed, so that an initial velocity could be estimated at a position of 3.05 m (10 ft) along the trajectory. Impact velocities were determined from the velocity screen data and high-speed cameras recording video of impact with the target within the fixture pictured in Figure 4.

For projectiles that fully perforated the tiles, residual velocities were determined by high-speed video cameras tracking projectiles exiting the back face of the target from both top and side views, as shown in the example of Figure 5. For projectiles stopped within the tiles, their position was measured from the back (non-strike) face of the target by a qualified laboratory (MCQ Labs, Inc., Aberdeen, MD) using radiography, as shown in the example of Figure 6. The penetration depths shown in Figure 6 include both calculated (C) and measured (M) values given in the computed radiography report.

Figure 4: *CLT tile mounted in steel frame for ballistic testing viewed from back, non-strike face (foreground) and looking toward velocity screen (background).*

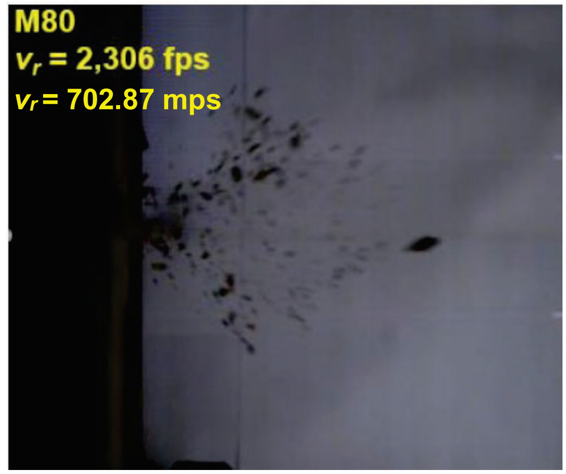

Figure 5: *Residual velocity video-recorded upon projectile exit.*

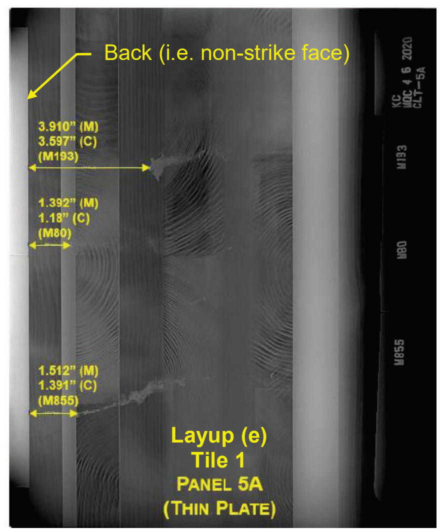

Figure 6: *Projectiles stopped from reaching exit face (datum).*
1 inch or 1.0" = 25.4 mm.

4 RESULTS

All nine projectiles fired at the Layup (a) tiles passed through the tiles (full perforation), while Layups (b), (e), (g) and (h), successfully stopped all projectiles from exiting the tiles (no perforations). Layups (c), (d) and (f) had multiple tiles perforated by M80 projectiles. Both Layups (c) and (f) stopped all shots of the M193 and M855 projectiles. Layup (d) failed to stop one of the M193 projectiles and all three shots of the M855 projectiles. Table 3 summarizes these results in terms of a binary pass-fail criterion. If panels stopped all the projectiles of a given cartridge type, it was deemed to pass. If at least one bullet passed through a panel and exited the back, non-strike face, the layup was deemed to fail. Regardless of the pass-fail determination, all targets were evaluated in more detail to estimate the energy absorbed by the CLT panels when shot with projectiles from each cartridge type.

Table 3: Pass-fail results of ballistic perforation test.

Layup	M80	M855	M193
(a)	FAIL	FAIL	FAIL
(b)	PASS	PASS	PASS
(c)	FAIL	PASS	PASS
(d)	FAIL	FAIL	FAIL
(e)	PASS	PASS	PASS
(f)	FAIL	PASS	PASS
(g)	PASS	PASS	PASS
(h)	PASS	PASS	PASS

PASS: Panel captured all bullets.

FAIL**:** One or more bullets exited the back face of panel.

Shaded: Layup failed to stop at least one bullet.

4.1 Perforated Targets

Figure 7 plots the striking velocity versus the residual velocity for projectiles associated with full penetration, where the M80 projectiles generally displayed the largest residual velocities. One residual velocity for the M80 round that breached Layup (c) could not be measured, though all three M80 projectiles exited the tiles. Since protective design is typically concerned with energy and a protective element's ability to dissipate energy, the recorded velocities of Figure 7 were converted to kinetic energy using the fundamental equation of one-half mass times velocity squared. For this calculation the mass of the bullet was assumed constant; (although this assumption cannot typically be made for ballistics traveling through hard or ductile materials, it is justified by video observations of the tests). Figure 8 plots the kinetic energy upon impact versus the residual kinetic energy for the projectiles associated with full penetration. The larger mass of the M80 projectiles results in a much larger striking kinetic energy then the M193 and M855 projectiles and, because the capacity of target tiles to absorb energy is finite, generally leads to a much larger residual kinetic energy.

To quantify the kinetic energy absorbed by each layup, the residual kinetic energy is subtracted from the striking kinetic energy. Figures 9, 10, and 11 show the differentiated kinetic energies for the M80, M193, and M855 projectiles, respectively. The total height of each bar chart represents the average striking kinetic energy on a specific layup. The light grey portion of the bar chart represents the energy absorbed by the impacted tile. The black portion of the bar chart represents the kinetic energy of the projectile after exiting the back of the tile.

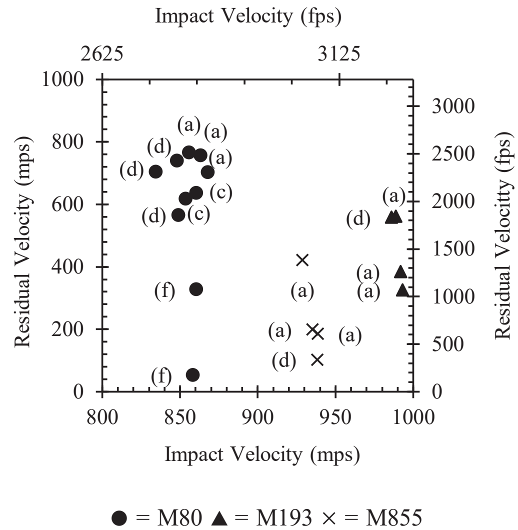

Figure 7: *Impact and residual velocities of projectiles breaching full thickness of panels.*

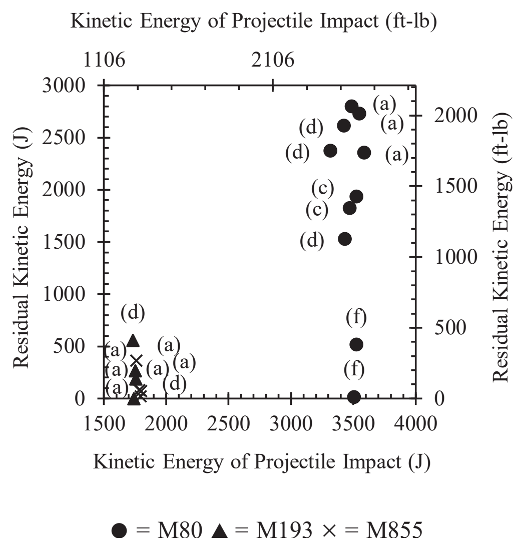

Figure 8: *Impact and residual kinetic energies of projectiles breaching full thickness of panels.*

Figure 9 shows that Layups (a), (c), and (d) absorbed less than half the kinetic energy of the striking M80 projectiles, in contrast to Layup (d) which absorbed nearly all projectile kinetic energy. Figures 10 and 11, plotted to the same y-axis scale as Figure 9, show that the M193 and M855 projectiles strike the tiles with approximately half the kinetic energy of the M80 projectiles. Though the full thickness of Layups (a) and (d) were breached by the M193 and M855 projectiles, Figures 10 and 11 show that nearly all the kinetic energy was absorbed by the tiles.

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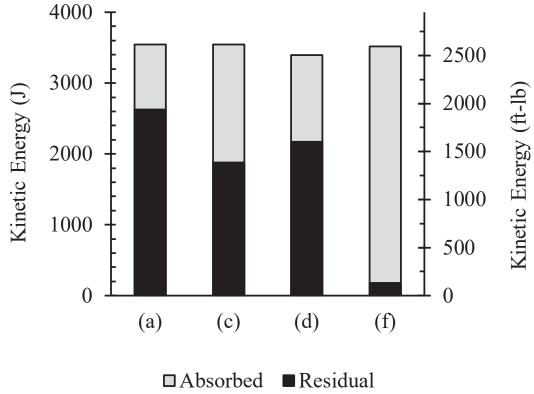

Figure 9: *Comparison of average striking and exiting kinetic energies of M80 projectiles.*

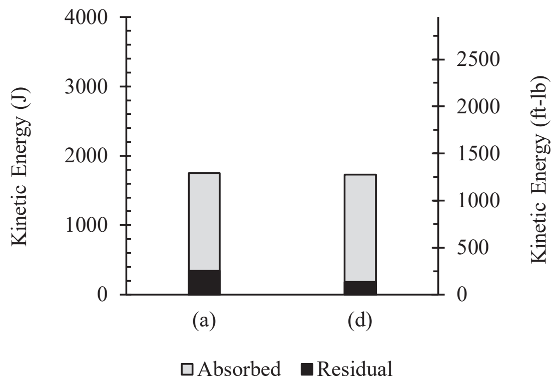

Figure 10: *Comparison of average striking and exiting kinetic energies of M193 projectiles.*

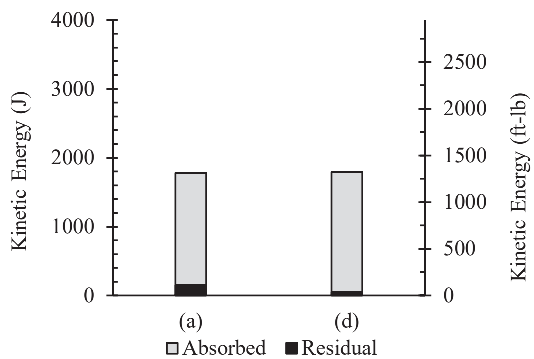

Figure 11: *Comparison of average striking and exiting kinetic energies of M855 projectiles.*

4.2 Embedded Projectiles

Table 4 provides the position of projectiles found within panel specimens, labelled as tiles, which were calculated using computed radiography. Blank entries of Table 4 indicate that no projectile of that ammunition type was found, supporting the penetration of full panel thickness observed during tests. The third M80 projectile into Layup (b) did not exit the panel but reached the back face and therefore was assigned a position of zero, to indicate near perforation.

Penetration depths of each projectile were calculated by subtracting position from total panel thickness, *t*. Because all shots were fired directly, with no oblique angles, the assume length of penetration of breached panels is the full thickness. Figure 12 shows the average depths projectile penetration alongside plots of average panel thickness for each layup. Projectile depths equal to panel thickness, *t*, indicate breaches. In panels that stopped bullets, the depth of penetration was generally proportional to the kinetic energy of the ammunition. Layup (h) reinforced with thick steel plates, however, presented an exception where the average depth of penetration of the M855 round exceeded the average penetration of the M80.

Table 4*: Positions of embedded projectiles measured from back face of panel.*

		Position from exit face		
Layup	**Tile**	**M80 (mm)**	**M193 (mm)**	**M855 (mm)**
	1	-	-	-
(a)	2	-	-	-
	3	-	-	-
	1	39	115	106
(b)	2	40	148	111
	3	0	138	118
	1	-	61	70
(c)	2	-	95	94
	3	-	107	70
	1	-	51	-
(d)	2	-	22	-
	3	-	-	-
	1	30	91	35
(e)	2	44	85	61
	3	42	101	68
	1	41	130	92
(f)	2	-	127	96
	3	-	136	140
	1	40	96	107
(g)	2	45	108	89
	3	42	121	83
	1	107	152	69
(h)	2	100	143	75
	3	95	142	70

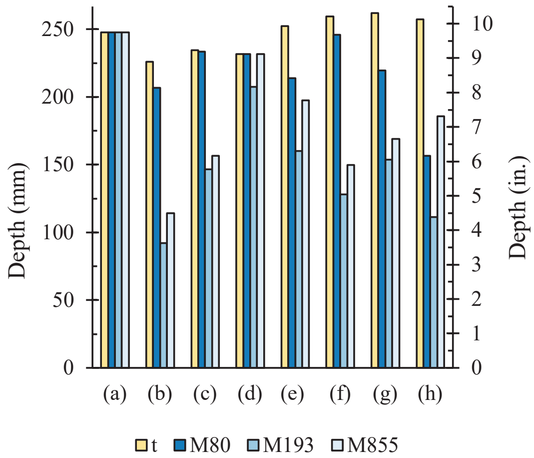

Figure 12: Thickness and penetration depths of projectiles.

4.3 Variation

Because all test ammunition was fired according to Table 2 specifications, with consistent velocities and mass, there was little variation in the striking kinetic energy. The coefficient of variation for the average striking kinetic energy of each tested layup given by Table 5 shows less than 2% variation in any given set of test ammunition. Variation of mass from the grain size specifications in Table 2 was neglected in the variation reported in Table 5, so the calculated variation is entirely attributable to the squared magnitude of velocity measured during testing.

Table 5: *Coefficients of variation for average kinetic energies of impact.*

Layup	M80 (%)	M193 (%)	M855 (%)
(a)	1.2	0.4	0.9
(b)	0.1	0.1	1.2
(c)	0.7	1.5	1.0
(d)	1.6	0.1	0.3
(e)	0.9	1.4	0.8
(f)	0.2	0.8	1.5
(g)	0.2	1.1	0.4
(h)	0.3	1.0	1.4

The coefficients of variation for averages of residual kinetic energy and penetration depth are respectively provided in Tables 5 and 6. Several factors account for the relatively high variation observed in the residual kinetic energy averages. First, the averages are based on a limited data set of three samples. In at least one instance, firing the M80 round into a Layup (c) panel, residual velocity could not be recorded, so results from two samples were averaged. In Layup (f), two M80 projectiles breached panels but one did not, which led to high variation in the average. With more tests, the effects of a limited number of samples would decrease. Second, woods have historically exhibited coefficients of variation greater than 20% for some mechanical properties [21]. The Spruce-Pine-Fir (South) commercial grouping further introduces variation by including 10 species [17]. Third, moisture content introduces additional variability that may affect results. In this study, ambient temperature and humidity readings were recorded and samples retained to verify that moisture content was typically 12% or less for each of the samples.

Table 5: *Coefficients of variation for average residual kinetic energies of breached layups.*

Layup	M80 (%)	M193 (%)	M855 (%)
(a)	7.4	47.6	78.9
(b)	-	-	-
(c)	2.9	-	-
(d)	21.4	141.4	48.2
(e)	-	-	-
(f)	135.9	-	-
(g)	-	-	-
(h)	-	-	-

The coefficients of variation for average depth of penetration listed in Table 6 range from approximately one to fifteen percent. For Layups (e) through (h) reinforced with steel, the variation is generally less than those of wood. For Layups (a), (c) and (d), the coefficients of variation are not reported for penetration values, because it is obvious that projectiles penetrated the full panel thickness. In these cases, the change in kinetic energy should be based on residual velocities with the variation reported in Table 5.

Table 6: *Coefficients of variation for average depth of penetration for layups with embedded projectiles.*

Layup	M80 (%)	M193 (%)	M855 (%)
(a)	-	-	-
(b)	14.0	15.5	4.7
(c)	-	13.8	7.2
(d)	-	10.0	-
(e)	3.1	3.3	7.0
(f)	7.9	2.7	14.0
(g)	1.1	6.7	6.1
(h)	3.3	4.2	1.5

4.4 Engineering model

Though variation poses challenges, it is possible to begin developing an engineering model from this limited data set. Ballistic modeling for wood has typically tried to correlate performance to fundamental properties of density, or specific gravity, and Janka hardness. Framing the problem in the context of energy is useful for the objective of stopping bullets. Although shape of the projectile is a factor in depth of penetration, the problem of armoring is largely dominated by kinetic energy delivered to an extremely localized scale. The challenge

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lies in determining how much energy absorption wood may offer via breakage, friction, and other means of damping. The introduction of steel undoubtedly adds hardness, density, and ductility that enhances energy absorption of the panels.

For this data set, some additional steps may be taken to extract information that may be useful for engineering modeling. Resistance drilling studies [22] have developed models for distinguishing driving force, torque, and friction in correlation to density and Janka hardness. Via resistance drilling of retained samples, there may be a practical method to predict the ballistic performance based on the driving forces, torque, and friction measured near the ballistic perforations. Such studies have shown that numerous samples must be taken to develop statistical confidence in the models and obtain reasonable fit.

4.5 Costs and additional considerations

Among the four layups that stopped all test shots, the cost ranked in order from least to greatest is:

1. Layup (e), thin steel plates,
2. Layup (h), thick steel plates,
3. Layup (g), welded wire fabric
4. Layup (b), select shagbark hickory hardwood.

This ranking primarily factors the cost of raw materials and additional labor to produce the layups. Steel embedment requires preplanning of cuts and fastening zones, so that tools do not have to pass through wood and steel simultaneously. Despite this added fabrication planning, steel reinforcement facilitates use of economical and abundant softwoods in protective applications. Because protective panels must also resist blast effects and forced entry, the added ductility offered by the steel armoring enhances overall ductility and energy dissipation. Therefore, considering costs and enhancements to local and global ductility of panels, steel-reinforced softwood layups appear to be the most viable solution to develop and include in engineering models.

5 CONCLUSIONS

With either embedded steel reinforcement or an all hardwood CLT panel, it is possible to prevent ballistic perforation within a 254 mm (10 in.) panel thickness. One of the four successful CLT layups, however, stood out, because softwoods and thin steel plates are the most economical material options among those considered. Steel reinforcement, furthermore, provides ductility that may enhance the performance of panels in response to other hazards, such as blast, considered in protective design. For additional details of the ballistic tests described in this paper and other related testing, see the project report [20].

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