PREDICTING AND COMPARING THE MECHANICAL PROPERTIES OF DIAGONALLY LAMINATED TIMBER (DLT) PANEL BY SHEAR ANALOGY APPROACH

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ABSTRACT

Wood is natural and orthotropic as a material which has been used in large and small scale construction for years. Cross laminated timber (CLT) is a product of several wood panels. From previous research it was found that mechanical properties can be improved by arranging the cross layers in angle named diagonally laminated timber (DLT). Soft wood white pine and hard wood black locust were considered for the proposed design of the specimens. In this study two cross layers will be considered in same angle but in inverse direction for four types of specimens as a) four layers of white pine, b) outer layers of black locust and cross layers of white pine, c) outer layers of white pine and cross layers of black locust, d) four layers of black locust. Effective shear strength and effective bending strength will be predicted through shear analogy approach and then the results will be compared with the existing standard of CLT. This prediction will provide a clear direction for further experimental research on the mechanical properties of the proposed design of DLT.

Keywords: *Cross laminated timber, bending and shear stiffness, soft wood, hard wood & shear analogy*

1. INTRODUCTION

With the rapid growth of the construction industry, material production rate is increasing. Most commonly used materials for construction are cement, steel, concrete and much more but what if we think a little deeper about the life cycle of these materials? These material production results in huge carbon dioxide emission which is a threat towards our environment. But construction is also important for the development of a country. In recent years idea of sustainable construction has become popular and people are thinking more seriously about protecting environment. The concept of sustainable construction is construction with the least disturbance to the environment and one way to achieve this is by using materials which have the least harmful impact on the environment. For example, timber is naturally available which is the reason of having a good market place comparing with the other construction materials. To use timber in construction and to give required stiffness, some layers of timber can be glutted together in a way that each of the layers will be perpendicular to the other which is called cross laminated timber (CLT)(P. Crovella, W. Smith, 2017). Sometimes these layers can be gutted in different angles or diagonally; in that case, we call them angle ply wood or diagonally laminated timber (DLT). The production of CLT and DLT is developing and innovating which might replace the usage of concrete and steel as a major element of construction for flooring, wall, roof and slab, stair, and others. Key advantages of laminated timber are early completion of projects, easy handling and preparing, high quality and accuracy in prefabrication stage, cheaper than other conventional composite structured lumber and also shows light weight framing of the building structure. Again, the usage of CLT has proliferated because of relatively high strength to weight ratio, fame of sustainable and environment friendly material and high prefabrication potential. Though the

Figure 1: CLT panel lay-up process

cross layers of CLT panels distribute the load in minor direction, they are weak in strength and stiffness because of facing rolling shear stress perpendicular to the radial tangential plane and the orthotropic nature of wood. So the overall strength and stiffness can be improved if we develop this cross layer condition(Bahmanzad et al., 2020b). Previously cross layers in lower angle than 90 were used and remarkable upgrade in strength and stiffness were found. Therefore, considering all these, the idea of our study is to arrange double cross layers in same angle but in opposite direction to predict how it behaves.

Figure 2: Angled ply CLT panel orientation detail

2. BACKGROUND STUDY

Three main structural materials used currently in construction industry are steel, concrete and timber. We can minimize environmental impact if timber is used in structurally efficient building. In parallel to the grain direction timber shows similar strength of reinforced concrete. Though hard wood is slightly stronger and soft wood is slightly weaker, timber cannot exhibit the same compression strength as modern high strength concrete. Again, stiffness in concrete is more than timber and stiffness in steel is far more than both concrete and timber. However, timber is quite efficient in long span and tall structure where a significant part of load can be carried by the structure is its self-weight because of its low density. For example: roofs, some bridges and the gravity load resisting system of tall buildings(Ramage et al., 2017). On the other hand, because of the low strength and stiffness properties for timber, loads perpendicular to the grain direction are suggested to avoid in timber constructions. Poor dimensional stability is another problem for timber. For the variation in moisture content, timber can shrink or swell. Cracks in the area of connection or where single load occurs are very dangerous because it decreases the performance of a construction and this crack can occur because of huge change towards dimension which is perpendicular to the grain direction. The poor properties of timber perpendicular to the grain direction can be improved using reinforcements : timber screws, glued-in rods, nail plates or glued-on timber products. Though these are efficient for local problems, they are quite inefficient when nearly the whole timber member needs to be reinforced. Considering all these, solid wood or glulam can be replaced by a building material with better properties perpendicular to the grain direction. For instance, CLT instead of solid wood or glulam could be used where no more additional reinforcements are needed. Though using CLT elements instead of solid wood and glulam would increase the dimensional stability, the crosswise orientation of the layers results in the smaller bending stiffness in CLT than the solid wood or glulam beams with identical dimensions. Hence, CLT is not suitable for the wide spanned beams as their performance is dependent on deflections and bending stiffness. Therefore, the field of application for CLT in beams has been reduced. Concentrating on all these, a new product diagonal orientated timber (DLT), was created. According to the study of Dr. I. Bejtka, for a symmetric DLT beam at least two diagonal layers of similar angle in opposite directions are needed and they can be separated by a parallel layer or not. He found that DLT beams are better than CLT for not only in terms of shear stress but also for the local modulus of elasticity (MOE) hence for the bending stiffness. Thereby, it was clearly indicated in his study that this result is more valid for DLT beams with side by side and in the opposite direction and diagonal to the beam axis orientated layers contrasting that, diagonal orientated layers, which are separated by at least one parallel layer, are not so good. Moreover, his results demonstrated that though bending stiffness increased, it was not significant for diagonal orientation of the layers ($\alpha = 45°$)(Bejtka, 2008). In 2012 researchers found in their study that shear strength decreases (around 65.9%) with the increase of grain angle from 0 to 90 degree(Gupta & Sinha, 2012). Again in one study using CLT of alternating 45 degree layer increased strength 35% in four point bending test and compression strength increased by 15% also stiffness increased by 15% in four point bending test where 30% in compression for Norway Pruce(Buck et al., 2016). Moreover, Dr. Bahmanzad determined that orienting cross layers in 30 and 45 degrees increased the shear strength 98% and 59% respectively. Surprisingly in his another study effective shear stiffness increased 209%, 367% and 828% for grain angle 60,45 and 30 respectively(Bahmanzad et al., 2020a). Considering them all our study proposes a design of diagonally laminated timber having double cross layers side by side in opposite angle. The aim is to apply different angles in shear analogy model and predict effective shear stiffness and effective bending stiffness to have an idea about the best angle and future application of this new product.

3. METHODOLOGY

Our proposed design for DLT is shown in a detailed table below:

Table 1 : Detailing of layers of DLT

SI No.	Layer 1	Layer 2	Layer3	Layer4
a	White Pine	White Pine	White Pine	White Pine
b	Black Locust	White Pine	White Pine	Black Locust
c	White Pine	Black Locust	Black Locust	White Pine
d	Black Locust	Black Locust	Black Locust	Black Locust

According to wood hand book, shear analogy is the most precise design method for cross laminated timber. Findings were confirmed by the tests performed by FPInnovations. In this method effect of modulous of elasticity and individual shear modulous of each layer are considered. Here the characteristics of multi-layer cross sections are considered as two individual virtual beams A and B. where beam A is given the flexural shear stiffness and beam B is given the increased moment of inertia because of the distance from the neutral axis and of the flexural and shear stiffness of the panel. These beams are coupled with infinitely rigid web members so that an equal deflection between beams A and B is obtained. By overlaying the shear and bending stiffness of both beams the end result of the entire cross section can be obtained. According to the approach following theories were used to predict the stiffness implementing their mechanical characteristics. Elastic moduli of hard wood black locust was used 2050,000 lb_f/in^2 and for the soft wood white pine was 1240,000 lb_f/in^2 according to wood data base. Cross section of the layers was considered 12x1.375 in^2 with length about 27 inches according to the requirement of CLT hand book.
Effective shear stiffness was predicted by the following theory (1):

$$(GA)_{eff} = \frac{a^2}{h_1/2G_1b + \sum_{I=2}^{n-1} h_i/2G_ib \ \ +h_n/2G_n.b} \tag{1}$$

Effective bending stiffness was calculated using theory (2):

$$(EI)_{eff} = \sum E_ib_ih^3/12 + \sum E_iA_iZ_i^2 \tag{2}$$

And finally for apparent bending stiffness theory (3) was used:

$$(EI)app = \frac{E_{eff}}{1+ EI_{eff}x\ k_s / (GA_{eff}xL^2)} \tag{3}$$

here Ei and Gi = modulus of elasticity and shear modulus of layer i, respectively; Ai = area of cross section of layer i; and Zi = distance between the center axis of layer i and the neutral axis of the entire cross section; a = distance between the centroid of the top and lower layers of cross section; and hi = thickness of layer I, b= width of layers, L = DLT span. Ks was solved from the table given in CLT hand book.

4. ILLUSTRATIONS

4.1 Figures and Graphs

Since Eastern White Pine is categorized as the soft wood and Black Locust is categorized as hard wood according to the wood hand book, it is not surprising from the prediction that proposed design of DLT completely with Black Locust is always exhibiting the higher bending stiffness then other combination of DLT. The second higher bending stiffness is shown by the specimen which is composed with the outer layers with hard wood Black locust and cross layers with soft wood White Pine. The lowest bending stiffness is as predicted from the whole panel designed with soft wood White Pine where outer panel with White Pine and cross layers with Black Locust is showing a little higher stiffness than the lowest. In all cases though effective bending stiffness given for V2 species in transverse angle in PRG-320 (standard performance rated for CLT) are lower than our predicted bending stiffness which are depicted in the graph below:

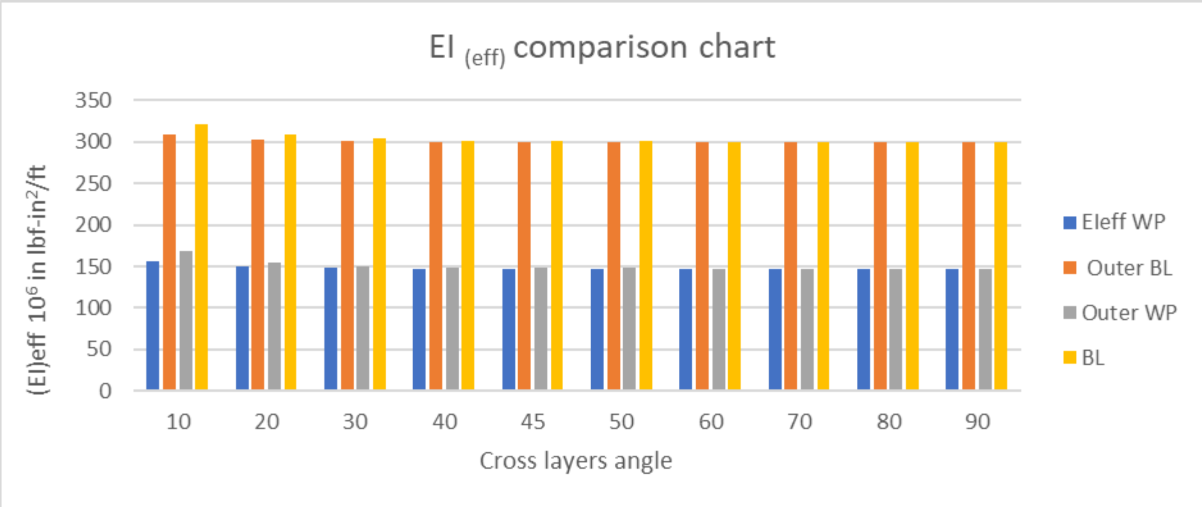

Figure 3: Effective bending stiffness prediction from the calculation

On the other hand, from the graph of effective shear stiffness comparison, unlike the bending proposed specimen built outer layers with White Pine and inner layers with Black Locust performs as good as the whole panel made of hard wood Black Locust while the other two are exhibiting the quite similar performance. Though the performance is better than CLT only for the angle 30 degree and lower according to PRG-320. So in the structure where there is a possibility of higher shear force outer layer of white combined with Black Locust can be used instead of full panel of hard wood Black Locust to be more cost effective.

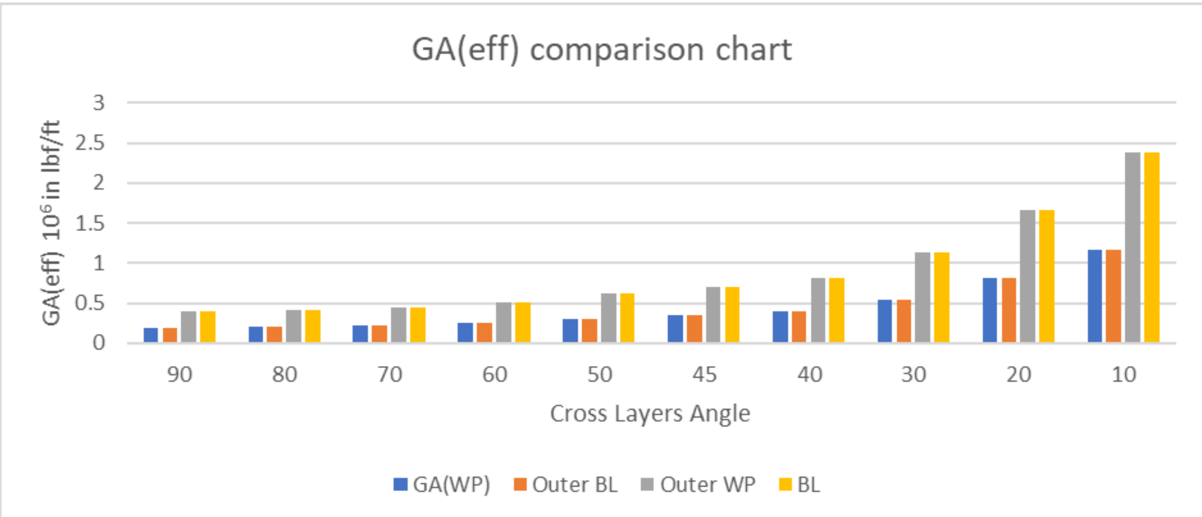

Figure 4: Effective shear stiffness prediction from the calculation

Finally in the term of apparent bending stiffness, which is a combination of both the shear and the bending gives us an overall idea of the performance of the proposed panel. As thought all the combined specimens were better performing than the specimen solely built with the soft wood White Pine and lower performing than the whole panel of Black Locust. It is noticeable that outer layers of White pine panels are stiffer than the outer layers of Black Locust CLT panel.

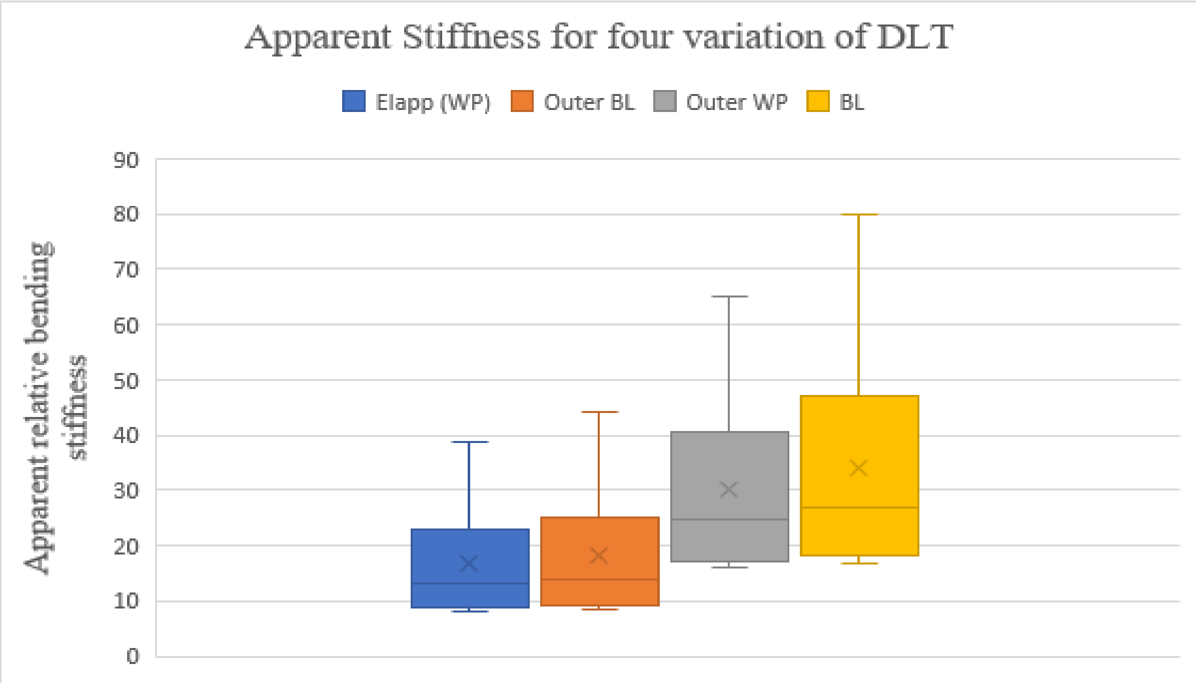

Figure 5: Apparent stiffness prediction from the calculation

5. FUTURE IMPLEMENTATION AND LIMITATIONS

Since CLT of different species have not been tested previously, this study would motivate the future experiment with new wood product made of heterogenous species also this study may create a new perspective of using cross layers side by side in different angles in inverse direction. Traditional CLT products have odd number of layers with an alteration of longitudinal and transverse angle. But this proposed design aims to reduce one layer from the middle and set two cross layers side by side in inverse direction which is ultimately going to reduce the cost of production. Also if available soft wood could be used in combination with the hard wood production cost might also be lower. To be more accurate about the performance of soft wood and hard wood combination lab tests along with the finite element method are recommended. The limitation of the study is that there is no previous test result of this new proposed design with which we can compare. Hope in future researchers would be motivated to do enough lab experiment to set the standard for this new DLT design.

6. CONCLUSIONS

This study aims to propose a new perspective in the design of timber products. Traditionally cross laminated timber has been used and researched about their mechanical properties. Analyzing those results this study theoretically predicts performance about employing double cross layers side by side in inverse direction. Predicted results were higher than the conventional CLT panels as per the standard for angle employed 10 to 30 degrees. Further experimental results are needed for more accurate prediction and real life implication in the construction industries.

ACKNOWLEDGEMENTS

This study was done under the supervision of Dr. Paul Crovella. Without his support it would be hard to accomplish this research.

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