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Experimental investigation of the static behaviour of a corrugated plywood sandwich core

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ABSTRACT

Sandwich panel structures comprising corrugated plywood core bonded between plywood face sheets were manufactured and tested in flatwise compression and bending. Thin 3-ply Radiata pine veneers were soaked in a hot water bath prior to forming in a heated matched die, resulting in a corrugated profile with a 9 mm height and 43 mm period. Sandwich panel specimens were assembled via a simple process of applying an epoxy adhesive along the joints of the corrugated core and plywood face-sheets and holding in position while the epoxy cured. Through-thickness compressive modulus and strength were tested following the method of ASTM C365. As compared to single layer core, double layer core had a similar modulus, but reduced strength due to instability at the joints between the corrugation layers. Bending behaviour of sandwich beams was investigated in both the corrugated core orientations, revealing that the core was stiffer in shear across the corrugations, but also weaker in this orientation, due to face sheet buckling. This work sets the foundation for future research involving the prediction of properties and experimentation with different core configurations.

1. Introduction

New ideas for structural materials are constantly emerging, but these remain only conceptual until appropriate research is carried out on their manufacture and performance. Materials derived from renewable resources are especially popular due to the desire to move away from materials with higher environmental cost. When these renewable materials are processed into sandwich panel configurations, as in [1–8], there is the additional advantage of providing superior stiffness and strength to solid panels of the same mass. The limitations of such newly developed renewable sandwich structures are often related to achieving consistent, cost effective fabrication and understanding mechanical behaviour, both of which can be complicated by their unique geometries. This paper describes the fabrication method of a novel wood-based sandwich core material and then presents a preliminary experimental investigation of its quasi-static behaviour.

Sandwich panels provide superior bending stiffness and strength by bonding thin face-sheets, which have high in-plane properties, to either side of a low-density core material that has adequate out-of-plane and shear properties. The body of knowledge regarding these structures is extensive, as evidenced by a significant handbook dedicated to the topic [9], having been published two decades ago. However, research in the field is by no means exhausted. New materials, geometries and combinations of these continually emerging. Appropriate selection of core materials can provide sandwich panels with the added benefits of impact resistance, acoustic and thermal insulation, and low environmental impact, allowing them to be tailored to suit many specific applications.

The primary application of sandwich panels is in engineering structures where weight is a concern, for example in aircraft, buses and trains, through to packaging and furniture [2]. Sandwich panels have also become successful in the residential construction industry, where the added benefits of insulation and impact resistance are important, and there is an increasing demand for transportability [10]. While the above-mentioned benefits still help in satisfying economic and performance design pressures, there is a growing concern about the environmental impact of the materials used. At present, a significant proportion of the materials used in sandwich structures are polymers sourced from fossil fuels and bound for landfill at the end of their life cycles. Consequently, considerable research is being carried out on the development of new sandwich structures that utilise naturally sourced and recyclable or biodegradable materials.

Wood is a renewable material that has great structural potential due to its high stiffness and strength to weight ratio, and the fact that its weaknesses can often be overcome in engineered wood configurations [3]. Examples of recent research in wood-based sandwich core

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materials range from simple solid plywood core [1] or plywood ribs spaced in rows [2], through to more complex wooden dowel lattice core [3], corrugated cardboard core [4], low density wood fibre core [5], wood-based strips arranged in iso-grid core [6], layered cork agglomerates [7] or 3D shaped wood strand core [8]. Towards the simpler end of this range are corrugated cores materials, that are typically manufactured by forming flat corrugated sheets of paper, metal or composite materials, into corrugations. These can be a cost effective option and are particularly useful in situations where highly directional core stiffness is beneficial, or where having closed cells would be a drawback.

This study investigates such a structure, which uses plywood in flat and corrugated forms to make mostly renewable sandwich panels. In the current work, readily available commercial adhesives were used for their known performance, but there is much promising research into more environment friendly plywood adhesives [11]. In future these could be used in combination with the material in this study to make fully renewable and biodegradable sandwich structures. Starting with a base material of thin New Zealand Radiata pine veneers, plywood with a [0,90,0] laminate was formed into corrugated profile and used either directly as a sandwich core, Fig. 1, or it could be further processed into a sinusoidal honeycomb, Fig. 2. In previous studies, extensive research into the forming of the plywood was carried out [12,13]. For commercial application of this material to progress, better understanding and prediction of the mechanical performance of the sandwich structures is needed. It should be noted that the sinusoidal honeycomb core, arranged as in [14], has superior out of plane mechanical properties to the corrugated core. However, corrugated core could be preferable for its ease of manufacture and continuous cells, and it is the focus of this paper.

A significant number of studies relevant to this one are concerned with corrugated paper board [15–17]. This widely used material has a similar geometry to the curved corrugated plywood of this study, but is on a smaller scale of size and performance. There are also several studies of large fibre reinforced and steel corrugated structures which are on a much larger scale [10,18,19]. Corrugated core with a curved profile and on the scale of 10–20 mm thickness, as is investigated here, is a relatively unexplored area. In the current work the primary mechanical properties of the corrugated plywood sandwich core material, namely through-thickness compression and shear, are tested experimentally. These through-thickness properties are of vital importance for any sandwich core, as the thin face-sheets do little to resist deformation under such loading. The overall bending performance of complete sandwich structures is also studied to further observe the core material's behaviour, and thus determine the potential for application.

Fig. 1. Bonding the core to face-sheets. Consistent lines of adhesive were applied to the corrugation peaks, then face-sheets were assembled and held in place as the adhesive set.

Fig. 2. A panel manufactured with sinusoidal honeycomb core, which was not the focus of this study, but has promising properties.

2. Materials and manufacturing methods

The base material for the sandwich structures was sourced from a local company who prepared 3-ply, [0/90/0], 5-ply, [0/90/0/90/0] and 6-ply, $[0/90/0]_S$ laminated plywood panels. These consisted of 0.6 mm thick peeled veneers of New Zealand Radiata pine, bonded with a two-part PVA_c glue (250 gm^{-2} application of Superlok 3042 M). Radiata pine is currently the dominant species of tree grown by the NZ forestry industry, so is used exclusively in this study for geographic relevance. Panels were pressed under 1.2 MPa at room temperature to consolidate the bond [12]. Such plywood panels, measuring 2400 × 1200 mm, were then cut to appropriate sizes for sandwich face-sheets (3, 5 or 6-ply) or for the manufacture of corrugated core. Only 3-ply sheets were formed into corrugations, due to the excessive strain that would be experienced by the outer plies of thicker laminates. The average density of this original plywood was measured as 540 kgm^{-3}.

Forming of the 3-ply plywood into a corrugated profile was carried out through a matched die process, which was chosen in this case over roll forming due to the relatively simple setup and control over forming parameters offered. Following the methodology of Srinivasan et al. [13], sections of plywood measuring 350 × 500 mm were softened prior to forming by soaking in a hot water bath for 90–180 s at 70 ± 5 °C. This had previously been shown to be sufficient to achieve a moisture content (MC) of 40–50% [13]. With a soaking time of less than 90 s, it was found that the outer plies of the plywood were not softened adequately and were more likely to exhibit fibre cracking and shear. Immediately after soaking, sheets were transferred to the matched die, pre-heated to a temperature of 180 °C. The upper die surface was then lowered by a hydraulic press, forcing the flat plywood sheet into the corrugated profile of the die with a compaction pressure of 300 ± 100 kPa. Once lowered, the die was held shut for a total of 30–45 s to dry the plywood to the point where the corrugated profile would be permanently maintained.

Corrugated plywood was initially formed with the outer ply grain direction (0° direction of the [0/90/0] laminate) oriented parallel to the Y-axis in Fig. 3, so that it runs 'across' the corrugations. In this orientation, with the bending axis for forming (X-axis in Fig. 3) perpendicular to the outer ply grain direction, the plywood had been shown to be resistant to cracking during forming [12], and the resulting corrugation remained stiff in bending around the X-axis. For comparison, some corrugations were also formed with the outer ply grain direction parallel to the X-axis. These were more prone to cracking and were significantly weaker in bending about the X-axis, so it was not considered worthwhile to test their properties. It should be noted that the orientation of the plywood during forming is not limited to grain alignment with the X or Y direction, and a range of angles could be tested, which would result in a range of corrugation properties. However, for the best through-thickness compression and across corrugation