Deployable Wood Structures for Disaster Relief and Military Use

Jayson Leonard[1], Weichiang Pang[2], Michael Stoner[3], Dustin Albright[4]

ABSTRACT: Rapidly deployable structures may be used to speed up the recovery after natural disasters and to provide shelters for military personnel in hostile zones. The recent unforeseen disruptions caused by the COVID pandemic highlighted the needs for temporary testing centers or backyard pop-up offices. This paper investigates the development of deployable wood structures via four key factors, namely (1) deployability, (2) transportability, (3) functionality, and (4) cost. Currently, the military does not have an optimum design that excels in all the previously mentioned criteria. This study aims to design a rapidly deployable structure for emergency response such as disaster relief with the potential for military applications. This research begins by covering existing deployable shelters used for disaster relief and military applications. Next, it presents several alternative designs using different materials and different functionality. Then, it addresses how these new designs compare to the existing shelters in each category. Finally, it discusses tests performed on the folding mechanism being used throughout the design of a deployable wood structure. As a result of the study, new designs are shown to be competitive with the existing ones. The results of an experimental study of how hinges perform as structural elements will be discussed.

KEYWORDS: Cross-Laminated Timber, Deployable Structure, Disaster Relief, Military Shelters, Hinge

1 INTRODUCTION

As a society, we have all come to realize it is not always possible to know when disaster will strike. Disaster can take the shape of many forms including but not limited to, natural disasters, man-made disasters, war, and more recently, pandemics. When these events happen there is potential for people to be displaced from their homes and resources to be overwhelmed. This immediately calls to action the need for new structures, such as temporarily shelters and medical facilities. To build one of these from the ground up can be time-consuming and demanding for labor and materials. Therefore, the use of prefabricated or deployable structures could be put into place instead. The two primary uses for these structures investigated in this study are post-disaster and military applications.

The U.S. military currently has both expandable and non-expandable rigid wall tactical shelters. For easier reference, National Stock Number, which is an identifying number assigned to materials and items, is used by the U.S. military to identify a shelter. One example of an expandable unit is shelter designated NSN 5411-01-136-9838, an expandable unit with interior dimensions (expanded) of 18’ 4” L x 21’ 6” W x 7’ 1” H (Figure 1). The nonexpanded exterior dimensions are 19’ 11” L x 8’ W x 8’ H. This unit has a weight of 6900lbs and an assembly time of only 30 minutes with four soldiers. These units are designed to have dimensions consistent with a standard ISO shipping container of 20’ L x 8’ W x8’ H. This allows for easy and consistent transportation methods. These units are also made from steel which gives the units a rugged and durable finish. Along with traditional transportation methods, the military may also drop these units from aircraft with parachutes.

Figure 1: An Example of Expandable Rigid Wall Shelter (NSN 5411-01-136-9838)

The U.S. military also utilizes soft wall shelters as a means of less permanent shelter. The soft wall shelters are typically a stretched fabric supported by either a frame or pressurized air. An example of a frame-supported soft wall shelter is NSN 5419-01-465-3025EJ. The dimensions for this unit assembled are 20’ x 32.5’. The weight of this unit is 1250 lbs., and the erection time is less than an hour with four soldiers. An example of an air-supported soft wall shelter is the Airbeam tent NSN 8340-01-558-8707 (Figure 2). This structure is supported by a series of Airbeams that are inflated onsite. The weight of this structure is around 1000 lbs. With the supplied compressor, the erection time is only 15 minutes with four

[1] Jayson Leonard, Graduate Research Assistant, Clemson University, USA, jbleona@g.clemson.edu
[2] Weichiang Pang, Professor, Clemson University, USA, wpang@clemson.edu
[3] Michael Stoner, Lecturer, Clemson University, USA, mwstone@clemson.edu
[4] Dustin Albright, Associate Professor, Clemson University, USA, dalbrig@clemson.edu

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soldiers. The deployment of this structure requires electricity.

Figure 2: An Example of Air Supported Soft Wall Shelter (NSN 8340-01-558-8707)

2 DESIGN OF STRUCTURES

The goal of this research is to design prefabricated and rapidly deployable structures using wood, a sustainable and renewable material. There will be four distinct shelter designs that fall under two separate categories. The two categories are construction material and deployment strategy. The material choices are light-frame wood construction or cross-laminated timber (CLT). The deployment strategies include non-foldable (static) and foldable (dynamic).

The need for rapidly deployable structures can be seen in many different environments and cases. This played a large role in the design of the structures and was one of the first areas of concentration. On the civilian side of this research, the expected mode of shipment is by land through the use of semi-trucks. In order to make shipment of these units as easy and seamless as possible, ISO standard shipping sizes played a large role in the design footprint (ISO, 2020). A twenty-foot-long unit became the basis of design due to standardization and practicality. The most typical 20 ft long shipping container is 8 ft wide x 8.5 ft tall. Another standard-size shipping container is known as the “high cube” container. These containers are 20 ft long x 8 ft wide x 9.5 ft tall. By moving up to the high cube size, the structures become more liveable and comfortable with more headroom. Table 1 shows the key dimensions of the static and dynamic structure types. The static unit does not fold; therefore, the folded dimensions are not applicable for this unit type.

Table 1: Dimensions of the Static and Dynamic Structures

Unit Type	Deployed			Folded		
	Length	Width	Height	Length	Width	Height
Dynamic	20'	19' 5"	8' 3"	20'	6' 8"	8' 3"
Static	20'	8'	9' 6"	NA	NA	NA

2.1 Static Unit

The static unit follows a shipping container-like design that conforms to ISO high cube dimensions. The unit is 20’ long x 9.5’ tall x 8’ wide. These units can be fitted out to take a role such as a housing or medical unit. Figure 1 shows a static unit being used as a temporary housing structure. With around 160 sq. ft. of living space, the unit is not abundantly spacious, however, the space that is provided is highly functional.

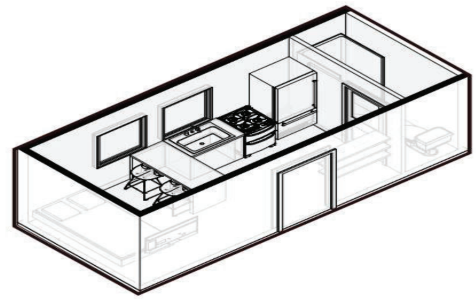

Figure 3: A Floorplan for a Static Unit.

2.2 Dynamic Unit

The dynamic unit is 20’ long x 8’-8” tall x 7’-3” wide when folded. When the unit is unfolded, it is 20’ long x 8’-8” tall x 21’-8” wide. Figure 2 shows one of many possible finished floorplans for a dynamic unit. The structure is supported only by the exterior walls allowing for the interior to be fully customized by the end-user. The top series of images shows the folding process. The bottom left image shows an exploded view of the entire unit, while the bottom right image shows the plan view of the floorplan.

By having both a static and a dynamic unit, users can choose based on their needs. For example, the end-user may prefer to have a static unit because it can be completely finished before shipment. Since the unit does not fold, all furnishings and finishes can be done before the end-user receives the unit. Also, there is no additional work once the unit is set on a foundation because the unit does not need to be unfolded. A dynamic unit may be chosen because they provide a larger liveable space that requires less room for storage and transportation.

When designing the dynamic unit, one of the first parts that needed to be figured out was how these units would expand and contract. There are many different strategies and designs that have been used in the past to achieve this task. For this research, continuous hinges were used as the folding mechanism. In addition, the hinges are designed to carry structural loads, namely, shear and uplift forces. By choosing hinges, the method of deployment would be through foldability of panels about the axis the hinge lies. This deployment method had many impacts on the design of the structure. One of which is the dimensions of each panel. Getting the structure within the ISO shipping standard sizes while also maximizing useable space took careful planning. Figure 3 shows the foldable unit in its final deployed state and locations of hinges needed for folding mechanism and for shear strength.

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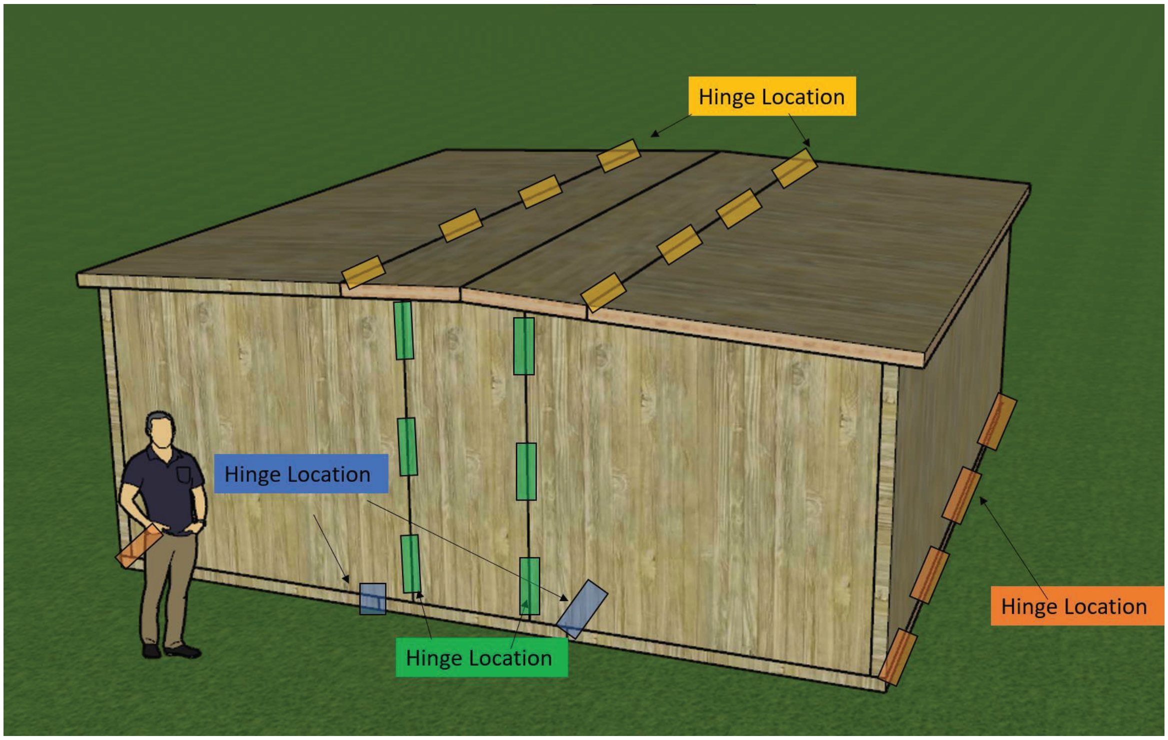

Figure 3: *Foldable Unit in Final Deployed State and Locations of Hinges Required for Foldability and Shear*

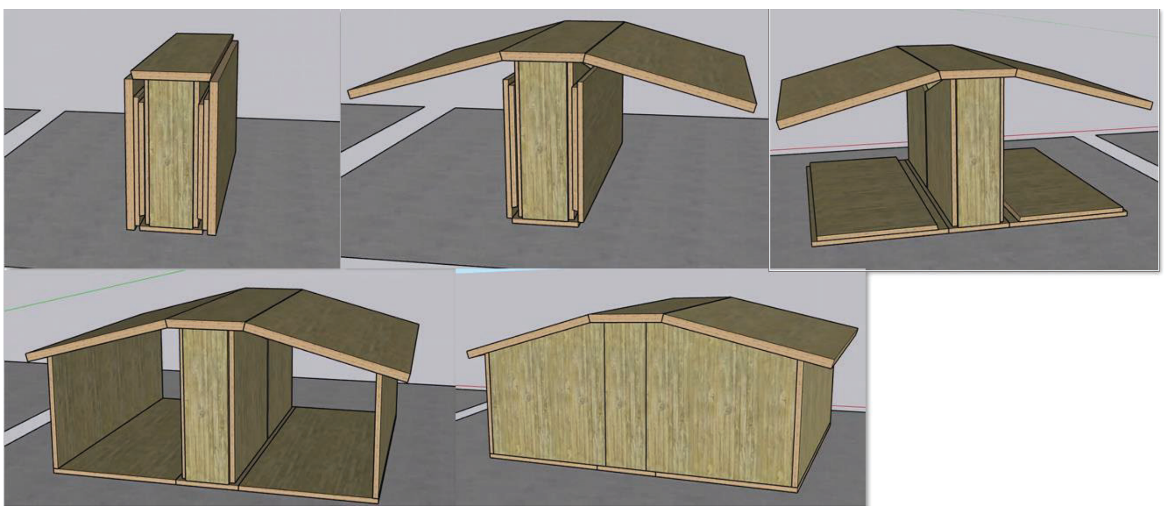

Figure 4: *Process of unfolding the dynamic unit.*

2.3 Light-Frame and Cross-Laminated Timber

Two materials are considered for both the static and dynamic units, namely light-frame wood and cross-laminated timber (CLT) panels. Light-Frame units are designed with traditional 2x dimension lumber or sawn lumber. The CLT units are designed using 3- and 5-ply Southern Yellow Pine CLT panels.

The static and dynamic units, each has its advantages and disadvantages. The light-frame units will be lighter than the CLT units allowing them to be transported and deployed more easily. Also, the light-frame units will have wall cavity space than can be filled with insulation which can provide a more comfortable and energy-efficient shelter. Light-frame units are also easier to hide electrical and plumbing within the walls. Also, since light-frame uses less wood than CLT, the final costs of these units are expected to be less than their CLT counterparts. The CLT models are much stronger and can be used in more extreme conditions. For example, CLT units should be able to provide greater resistance to threats such as blasts and ballistics.

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3 EXPEIRIMENTAL TESTING

3.1 Hinge Testing

This research also contains load testing on hinges that will be used within the dynamic structures. The hinges' main role is to provide a means of rotation for individual panel elements. Typically, the hinges would be ignored as structural elements, however, there is potential to expand the use of the hinges to act as shear and hold-down connections for the wall panels. The hinges would also need to be able to take the moment and shear applied by the wall members during deployment. Therefore, by gathering data on the strength of the hinges, one will be able to identify the capacity of the hinge connections.

A series of tests were performed on hinges to determine the structural load carrying capacities. There were two hinge types that were used for the testing in this research, continuous style hinges, also known as piano hinges, and residential butt hinges. Table 2 shows the hinge types and properties. For simplicity of naming and referencing, each hinge type may either be referred to as hinge A or hinge B throughout this research. Figure 5 shows some key dimensions of each hinge type.

Table 2: *Hinge Properties.*

	Hinge	
Property	A	B
Hinge Type	Continuous	Butt
Leaf Thickness	0.12"	0.0855"
Pin Diameter	3/8"	15/64"
Length	12"	4"
Width	5"	4"
Screw Diameter	0.25"	0.137"
Screw Length	3.5"	1"

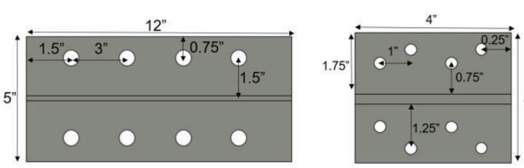

Figure 5: *Key Dimensions of the continuous hinge (left) and the butt hinge (right).*

Each hinge type was tested in two directions, loading parallel and perpendicular to the pin. Parallel to the pin tests will be referred to as shear tests, and perpendicular to the pin test will be called tension tests. Figure 6 shows a conceptual drawing of the directions each hinge was tested in. Multi-directional strength properties are important because the deployment stage will induce forces on the hinges. By completing these tests, the hinges could be incorporated into the structure's strength rather than ignored when in the deployed state. Along with the load tests performed on the hinges, there was also a material test performed on the leaf of each hinge. The material test provided key materialistic properties such as ultimate stress, yield stress, and modulus of elasticity of the steel used in the hinges. All these properties are important metrics when describing how a structural element performs. A summary of the load tests performed on the hinges can be found in Table 3.

Table 3: *Summary of Tests Performed on Hinges*

Test No.	Loading	Hinge Type
1A	Shear	A
1B	Shear	B
2A	Tension	A
2B	Tension	B

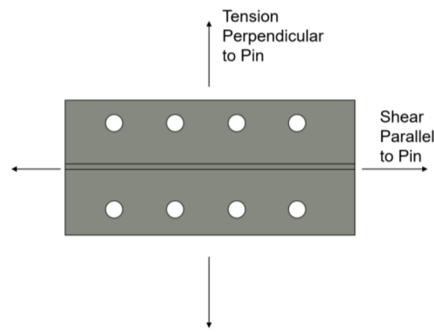

Figure 6: *Testing Directions on Hinges.*

3.2 Shear (Parallel to Pin) Test

Shear tests were performed on the continuous and butt hinge and are referred to as Test 1A and 1B, respectively. The shear tests were done to gather data on how these hinges would perform when loaded in the direction parallel to the pin. One way this type of loading could be observed in a structure is when shear is transferred from wall to floor panels. Both tests, 1A and 1B, were performed with cyclic loading. Cyclic loading is when a load is applied in one direction, then removed and applied in the opposite direction. The loading setup in both shear tests was set to follow CUREE standard loading protocol. Cyclic loading is often chosen over monotonic loading, single-direction loading without load removal, because it may represent loading caused by wind gusts or earthquake accelerations better. Figure 7 shows a conceptual drawing of the test setup for Test 1A (Shear of Continuous Hinge). Figure 8 shows the picture of Test 1A. 3-ply southern yellow pine CLT panels were used as the main member throughout these tests.

The string potentiometers were used to measure localized displacement, and the actuator was used to measure forces and displacements of the entire system. A displacement-controlled reversed cyclic loading protocol was utilized to perform the shear test. Figure 9 shows the force vs. actuator displacement of Test 1A. The figure also shows the expected design strength as well as measured stiffness. For the continuous hinge, Simpson Strong-Tie SDS screws were used to fasten the hinges to the CLT panels. The manufacturer provided the design ASD values, which are displayed in blue. The ASD value was then multiplied by the format conversion factor (K_F of NDS) to show a

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non-factored LRFD value (green line). A strength reduction factor was not used because the goal was to try to estimate the test peak value rather than a design value. Figure 10 shows the failure mechanism of Test 1A.

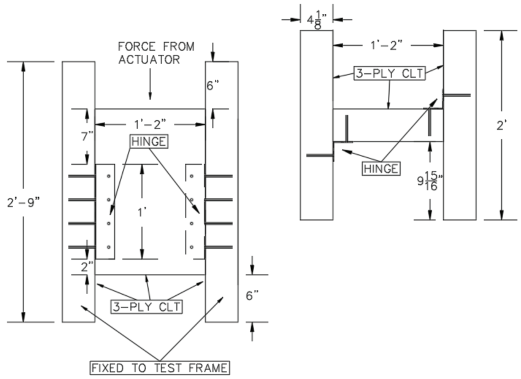

Figure 7: *Setup for Shear Test of Hinge Connection.*

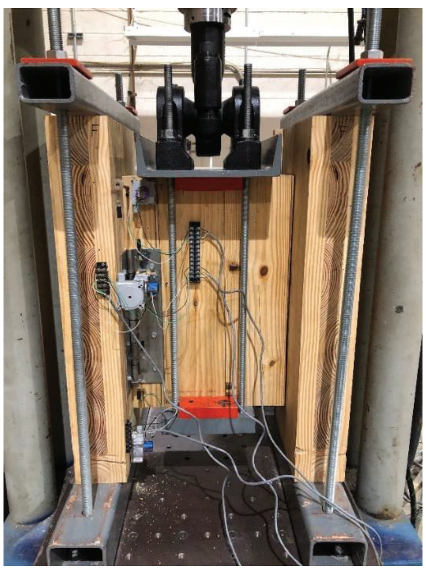

Figure 8: *Test 1A Setup and Instrumentation.*

The ultimate strength, yield strength, and initial stiffness of each hinge connection were determined from the test (Table 3). The ultimate strength was determined by identifying the peak force for the push and pull cycles. The yield strength was determined by offsetting the initial stiffness by 5% of the screw diameter (ASTM, 2018). The initial stiffness was determined by taking the slope of the initial part of the curve.

Table 3: *Summary Results of Shear Test 1A*

	Hinge A		
	Push	Pull	Average
Ultimate Strength (kip)	9.06	6.72	7.89
Yield Strength (kip)	5.08	3.12	4.1
Initial Stiffness (kip/in)	35.62	35.68	35.57
Initial Stiffness (kip/in)	18.1	21.9	20.0

Figure 10: *Failure in Test 1A*

3.3 Tension (Perpendicular to Pin) Test

Tension tests were performed on the continuous and butt hinge and are referred to as Test 2A and 2B, respectively. The tension tests were performed to gather data on how these hinges would perform when loaded in the direction perpendicular to the pin. Loading conditions that could cause these forces on the structure could be through deployment, raising panels into place, and forces that act normal to the panels, such as suction caused by wind. Both tests, 2A and 2B, were performed with monotonic loading, which is when a load is applied in one direction at a constant rate until failure. Monotonic loading was chosen for this direction because compression toward the pin would not provide useful or practical data. Figure 11 shows the test setup for Test 2A.

Figure 11: *Test 2A (Tension of Continuous Hinge)*

Table 4: *Characteristic Properties Concluded from Test 2A.*

Ultimate Strength (kip)	8.4
Yield Strength (kip)	3.6
Initial Stiffness (kip/in)	42.2

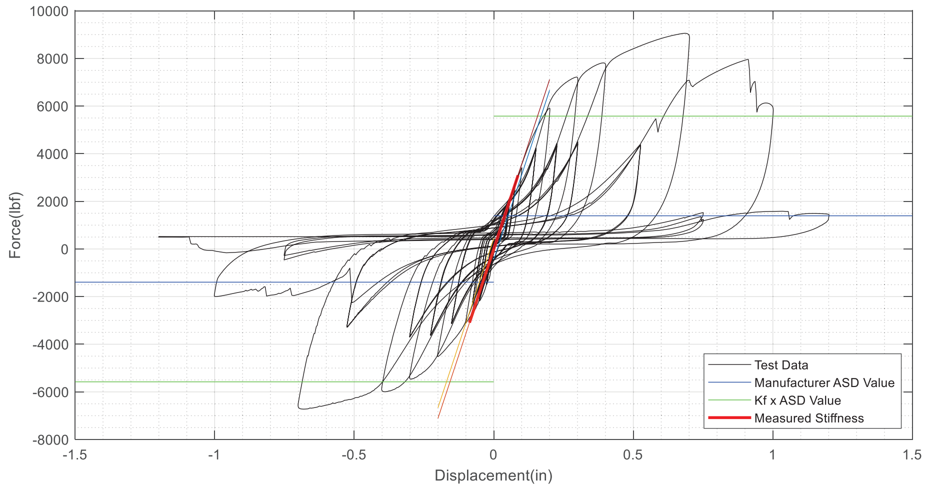

Figure 9: *Force versus Displacement of Continuous Hinge (Test 1A).*

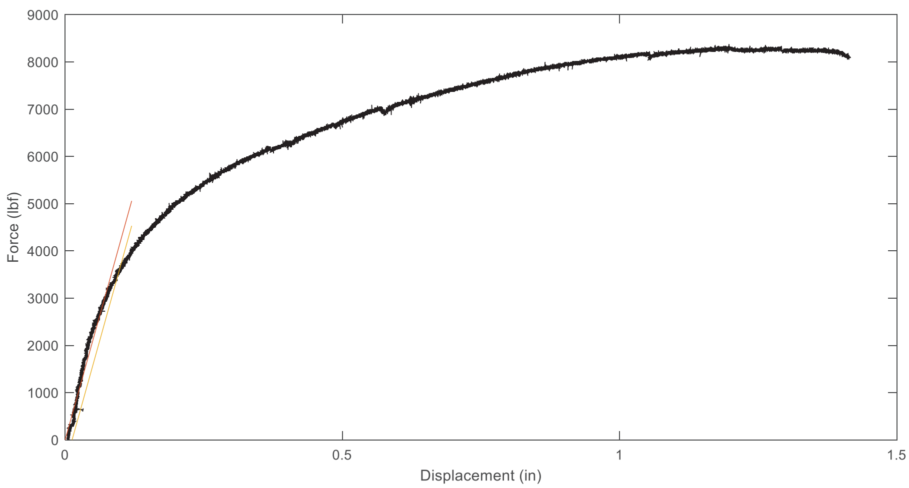

Figure 12: *Force versus Averaged Displacement of SP1 and SP5 for Test 2A*

4 PERFORMANCE MEASURES

Both the static and dynamic units were designed for gravity loads (live and dead loads), wind and seismic loadings. The results from the hinge tests were used to design the dynamic units. Four designs were produced from this study: (1) Static Light-frame Unit, (2) Static CLT Unit, (3), Dynamic Light-frame Unit, and (4) Dynamic CLT Unit. Four metrics were used to measure the performance of each of the four designs. These metrics are (1) Deployability, (2) Transportability, (3) Cost, and (4) Building Envelope Resistance. By providing each structure design with a score in each category, the end user can quickly determine which structure will best suit their needs. Some of these categories could be subjective; however, the goal of the scores is to relate the structures relative to each other. Scoring in each category ranges from 1 to 4. A score of 1 means the structure did not perform relatively well in that category. A score of 2 or 3 means that the structure performed about on average in that category. A score of 4 means that the structure performed the best.

4.1 Deployability

Deployability is a measure of how easy it is for the structure to be deployed. Factors that affect deployability include weight, time to assemble/erect, and required tools. Deployability is an important metric as it relates to ease of use. The concept of disaster relief is to be able to provide assistance in a quick and easy manner. If a structure requires specialty tools or labor to be usable, it would not be considered especially deployable. Another reason deployability is important is that in remote areas, there may not be access to large machinery to lift the panels to unfold the unit. As a full-scale model was not in the scope of this research, assembly time could not be measured. However, estimation could be made from similar-sized structures used in the military. Also, an exact time deployment is not as important as the general time between each structure as this scoring system is only meant to compare relatively between each four structure designs. A score of 1 in deployability would be because a structure is lightweight, requires very little if any work upon arrival, and does not require special tools or machines.

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4.2 Transportability

The transportability category is a measure of how easy it is to transport these structures. Another consideration is how many structures can be shipped on one truck. Transportability is a function of the weight and size of the unit. All these units were designed to be within ISO standard shipping sizes. The maximum weight of a step deck trailer is 45 kips, and the maximum dimensions are about 50 ft long x 8.5 ft wide x 10.5 ft tall. This limits both the static and dynamic units to two units per shipment. However, when looking at shipment in terms of square feet per shipment, the dynamic units has clear advantage. The light-frame dynamic unit scored the best because it is relatively lightweight and can deliver more usable square footage than its static unit counterpart. The CLT dynamic unit scored the worst because it weighs the most.

4.3 Cost

Cost is important because it shows the feasibility of implementing these structures on a wide scale use. As with any product, the price can fluctuate depending on the materials used in production. Also, the price can be reduced when built in large quantities. However, for this research price of a single unit will be estimated at the current prices. The current price for 3-ply southern yellow pine CLT is around $39 to $44 per sq. ft. (J. Gouge, personal communication, January 19, 2022). For the CLT structures, a cost of $40 per sq. ft. was used as this is within the expected price range. These prices do not include the assembly of the units.

4.4 Building Envelope Resistance

Building envelope resistance is an important category for consideration in both civilian and military sectors. Some factors that could be used in this category include debris impact resistance, insect resistance, and fire resistance. Some factors that may play a larger role in military use are ballistic and blast resistance. The latter two factors will be used to create a score for each structure in this category.

The ballistic performance of the CLT panels was estimated using the THOR CLT model introduced earlier and shown in equation 2.5.2-1. The calculation was performed for a half-inch diameter steel ball projectile. The estimated striking velocity that can be resisted by a 3-ply southern yellow pine CLT panel is 1650 fps. Modern firearms do not use spherical steel balls as projectiles, and therefore these results are difficult to compare to real-world ammunition types. However, comparing the striking velocity to the velocities shown in Figure 2.8, it can be estimated that the CLT structures may show ballistic performance around the III-A NIJ rating. This roughly means that the CLT structures could be able to all common handgun bullets. Level III-A exceeds or meets most law enforcement agencies' requirements in the U.S. (T. Muszynski, personal communication, June 27, 2022). The light-frame walls are built up from ½ in. dry wall and 7/16 in. OSB sheathing with studs spaced at 24 in. O.C. The light-frame walls will provide practically zero ballistic resistance. These walls will not even meet the lowest NIJ rating of level I.

4.5 Performance Measure Summary

Each structure was assigned scores in the categories of deployability, transportability, cost, and building envelope resistance. A radar chart shown in Figure 13 was made to show each performance category for all structure types together. This chart makes it easy to see which units perform best in each category and helps the end user determine which unit is right for their purposes. If a structure type has a higher score, it means that it performs comparatively well in that category.

5 CONCLUDING REMARKS

This research has contained the design of four types of rapidly deployable structures using different materials and deployment strategies. These units could be used in many different environments for multiple purposes; therefore, variety is important. There have also been tests performed on multiple hinges that will be used to gather important parameters. Moving forward experimental testing on the hinges will be completed and a better understanding of their behavior will be discussed.

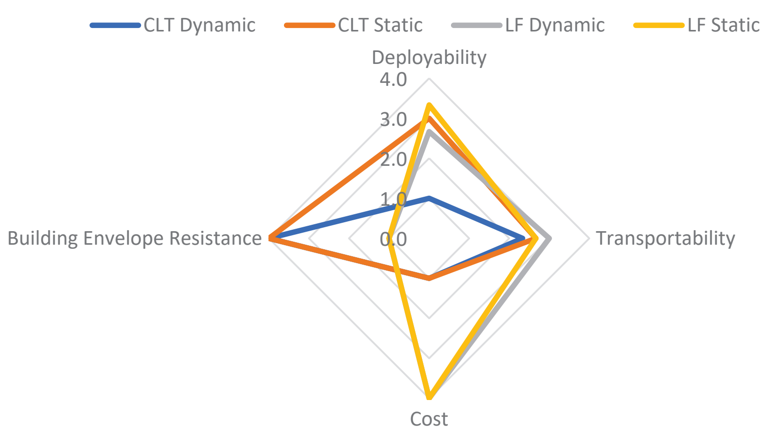

Figure 13: *Radar Chart Showing the Results of the Performance Measures*

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