Understanding the applicability of natural fibre composites in hybrid folded structures

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Abstract

One of the important by-products of wood is veneer sheets which can be pressed together to form plywood. Also known as radiata pine veneer, plywood has been increasingly used in different engineering applications and its unique thin structure, with significant mechanical properties, has increased its demand for hybrid deformed structures. The main scope of the present work is to understand the formability characteristics of the plywood with multiple bend axis on the same plane. The properties of wood nullify the normal bending process due to the significant amount of spring-back for the inherent properties of the constituent natural fibres bounded by a predominant lignin component. The process of in-situ curing and post-forming curing were used to achieve the desired folds. Experiment was performed on various plywood samples, with 4-point bending rig, to understand the variation in stress and strain due to variable distances between the bends and the maximum post-curing time. Finally, the overall spring-back analytically varied oby1.96%. Copyright © 2018 VBRI Press.

Keywords: 4-Point bending, forming of 3-ply laminates, spring-back, spring-forward, structural significance of plywood.

Introduction

Fibre reinforced polymer composites have gained wide acceptance in civil engineering community for the past few decades [**1, 2**]. FRP composites possess several advantages over traditional construction materials, including a high strength-to-weight ratio, excellent corrosion resistance and reduced construction effort. AllFRP structural systems have been explored by many researchers [**3, 4**]. The fibre is predominantly unidirectional, either aligned parallel or perpendicular to the element direction. This limitation arises from existing manufacturing technologies and the inability to tailor the fibre direction often results in uneven distribution of strength across the section and buckling failure modes. Material thickness can be increased to prevent these problems, but this is an inefficient usage of expensive FRP materials and subsequently the cost becomes significant. While some research has investigated optimizing the design of fibre composite structures for civil engineering applications [**5**], such optimizations only consider existing structural profiles, and therefore, are subjected to the same disadvantages. Development of FRP-reinforced timber hybrid structures has been rather limited compared to concrete and steel structures. This is believed to be mostly due to economic factors and complexity of issues related to bonded interface, durability, and performance under fire. However, current increase in interest in sustainable timber structural systems means that there has been recent work towards novel FRP-reinforced timber hybrid forms [**6, 7, 8**]. Investigated applications include FRP retrofitting of end-of-service-life timber bridges and ancient timber structures [**9, 10**], FRP reinforcement of weak sections in glulam beams [**11, 6**] and new forms of FRP-timber construction that utilise low-cost non-structural timber [**7, 8**]. Such hybrid systems minimize the required usage of expensive FRP materials; however, significant amount of fundamental research remains un-touched.

Engineers have significant knowledge about thin-walled plates being folded to increase any shell's second moment of area and bending stiffness. This is more commonly known as origami-inspired engineering. It is indeed a rapidly growing research field [**12**]. The use of developable folded patterns additionally allows origami engineers to efficiently and easily manufacture applications that can utilise these improved behaviours. Current applications are already seen in deployable and modular housing [**13**], energy-absorbing barriers [**14**] and lightweight automobile and aircraft components [**15**].

Veneers of radiata pine is a primary aspect of woodworking in order to produce flat panels and surface coverings. The main advantages of the radiate pines being their significant laminating, turning and shaping characteristics [**16**]. However, commercially available veneers (usually less than 1 mm thick), glued into core panels or plywood, can have other value added applications, such as, channel sections, hollow-sandwich structures, corrugated sheets and others, if they can be formed into desired profiles [**17**]. Srinivasan et al. [**16**] concluded that 3 ply veneer sheets have the most significant properties in forming. Therefore, applicability of commercially available veneer plywood, in the field of origami-inspired engineering, is a possibility and may lead to the goal of developing the required hybrid systems. The main scope of this research work is to study and observe one of the various formability characteristics of the plywood made of 3 plies of radiata pine veneers.

The radiate pine veneers are softened, to make it pliable, by soaking into a hot water bath [**16, 18, 19**] and the characteristics during double bend by a 4-point bending rig are studied. Temperatures above the glass transition temperatures (GTT) of the constituent hemicelluloses and lignin are ideal to make the wood soft for forming. The GTT also decreases as the moisture content reaches the fibre-saturation point. Even after softening, the anisotropic nature of the wood structures may result in unwanted and unaccounted distortions after forming, due to the variation in the moisture content and the temperature of the veneers [**20-22**].

The problem of efficient manufacturing of curved-crease geometries at large scale was solved with the development of an innovative, cured-in-place manufacturing process [**23**]. The introduction of the process resulted in opening up a new avenue where 3D structures could be formed from flat surfaces of laminates. This invention led to the possibility of bending/forming plywood to form origami structures. In order to achieve that objective, detailed understanding of the forming parameters is required. This detailed study, for a single bend, in a static vee-bending rig was conducted by the authors. The results obtained from that is implemented into the current study, to observe whether they are valid for multiple bend cases. The analytical validation is also carried out for the study. This forms a significant step towards understanding the rig for forming complex structures in plywood, with multiple bends. This will also help in observing the limitations for manufacturing further complex origami structures.

Experimental

Sample

The sample used for the detailed parametric analysis is illustrated in **Fig 1**. **A** 3-ply laminate was used for the experiments, with each veneer sheet being 0.6 mm thick and the plywood being 1.9 mm thick. The length of the samples was made from 280x30 mm to 90x20 mm, cut-out from the commercially available plywood sheet (1220x2440 mm). The orientation of the grains of the plywood was 0˚/90˚/0˚, with the veneer grains being perpendicular and parallel to the bend axis alternatively. The glue used for preparing the plywood was the commercially used poly (vinyl acetate) or PVA, as established through Attenuated Total Reflection (ATR-FTIR) process.

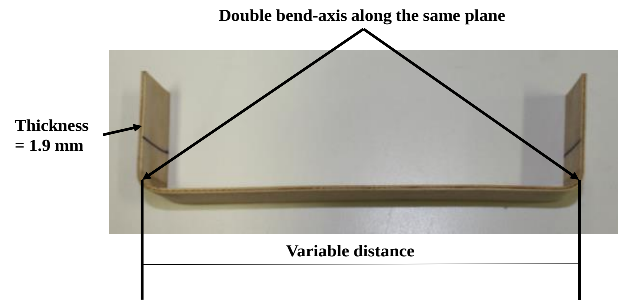

Fig. 1. The plywood sample used for the experiments.

Experimental setup

A 4-point bending rig was designed in CREO Parametric, with a wider span, for conducting the experiment. The top supports, responsible for performing the bending, were heated to about 200°C using heating elements and the temperature was controlled using a temperature controller and thermocouple, as shown in **Fig. 2**. The bottom supports, responsible for providing support and shape to the structure, were kept at room-temperature. High temperature resistant plastics were used as insulators to make sure the temperature is not passed to the load cell of the Instron through the top scale. A cooling fan and compressed air were used as the cooling system to keep the high temperature under control

The samples were cooked in a water-bath at 70°C for 60 sec giving a moisture content of 24.8%, as established from the previous studies conducted by the authors. The Instron was set to achieve 400 N load at the end of the experiment, when it displaces the entire length of the supports at a rate of 200 mm/min. The in-situ curing was carried out for 60 sec and the post-forming curing was observed after 10 min, 24h, 48h and till 72h.

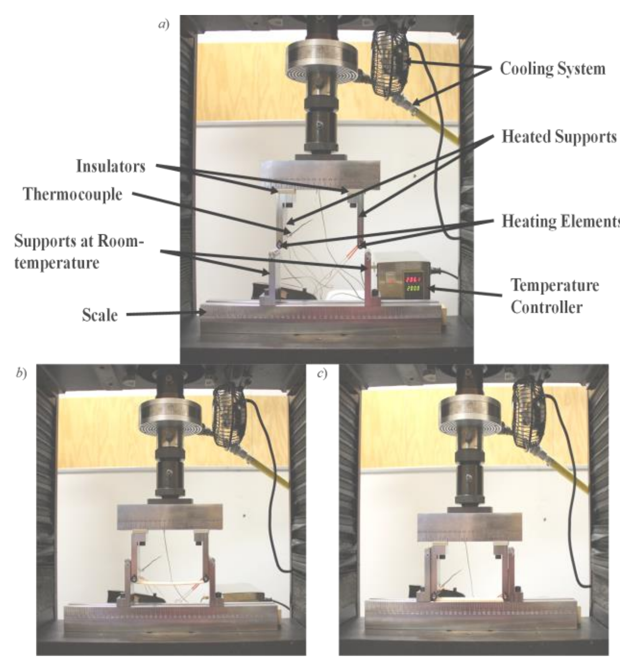

Fig. 2. Representation of a) the experimental setup, b) the rig during the experiment and c) the rig when the supports have reached the final position before retraction.

Experimental procedure and response measurements

The Instron was programmed in a way so that it captures the strain variation for each test, the flexural stresses, the hold value, the in-situ curing time and the flexural extensions experienced. The distance between the bends were varied from 200 mm, through 150 mm, 100 mm, 80 mm, 60 mm, 50 mm, 40 mm, 30 mm, 20 mm and 12 mm. With the variation in the bend distances, the length of the samples was also varied along with the thickness, to minimize material wastage. Each sample was tested for 5 times, to eliminate human error during experiment. The strains and stresses were tabulated for each case, averaged over the 5 cases for each sample type and finally plotted to observe the response.

Results and discussion

Experimental Finding

The detailed study helped in achieving the primary objectives of the study. Plywood having various spans were analysed to observe the variation in the respective stress and strain of the structure, while bending. To eliminate human errors and experimental errors, each span was tested 5 times and the overall average was considered for detailing each and every result. Literature has shown that the post-forming curing time to be 24 h usually, however, this study has investigated further in understanding the actual post-forming curing time and in estimating the actual time for achieving almost complete stability of the formed or bended plywood.

The plywood was bended at a right angle, with the 4-point bending rig, and the subsequent effect and the amount of spring-forward and spring-back were measured after initial 10 min of the test, after 1 day, after 2 days and finally after 3 days. The outcome of the spring-forward and spring-back values are given in **Table 1**. It can be observed that the amount of spring-back is relatively low at the initial 10 min threshold. In fact, for smaller spans from 40 mm to 12 mm, the plywood was found to experience spring-forward phenomenon in the initial stages. The plywood was placed at room-temperature and in an open yet safe place over the night(s). It is prominent that, the percentage difference between the spring-back (forward) experienced during the initial 10 mins and a day was huge. All the sample experienced spring-back motion to about 90%, with a few even going above 100%. Therefore, it is obvious that the plywood was stabilizing over the 24 h. However, the results obtained from observations after 48 h and 72 h are very similar to that of 24 h. The highest percentage deviation is 1 %, with a few having null deviations. The overall variation on the 2nd day was as little as 0.23% and that on 3rd day was negligible at 0.09%. The results also imply that the plywood experiences very little amount of spring-back even after the 1st day which gradually decreases to a negligible amount on the 3rd day. The strain analysis is carried out, with respect to time, based on the data provided by the Instron. **Fig. 3** illustrates the various strains experienced by the sample when the spans are varied from 200 mm to 12 mm.

Table 1. The final spring-back observed from forming the plywood.

Span (mm)	*Post 10 min (°)*	*Post 24 h*		*Post 48 h*		*Post 72 h*	
		Spring-back (°)	*%*	*Spring-back (°)*	*%*	*Spring-back (°)*	*%*
200	0.1	7.91	98.74	7.87	0.51	7.88	0.13
150	1.15	7.39	84.44	7.40	0.07	7.43	0.47
100	2.51	7.87	68.11	7.88	0.13	7.88	0.00
80	2.8	7.89	64.51	7.89	0.00	7.89	0.00
60	0.88	7.18	87.74	7.13	0.70	7.15	0.28
50	0.67	7.18	90.67	7.23	0.00	7.22	0.14
40	-0.39	7.12	105.5	7.19	0.97	7.18	0.14
30	-1.06	7.52	114.1	7.55	0.40	7.57	0.26
20	-0.74	7.52	109.8	7.55	0.40	7.57	0.26
12	-1.35	6.93	119.5	7.00	1.00	6.98	0.29
Overall % variation between the post-formation curing time							
Variation between 1st and 2nd day			0.23	Variation between 2nd and 3rd day			0.09

The strains are tabulated for each span by averaging all the strains achieved from the 5 trials, conducted to minimize human errors. It can be observed that the strain experienced increases gradually with the decrease in span length, with the minimum strain being 0.01325 when the distance between the bends is 200 mm and the maximum being 0.3418 when the span length is 12 mm.

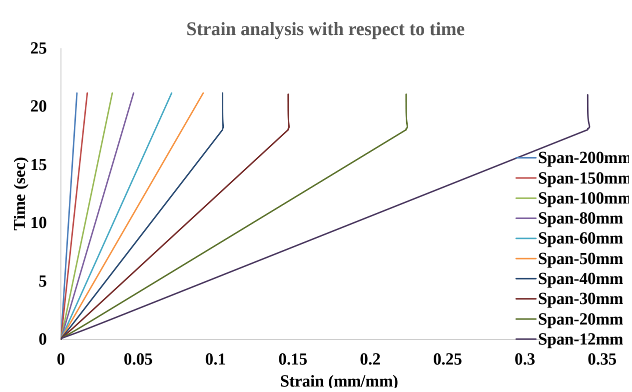

Fig. 3. Variations in the strains experienced due to changing the span lengths of the plywood from 200 mm to 12 mm.

The strain analysis outlines that a huge variation in strain takes place when the span length changes, with an increase in more than 96% with a decrease in span length of about 94%. Therefore, it will be extremely interesting to conduct the strain analysis in a more detailed manner, using complex methods, such as, grid strain analysis or others. Another interesting aspect studied include the stress variations of the spans with respect to time. A particular trend is not followed in this case, with the maximum stress being experienced with the span length of 100 mm and the minimum for the span of 50 mm. However, three peaks were obtained and interestingly the maximum for all the three belonged to different span lengths, with the highest peak between 0 and 10 secs being of 150 mm, that between 10 to 20 sec being of 30 mm and the last one between 20 and 30 sec being of 100 mm and also represented the highest peak and the maximum stress experienced. The details of the stress versus time analysis is represented in **Fig. 4**.

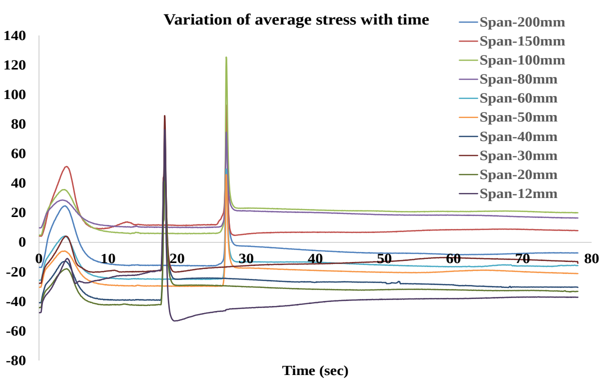

Fig. 4. Variations in the stresses experienced due to changing the span lengths of the plywood from 200 mm to 12 mm.

The maximum flexural stress experienced during the bending, was for the span length of 100 mm, with a value of 125.12 MPa and the least was experienced by the plywood with a span of 12 mm, with a value of -53.23 MPa.

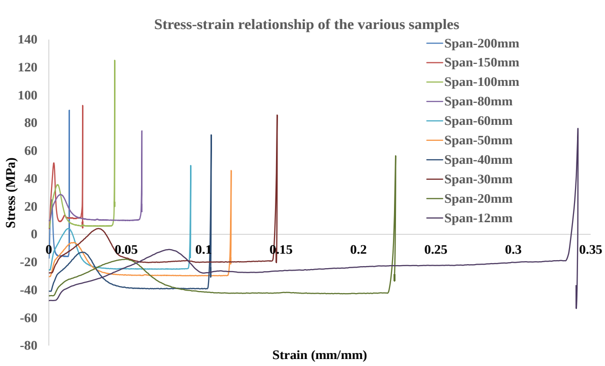

Fig. 5. Stress-strain analysis of the carious span lengths of the plywood from 200 mm to 12 mm.

This strange behaviour prompted the authors to perform a stress strain analysis, to get a better picture of the stresses and to define the variations in a more technical way. **Fig. 5** outlines the stress strain behaviour of the samples, when the span lengths change gradually. The averages of both the stresses and strains, for all the 5 trials of each span length, were considered to plot the graphs.

The analysis helped to identify that the maximum stress experienced in the elastic region was by the sample with the span length of 150 mm. Also, the maximum stress experienced in the plastic region was by the sample when the span became 100 mm. Another important aspect to notice was that the samples experienced negative stress when the span length decreased to 60 mm and the amount of negativity gradually increased, with the minimum being achieved with a span of 12 mm. Samples with span length 12 mm experienced the highest strains and therefore comprised the longest plastic region, with the shortest one being for the samples with 200 mm span length. Furthermore, the pattern of the stress-strain curves indicates that the plywood has high strength, high ductility and high toughness. Another interesting aspect was that the amount of spring-back was negligible even after 72 h for a few cases. These cases, though not considered for being over-burnt, definitely gives a possibility of having lesser spring back, with the increase in in-situ curing time.

Analytical validation

The results obtained were analytically correlated with the established formula. The primary equation [**24**] did not consider the effect of moisture content and the subsequent shrinkage experienced, two vital aspects for forming plywood. On further development, the coefficients of in-plane and out-of-plane shrinkages and the moisture content parameter were introduced for calculating the final sector angle. The equation can be represented as:

$$\delta\theta = \left(\alpha_y - \alpha_x\right)\theta\delta T + \left(\beta_y - \beta_x\right)\theta\delta M \qquad (1)$$

where, δT is the change in temperature, the sector angle is given as $\theta = 180 - \phi$, where ϕ is the included angle of the punch nose (90°), the thermal expansion coefficients, in-plane and out of plane, are α_x and α_y respectively, $\delta\theta$ represents the change in sector angle, β_x and β_y are the in-plane and out of plane shrinkage coefficients and δM represents the change in pre-forming moisture content. The coefficient of in-plane thermal expansion (α_x) was formulated to be 4.95×10^{-6}, the coefficient of out-of-plane thermal expansion was 45×10^{-6}, the in-plane shrinkage coefficient was 1×10^{-5} and the out-of-plane shrinkage coefficient was 3×10^{-3}.

Table 2. Validation of the experimental results with that of the analytical values.

Overall spring-back average (°)	Analytical value (°)	Deviation	% deviation
7.464833	7.318886	0.019551	1.9557385

Table 2 illustrates the overall spring-back experienced from all the samples, averaged out from each trail. The deviation of the experimental value was calculated to be around 1.96% more than the analytical value. Thus, the experimental value was extremely close to the analytical value and helps in establishing the process followed. Also, the method being analytically verified, can be further modified and applied to more complex and definite structures.

Conclusion

The study helps in strongly understanding the possibility of performing multiple bends to manufacture complex structures from plywood. 3-ply laminates, in 0°/90°/0° orientation, were used to perform the experiments. A 4-point bending rig was used to perform double bends on the plywood, with varying span lengths, between the two bends. The thickness of the plywood was about 1.9 mm and the span lengths between the bends were varied from 200 mm to 12 mm.

The experimental results show that the average amount of spring-back achieved from the experiments was about 7.46°. Therefore, this deviation when considered in the designing of the bending/forming rig, has the potential to give exact geometric structures. Moreover, the study also exposes the possibility of getting further reduced spring-back values, with the increased amount of in-situ curing time. A study on that aspect has the potential of opening many other new avenues and possible solutions to many problems in forming plywood. Moreover, the strain analysis reveals that there is a huge change in the strain experienced by the plywood, when the span lengths change, with the strain being minimal for larger spans and higher for smaller spans. This again leads to the illustration of the importance behind carrying out a proper strain analysis through an established method. The study based on finding the precise time for post-forming curing showed that the plywood mostly stabilises over the initial 24 h, with about 0.23% variation between the 1st and the 2nd days and about 0.09% variation between the 2nd and 3rd days. Therefore, the variation over the days being significantly minimal, it can be inferred that the bended plywood stabilises over the initial 24 h, though a further detailed study for defining the exact hours might be interesting and helpful.

Analytical validation of the entire process shows significant similarity, with a very little deviation of about 1.95%. The experimental data had a slightly higher average value when compared to that of the analytical value. However, this deviation is greatly acceptable and helps in proving that the method is justifiable and can be used to create further complex shapes, with the required design modifications, for achieving a better and standard structure. This gives a huge step towards manufacturing origami structures from plywood.

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Authors' contributions

Conceived the plan: AC & DB; Performed the expeirments: AC; Data analysis: AC; Wrote the paper: AC; Proof reading and corrections: DB & AC. Authors have no competing financial interests.

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