THE DEVELOPMENT OF HOLLOW CORE COMPOSITE PANELS FOR VALUE ADDED APPLICATIONS

by

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Abstract

An ongoing shortage of suitable woody waste materials due to the many recent saw-mill closures in Canada has been a major concern for particleboard manufacturers. The existing particleboard plants are currently competing with other industries for the scarce fiber resources available and facing significant competition from the cheap lower grade substitutes being imported from China. This thesis presents a solution through the development of hollow core sandwich panels for modular furniture components that serve the same function as solid slabs of particleboard but with reduced amounts of raw material inputs (wood and resin).

Through a series of preliminary experiments, prototype honeycomb sandwich panels were fabricated with a variety of face and core materials. The characteristic effects of different types of Kraft paper honeycomb materials, its cell size, orientation and cell wall height as well as the influence of different wood-based face materials on the sandwich strength and stiffness properties were established.

The results indicate that by combining thicker (6 mm) face sheet materials with Kraft paper honeycomb with cell size less than 16 mm, cell wall height 38 mm and oriented with the core ribbon direction perpendicular to the long axis of the panel, a sandwich panel with significant strength properties can be produced. The findings also imply that the performance of the honeycomb sandwich panels can further be improved through the application of edge rail enforcements and edge band application. The outcome of this study has the potential of reducing the total weight of finished products for the furniture manufacturers and provides avenues for product differentiation.

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Co-Authorship Statement

The research work conducted in this thesis was identified by Dr. Gregory D. Smith (supervisor) and Dr. Kate Semple. The research work including the review of the sandwich technology, the design of experiments, fabrication of sandwich panels for different furniture components, manufacture of wooden jigs for testing sandwich panels and analysis of the results were conducted by Solace Araba Sam-Brew. Dr. Semple was also involved in the preliminary experiments to identify processing issues related to the manufacture of honeycomb sandwich panels. The manuscripts in the thesis, Chapters 2 and 3, were prepared by Solace Araba Sam-Brew, and co-authored by Drs. Smith and Semple. A version of chapters 2 and 3 has been submitted for publication.

1 Introduction

1.1 Background

Light weight sandwich technology has been in existence for centuries and has been employed in several industries — aerospace, transportation, door, furniture and sports equipment (Bitzer, 1997). A sandwich panel consists fundamentally of two strong thin face sheets glued to a thick light weight core where both constituents can be of wood, plastics, and/or metal.

This sandwich technology was initially adopted in the woodworking industry in previous years mainly because of the scarce raw materials and the high price of wood; the sandwich panels were made of solid wood or plywood faces and various core materials (D'Antoni, 2007). In most cases the core materials are in the form of a lattice to ensure light weight; an example is a Kraft paper honeycomb which looks similar to the interior structure of a bee hive. Presently, of all the materials being utilized in the production of honeycomb core materials the Kraft paper honeycombs are the cheapest and most easily obtainable.

Products based on this sandwich technology have a high stiffness to weight ratio (Zenkert, 1997); sandwich panels have been reported to "weigh up to 70% less" than similar products made from solid wood or plastics (Wisdom, 2005). In Canada, a 2008 survey conducted on the market trends of interior door products revealed that of the approximately 99% market share held by wooden doors, the light weight sandwich (hollow core) doors had an 85% market share (Fell, 2008). This huge share was attributed to the fact that hollow core doors made use of relatively small amounts of wood.

Their light weight is advantageous in terms of safety on or off the manufacturing environment, as they can be easily moved around and assembled by fewer people (Davies, 2001; Wernlund, 2004; Anonymous, 2006a). Using the sandwich technology also helps reduce material costs since the panels can be fabricated with smaller quantities of the relatively expensive face sheet materials and more of the inexpensive core materials (Wisdom, 2005; Moody *et al*., 2007). Lower density, light weight panels have another benefit in terms of transportation cost since less weight means lower freight charges (Busch, 2006a; Wernlund, 2004; Wisdom, 2005; D'Antoni, 2007). Light weight panels made from a combination of wood composite panels and paper core materials also offer a number of advantages in that their constituent materials are renewable, are easily recycled, and have low formaldehyde emissions (Wisdom, 2005).

Although for years the woodworking industry kept using this light weight sandwich concept in the production of slide doors, it was abandoned in the early 70's with the introduction of particleboard in the furniture industry (D'Antoni, 2007). In recent years the European furniture industry has re-adopted and made several improvements to the technology (Stosch, 2008), like the EUROLIGHT™ products made by Egger Industries which consists of thin particleboard or medium density fiberboard (MDF) and paper honeycomb cores. IKEA has also successfully embraced and incorporated this technology into their product lines (Busch, 2004; Anonymous, 2006b). However, there are still less than 5% of global furniture makers using lightweight sandwich panels (Kirkbride, 2008) and this technology is rarely used in the furniture industry in North America. In 2006, OFC Panel Processing, a furniture and cabinet company in Iowa, USA was the first to officially adopt the light weight technology on a small strategic scale using particleboard frames (Anonymous, 2006a). The acceptance of the technology by the furniture market segments in Canada is still at the stage of educating designers and consumers about its numerous advantages and uses (Busch, 2006b; Anonymous, 2006a).

The major reason for not using the sandwich technology on a large scale was that the fabrication process was labour intensive, requiring at least eight people to manually assemble sandwich panels (Busch, 2006a). However, in recent years the introduction of automated panel assembly systems and the development of appropriate fitting solutions for light weight panel production have made it far easier and more economical to adopt this concept than a decade ago. Now using the automated systems, two or three people could fabricate three times the amount of panels produced manually by eight people, resulting in a per person through put increase of over 900%. This strongly suggests that the light weight panel technology is about to become much more common. In order to reap the maximum benefit from this technology, Canada needs to invest in it at an early stage.

1.2 Literature review on light weight composites

The application of light weight sandwich technology in combination with wood-based materials began as early as the Second World War. An example is the Mosquito bomber developed by the de Havilland Company (Sutherland, 2005). The legendary Mosquito was constructed from wood, mainly consisting of faces of plywood made from layers of birch, and a core of balsa wood and laminated spruce (Fredriksen, 2001; Herrmann *et al.*, 2005). The design made this warplane light weight and one of the fastest during WW2 with a maximum speed of 425 miles per hour (Fredriksen, 2001; Sutherland, 2005).

During 1950s, studies by forest based organizations identified the sandwich construction concept as a viable means of utilizing wood and generating newer wood-based products (Sweets, 1953). The United States Forest Products Laboratory in 1956 conducted extensive research on sandwich panels for building applications; the sandwich panels were fabricated from corrugated paper cores impregnated with low amounts of resin, and were exposed to wet and dry conditions (Seidl, 1956). The results obtained indicated the sandwich panels were comparable in strength and performance to conventional building panels, further research on the behaviour of the paper sandwich panels under other exposure conditions was recommended.

The U.S. Forest Products Laboratory continued to perform considerable research into the possibilities of using the impregnated Kraft paper honeycomb sandwich panels as a building material in doors and partitions; however, these applications required that the sandwich panels possess some thermal insulating and sound absorbing properties. Thus in 1958, Wood conducted experiments into the fabrication of wood-based materials using paper honeycomb cores for building construction with emphasis on its design principles (Wood, 1958). With significant developments being made in the structural design of paper sandwich panels, subsequent research work focused on the long-term structural performance of the sandwich panels, and the possibility of improving the thermal insulation properties of the paper core (Markwardt and Wood, 1959; Fahey *et al.*, 1961; Anderson and Wood, 1964,).

Owing to the increasing popularity of the light weight sandwich technology and its relatively new introduction into the building and construction industries, more studies were centered on effectively understanding and applying the concept. Most research focused on evaluating and analyzing the structural and mechanical performance properties (flexural strength, shear, deformation, compression, tension) of sandwich panels constructed with diverse designs from different face and core materials (Allen, 1970; Worrell and Wendler, 1976; Chong *et al.*, 1979; Johnson and Sims, 1986; Johnson *et al.*, 1990; Basunbul *et al.*, 1991; Desayi and El-Kholy, 1991). Other concerns related to the acceptable levels of durability of the different face and core materials used for the fabrication of structural panels and how these materials reacted to fire were also addressed (Berner *et al.*, 1994). Theoretical models were also developed by Petras and Sutcliffe (1999) to help sandwich panel manufacturers predict the failure modes of sandwich panels constructed with glass fibre reinforced plastic laminate faces and Nomex™ honeycomb cores loaded in 3-point bending.

As the sandwich technology evolved, companies researched into the possibility of producing ready-to-assemble (RTA) and office furniture from wood pulp (Ince and McKeever, 1995). Gridcore Systems International in collaboration with the U.S. Forest Products Laboratory developed a 3-Dimensional honeycomb sandwich panel, Gridcore, molded from recycled pulp materials (Scott *et al.*, 1995; Blackman, 1998). This Gridcore panel had significantly better mechanical properties compared to particleboard and medium density fiberboard (MDF) of similar size — a 19 mm thick Gridcore was 40% stronger and 16% stiffer than its 19 mm particleboard and MDF counterparts respectively (Blackman, 1998). In 2000, Pflug *et al.* developed and patented a new continuous production concept for the manufacture of a low cost honeycomb core material made from folded cardboard (Pflug *et al.*, 2000).

To potentially improve the sandwich panel strength properties and meet the demanding construction and transportation requirements, more research work was conducted into the development of new wood-composite panels (Simpson, 2003; Banerjee, 2003). Since the constituents of the sandwich construction were a major determinant of its structural performance, the opportunities explored included a combination of wood with thermoplastics, synthetic fibres, or foam products. Pflug *et al.* (2000) researched the use of sandwich panels consisting of polypropylene or natural fibre face sheets and low cost paper honeycomb core. The aim was to reduce weight and develop a more cost efficient product which had high strength properties and was "renewable resource based and fully recyclable" (Pflug *et al.*, 2000). Similarly, Kumar and

Ramani (2000) investigated the dynamic mechanical properties of a wood composite — oak wood and glass fibre reinforced polypropylene — with the goal of producing a strong and/or stiff composite capable of replacing the heavier wooden members in buildings (Kumar and Ramani, 2000).

Most recently, Barboutis and Vassiliou (2005) compared the strength properties of a 51.7 mm thick honeycomb sandwich panel with that of 8 and 16 mm thick particleboards. The sandwich panels were made of 8 mm particleboard faces and recycled paper honeycomb core of cell size 30 x 30 mm. They found that their honeycomb panels of density 321 kg/m^3 were low in bending strength properties compared with particleboard of thickness 8 mm (density 766 kg/m^3) and 16 mm (density 658 kg/m^3), still the honeycomb panel exhibited a higher impact bending strength. The authors however indicated that to effectively take advantage of the inherent properties of paper honeycomb panels for use in furniture manufacture, further research on the effects of honeycomb cell size, cell wall thickness, weight and type of paper et cetera were required.

In the years that followed, lots of other studies were conducted to establish the fatigue and velocity impact behaviours of sandwich panels constructed with different configurations and types of face and core materials (Zhou and Stronge, 2005; Schubel *et al.*, 2005; Grewal *et al.*, 2006; Foo *et al.*, 2008; Mamalis et *al.*, 2008). Other studies were centered on the possibility of constructing continuous sandwich panels and evaluating the advantages of different types of edge banding materials (Wisdom, 2005; Kintscher *et al.*, 2007; Kirkbride, 2008; Song *et al.*, 2008).

The reviewed literature shows that there has been keen interest in adopting the sandwich construction technology. The complex nature of this technology has made it an active research area which continues to receive great attention. This study therefore aims at exploring the practicability of using wood based panels and Kraft paper honeycomb cores in the construction of sandwich panels for furniture applications. The research results are expected to serve as useful information in the design and choices of wood based products for sandwich panels, and increase the understanding of the behaviour of these wood composites.

1.3 Sandwich design and construction

The honeycomb sandwich design has been compared to that of the I-beam; the face sheets carry bending loads (compression and tension) and function structurally as the flanges of an I-beam while the core function like the web of the I-beam and bear the shear loads (Kollmann *et al.*, 1975; Song *et al.*, 2008). The type of face and core materials chosen for a particular application are determined by functional requirements such as strength, stiffness, damage tolerance and appearance at minimum overall cost (Moody *et al.*, 2007). Figure 1.1 illustrates the components of a honeycomb sandwich panel.

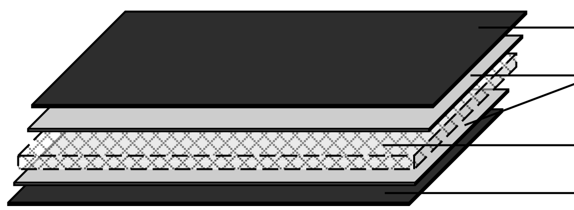

Figure 1.1: Exploded view of a honeycomb sandwich panel.

Kraft paper honeycomb is formed by gluing together thin sheets of paper in a way that results in a collection of identical open cells (Bitzer, 1997; Davies, 2001). The most common cell configuration manufactured is the hexagonal cell; others include the square, rectangular, corrugated, flex-core and reinforced cells shown in Figure 1.2 (Zenkert, 1997; Davies, 2001). The reinforced honeycomb core is a variation of the hexagonal cell configuration and is mainly utilized for sandwich products requiring high mechanical strength properties as it has extra sheets of paper glued to the cell nodes (Bitzer, 1997). For curved sandwich products the flex-core cell configuration is employed as it can be easily curled.

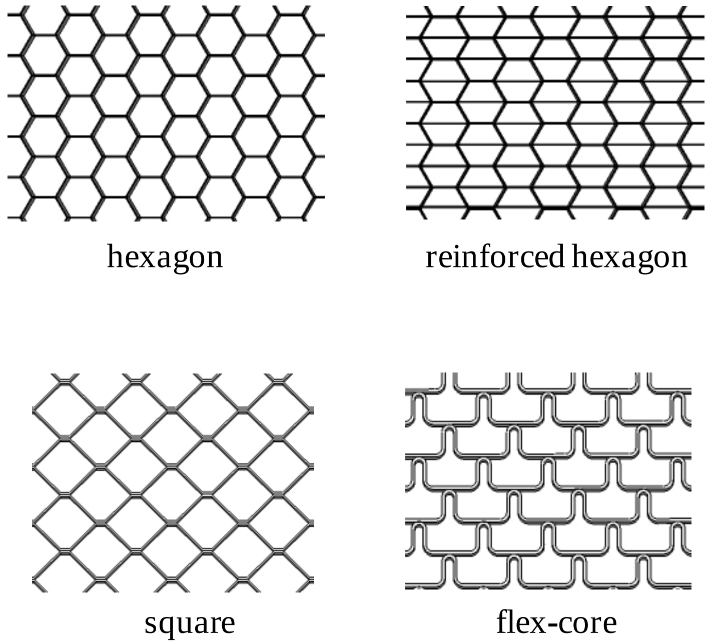

Figure 1.2: Commonly used honeycomb cell configurations (adapted from Bitzer, 1997).

Traditionally, there are two different methods for the manufacture of honeycomb core — the expansion process and the corrugated process (Bitzer, 1997; Zenkert, 1997; Pflug *et al.*, 2000). With the expansion process (Figure 1.3), flat sheets of paper are cut from a huge paper roll fixed on a rotating drum; as the sheets are stacked alternating lines of glue are printed on each sheet. When the required number of sheets per stack is obtained the glue is cured and the block of sheets sliced into the required thickness — usually above 10 mm (0.39 inches) since slicing cores thinner than this size is more time consuming and quite difficult (Pflug *et al.*, 2000). To obtain the desired honeycomb cell configurations, the slices are pulled apart to expand them.

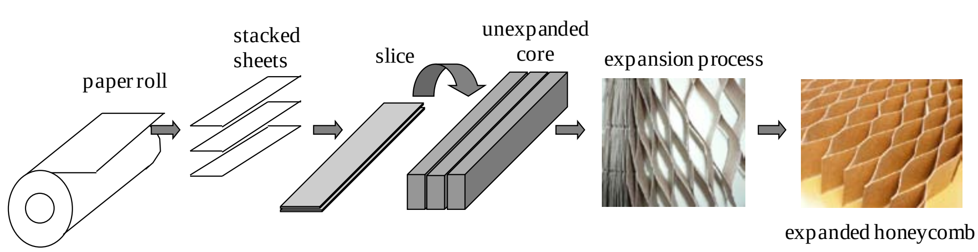

Figure 1.3: The expansion process of honeycomb manufacture (adapted from Pflug et al., 2000).

The corrugated process in comparison is considered a rather expensive method requiring more labour to stack and bond corrugated sheets of paper together. This process makes use of pre-corrugated sheets; glue is applied to the nodes of the sheets as they are stacked into blocks and cured as illustrated in Figure 1.4. Sheets of corrugated honeycomb material of the desired thickness can then be cut from the cured blocks (Bitzer, 1997; Zenkert, 1997).

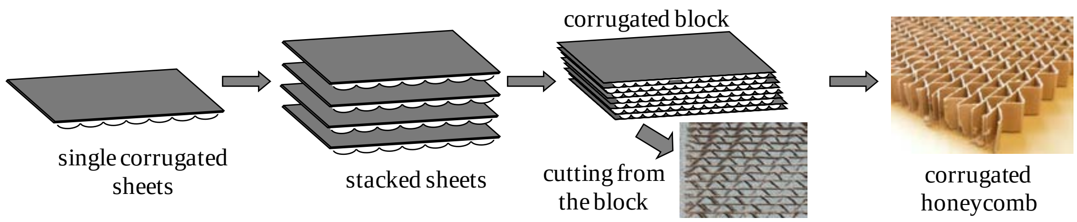

Figure 1.4: Steps involved the corrugated process of honeycomb manufacture (adapted from Pflug et al., 2000).

1.4 Justification for the development of hollow core panels

A survey by Tabarsi *et al.* (2003) found that, on a volume basis, particleboard constituted the most common wood composite panel (39%) used in furniture manufacturing in North America. In Canada, three grades of medium density particleboard — MS, M2 and M3 with panel densities in the 640-800 kg/m^3 (40-50 lb/ft^3) range, are used in the manufacture of ready to assemble furniture because of their light weight and high surface quality suitable for lamination.

In recent years the Canadian particleboard industry has been in limbo due to its reduced production capacity, owing mainly to the closure of a number of sawmills that has lead to scarce furnish supply and other factors such as increased energy costs and weakened construction markets (RISI, 2006). Of the approximately 1,300 softwood sawmills in Canada and the United States, “149 were permanently closed between 1996 and 2003” (Spelter, 2002). The closed mills represent a total capacity of 17.6 million m^3, with 4.9 million m^3 (28%) of the total representing 30 sawmills located in Canada; with British Columbia being the worst hit province. Subsequent reports in 2007, revealed out of the approximately 1,300 softwood sawmills recorded in 1995, only 990 were left as of June 2007 (Spelter *et al.*, 2007). The mill closures have lead to a shortage of available wood residues for the particleboard industry; increasing the competition for the scarce wood fibre resources available and significantly increasing transportation costs to deliver the furnish to the particleboard plant site.

The production costs for particleboard continue to increase due to increasing wood and resin costs with sharp increases in resin cost being the dominant factor (RISI, 2006; RISI, 2007). According to Crow's weekly market reports, the Canadian wood panel market indicates a general increase in particleboard prices from 2006 to 2008; in 2006 19 mm (¾ inch) particleboard was approximately $335 per thousand square feet (MSF), decreasing marginally to approximately $297/MSF in 2007 and increasing to $370/MSF as of October 2008 (RISI particleboard and MDF commentary, 2008). Based on present market conditions, particleboard prices are expected to continue to increase in the coming years (RISI, 2009).

Simultaneously the Canadian modular furniture industry is facing considerable competition from the surging imports of cheap, lower grade, wood-panel substitutes from the Chinese market (RISI, 2006). A report by Statistics Canada in December 2007 revealed an increase in furniture's percentage share of total imports from China by 21% from 2005 to 2006 (Khondaker, 2007). These cheaper imports pose a direct threat to the domestic furniture companies who mainly use particleboard panels in their product lines. Economic analysis reports in the past 3 years show a general decrease in the amount of particleboard used for furniture and its related production (RISI Particleboard and MDF commentary, 2008). The particleboard and furniture industries therefore need to enhance their competitiveness through cost reduction and/or product differentiation (Martin and Porter, 2000; RISI, 2006). Unfortunately the largest single cost in the production of particleboard is typically the resin, and any reduction in the amount of resin used to make these panels typically results in low grade particleboard panels that cannot command a premium price. Therefore product differentiation that adds significant value is a better alternative.

Meanwhile the ready-to-assemble (RTA) furniture manufacturers have expressed the desire for light weight wood composite panels with high strength properties for the manufacture of their products. This requirement is because of the growing consumer preference and demand for furniture designs with a heavy look, i.e., thicker panels, but that are actually lighter than existing solid slab furniture and sold at a lower cost (Wisdom, 2005; Busch, 2006b). The intent is that these new lighter composite panels will function in the same way or better than the present wood-based panels, and have good surface quality and fastener holding abilities. For both manufacturers and consumers, the weight reduction translates into easier handling and installation. The customers in recent times are also leaning towards more environmentally friendly products (Ozzane and Smith, 1996).

Consequently to improve the competitive edge of the Canadian particleboard and modular furniture industries while addressing the needs of the RTA manufacturers and consumers, there is a need to shift emphasis from commodity panels to the design and development of innovative value-added products that make use of the available wood-based panels (particleboard, MDF, hardboard, solid lumber) in new ways. The light weight sandwich concept presents a great opportunity to meet these needs through the development of novel honeycomb core sandwich panels. The projected outcome is that these new products will serve the same functions as thick blocks of particle and fiberboard products with the added light weight benefit and more added values.

This technology is far less developed in North America than Europe and there are no published data on the strength properties of the different honeycomb cores or the loading performance of light weight sandwich panels. To ensure the acceptance and integration of this technology in the Canadian furniture/wood working industry, there is a need to investigate the types of honeycomb core materials readily available to the manufacturers and to develop and test a range of prototype honeycomb core sandwich panels made with particle and fiberboard products. In the process data would be compiled on the service performance of these honeycomb panels to serve as a reference for companies and furniture manufacturers and aid in a smooth transition into the light weight sandwich market.

This study is part of a collaborative research with the University of Toronto and FPInnovations (Forintek Eastern Division) to develop novel hollow core composite panels. The University of British Columbia is responsible for the design and manufacture of prototype honeycomb core panels, the University of Toronto for the generation of Finite Element models to predict the loading performance of prototype honeycomb core panels, and FPInnovations (Forintek East) for the development of low density fibre core materials.

1.5 Potential impact of the study

In the past decade, the production and export of Chinese wooden furniture has experienced rapid growth such that in 2004 China replaced Italy to become the world's largest wooden furniture exporter. However, in terms of quality and unit price, China falls far behind that offered by companies based in Italy and Germany (Han *et al.*, 2009). Over the past 8 years, Canada has generated a trade deficit with China as the percentage of imports from China into Canada has outgrown that of exports from Canada to China. From 1997 to 2006, Canada's trade deficit with China has grown from $3.9 billion in 1997 to $26.8 billion in 2006 (Khondaker, 2007).

Thus it is anticipated that if these hollow core panels find applications in Canadian furniture products, these innovative products will provide the furniture industry with a competitive advantage over the low quality imports and could expand the domestic and global Canadian market share.

1.6 Research objectives

Kraft paper honeycomb is produced from unbleached Kraft fibre, and is presently the most common type of paper honeycomb on the market. Accordingly the primary objective of these studies was the utilization of low density Kraft paper cores in combination with particleboard and fiberboard to develop hollow core composite panels for value added applications. Kraft paper honeycomb core was selected because of its light weight, reasonably low price ($0.6-0.8 per square foot of the expanded core), and very high recyclability. The properties of the Kraft paper material (as obtained from the manufacturer) used in the manufacture of the honeycomb core can be found in Appendix A.

In order to make the overall project goal more manageable, it was subdivided into 3 smaller objectives:

1. To examine the physical and mechanical properties of a variety of Kraft paper honeycomb cores and face sheet materials, and determine their suitability for the fabrication of light weight sandwich panels.

2. To manufacture and test the load bearing performance of prototype honeycomb core sandwich panels to identify and tackle key processing issues if any.

3. To effectively strengthen the edges of honeycomb core panels to prevent damage, enhance the strength properties and aesthetic appeal of panels.

The following hypotheses were proposed:

1. The use of thicker face sheet materials for the fabrication of sandwich panels will increase panel strength and stiffness properties.

2. Smaller cell honeycomb core material will result in stronger sandwich panels than larger cell honeycomb cores.

3. Increasing the width of edge rail supports in honeycomb core panels will improve their load bearing performance.

4. A method of edge band application which maximizes the adhesive contact area between the edge band and the honeycomb sandwich panel will lead to the greatest panel reinforcement.

1.7 Structure of the work

The study was performed in three phases; the first phase entailed a test survey of furniture manufacturers across Canada to identify the types of composite panels currently being used and the major processing problems confronting their use. The survey also determined the manufacturers' awareness and use of hollow core honeycomb panels, and any likely constraints they may have in the adoption of this technology. Questions regarding the common product dimensions produced, fastening systems frequently used, edge band material, and the general product qualities customers prefer were included to gain an insight into the Canadian furniture industry.

The surveys showed that the majority of companies were using laminated particleboard and sometimes MDF panels, even for thicker sections above 25.4 mm. Three of the 12 companies surveyed used honeycomb panels for their thicker tabletop lines but fabricated these in house. One company expressed a strong desire for a local supplier of honeycomb stock panels that they could closely liaise with to have panels manufactured to their specific requirements. This option would allow them to expand their manufacturing and supply to furniture outlets. At present there is no company in Canada that meets this need.

Issues that most companies had in relation to the use of hollow core sandwich panels included:

1. Fastening techniques: how to insert fittings into the honeycomb panel
2. Edge banding techniques: how to edge band directly onto the honeycomb core without a frame.
3. Air circulation between cells: this was needed to permit movement of air and moisture throughout the panel.
4. Increased flammability.

Due to the limited responses received and low number of furniture companies sampled, the results were not statistically analyzed. However, the survey gave a better understanding of the perception of hollow core products, and the issues related to its processing and use in the

Canadian furniture industry. Appendix B contains a summary of the general response of the surveyed companies.

The second phase focused on the design and manufacture of prototype honeycomb core panels. Domestically produced wood-based panels such as hardboard, medium density fiberboard (MDF) products, particleboard and plywood were obtained and compared as candidate face sheets. The major types of Kraft paper honeycomb materials — Verticel™, paper laminated and open cell expandable Kraft paper honeycomb — which were relatively light weight, inexpensive and readily available in Canada were considered as core materials. Verticel™ a trademark of Tricel honeycomb is produced by the more labour intensive corrugated process and usually employed when a higher density core material is required. The paper laminated and expandable Kraft paper honeycomb cores are both made from the expansion process; the laminated core materials are predominantly used by the packaging industry as it can be profiled to fit any shape, while the open cell expandable paper cores are used in the manufacture of doors and furniture panels.

The general mechanical strength properties of the face and core components were measured in accordance with the American Society for Testing and Materials (ASTM); the data from these tests were analyzed and the results sent to the University of Toronto to be used in the generation of a predictive finite element model as part of the collaborative research work. In preliminary experiments, prototype honeycomb panels were fabricated to determine the procedures for their manufacture. A challenge in using the expandable honeycomb core was that it came in an unexpanded form, unlike the other forms of honeycomb. After a series of trials a process for effectively expanding and setting the core material was determined. To achieve a strong bond between the honeycomb core and the face sheets during assembly, five gluing techniques were considered with the aim of choosing the most appropriate and efficient one. These series of experiments were reported in the Natural Resources Canada quarterly reports (Semple *et al.*, 2007), however for the sake of brevity these are not reported here.

Subsequently, three distinct experiments were designed to investigate the effects of varying face to core thickness ratios (shelling ratios), different Kraft paper honeycomb core materials and face sheet types on sandwich panel performance. The results from this phase are reported in Chapter 2 of this thesis. The most practical outcome of this research was that using a face material of higher stiffness (either because it was thicker or made of a denser, stronger material) had a large effect on the mechanical strength performance of the sandwich structure. The honeycomb cell size and wall height were also identified as characteristics that significantly influenced the performance of sandwich panels under bending load.

The final phase of this work (Chapter 3) was concerned with the improvement of honeycomb panel strength and stiffness through the use of edge reinforcement and edge band material. Supporting the edges of the honeycomb core panel also provides a substrate into which fasteners can be inserted and prevents damage to the fragile Kraft paper honeycomb core material. Two experiments were designed; the first one focused on honeycomb core panels containing different types and widths of edge reinforcement material and different fastener systems. The second experiment centered on identifying the most effective technique for the application of edge band material to honeycomb core panels. The findings suggest that the strength of honeycomb core panels can be significantly enhanced through the use of edge rail materials and/or edge band application.

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2 Preliminary experiments on the manufacture of hollow core composite panels[1]

2.1 Background

Light weight honeycomb sandwich technology has been in existence for decades in the aerospace, shipping and transportation industries. The structure of honeycomb sandwich panels follows a basic pattern; two face sheets which are relatively thin yet strong, enclose a thick and light weight core. A number of studies have been conducted on the panel characteristics and strength properties of several honeycomb core materials in conjunction with different face materials (NASA, 1969; Worrell and Wendler, 1976; Chong *et al.*, 1979; Desayi and El-Kholy, 1991; Hassinen *et al.*, 1997; Petras and Sutcliffe, 1999; Vaidya *et al.*, 2000; Côte *et al.*, 2004; Onkar Murthy *et al.*, 2006; Foo *et al.*, 2008). Only a few of these studies have focused on using wood materials and/or composites for both the face and core materials (Wood, 1958; Fahey *et al.*, 1961; Pflug *et al.*, 2002; Barboutis and Vassiliou, 2005).

The manufacture and use of Kraft paper honeycomb panels for furniture and cabinetry is currently much further advanced in Europe than in North America (Stosch, 2008). However, there is increasing interest in North America to employ this technology for the manufacture of commodity and specialty furniture, which until recently was made from either solid composite board or solid wood. Several factors are driving the shift away from the use of solid composite boards in furniture; one of which is the competition pressures facing the particleboard industry, which are passed onto domestic manufacturers of commodity furniture.

There is a strong desire among producers of ready-to-assemble (RTA) furniture for lighter weight components for furniture assembly packs. This desire translates into reduced materials input, reduced transportation costs and easier installation. Furthermore, honeycomb core panels can potentially provide the necessary strength and stiffness in a wide range of thicknesses for

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parts such as table tops and shelving at a fraction of the weight – as much as 70% reduction (Wisdom 2005) – representing significant savings on the wood and resin required to produce the parts from solid composite wood. In addition, formaldehyde emissions are also lower and panels are biodegradable or recyclable at the end of their service life (Wisdom, 2005).

Hampering the wider adoption of honeycomb panels for furniture in Canada is the lack of domestic manufacturers of acceptable stock panels; requiring furniture manufactures to custom fabricate their own on site which reduces the time and resources available for their primary task of making furniture or components. Investment in domestic fabrication of hollow core stock panels is in turn hampered by a general lack of knowledge and data pertaining to the fabrication, properties and performance of honeycomb panels made from locally available face and core materials.

This project aims to fill this knowledge gap by constructing and testing Kraft paper honeycomb sandwich panels using domestic face and core materials in several thicknesses, and identifying zones of weakness and significant problems (if any) that might hamper their adoption in the modular furniture industry. The objective of the work reported here was to test a range of honeycomb panels and their constituents and obtain technical data that could be used for furniture components. Two hypotheses were posed

1) A combination of thick face sheets and Kraft paper honeycomb cores of small cell size will produce panels with high strength and stiffness values.
2) The orientation of the Kraft paper core in the sandwich panel will have no significant effect on the resulting panel properties since the core is made of a weak and low density material.

2.2 Sandwich structural design

Four different kinds of honeycomb core material: (i) Verticel™, (ii) Open cell expandable paper honeycomb, (iii) Paper laminated small cell and (iv) Paper laminated large cell were supplied by local North American manufacturers (Casewell and Pregis) and are shown in Figure 2.1. The small cell (sc) paper laminated honeycomb had a cell size of 16 mm, the large cell (lc) paper laminated 32 mm, the open cell expanded honeycomb 32 mm and the Verticel™ 13 mm. The standard structure of the hexagonal paper honeycomb cores (not Verticel™) is shown schematically in Figure 2.2. The axis running along the continuous sheets of paper is termed the core ribbon or *x*-direction, while the axis running across the paper ribbons in which the core is expanded is termed the *y*-direction.

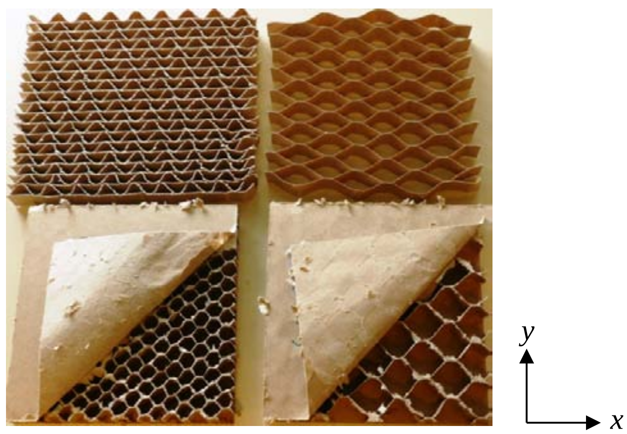

Figure 2.1: The appearance of the four honeycomb core types. Top left: 13 mm Verticel™, top right: 32 mm open cell expanded honeycomb, bottom left: 16 mm paper laminated honeycomb, and bottom right: 32 mm paper laminated honeycomb. All cores have the ribbon-direction oriented horizontally (left to right).

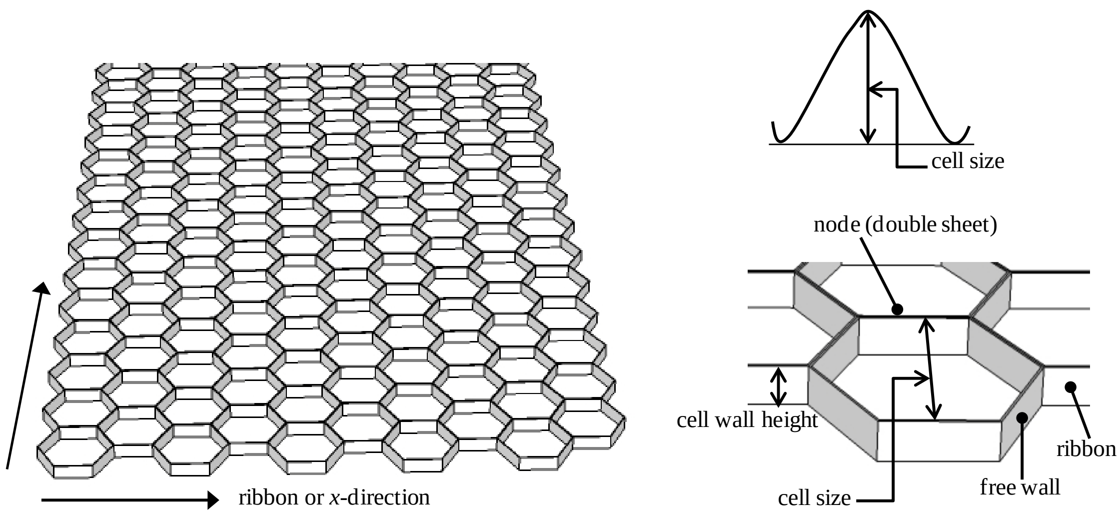

Figure 2.2: (Left) *The different honeycomb orientations, (right top) cell size for the corrugated Verticel™ material, and* (right bottom) *cell size for the open cell honeycomb material.*

To make up sandwich panels, seven face sheet materials which are commonly used in the furniture industry were selected based on a survey of the Canadian market (Semple *et al.*, 2007) and purchased from local building supply stores. The panel types were: 3 mm hardboard (3/h), 6 mm hardboard (6/h), 3 mm medium density fiberboard (3/mdf), 6 mm medium density fiberboard (6/mdf), 4.5 mm meranti plywood (4.5/p) and 6 mm Douglas-fir plywood (6/p). The plywood materials were both 3 ply, the Douglas-fir plywood was made with phenol formaldehyde resin and the meranti with urea formaldehyde resin. Sandwich panels were fabricated using DURO-LOK 422150 (a cross linked PVA with phenolic resins, no catalyst required for interior purposes), an adhesive used for gluing solid and hollow core doors.

2.2.1 Properties of constituent materials

The physical properties of the face sheets and honeycomb cores were measured in a 3 point bending test on an Instron Universal testing machine: Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) for both the core and face materials in bending. These tests were conducted in accordance with the ASTM standards D1037-99, C393-00 and C365/C 365M-05. Four replicates were prepared for the core materials and twelve for the face sheet materials. The properties of the constituent materials were measured for the purpose of developing a Finite Element model (Chen and Yan, 2009) of the behaviour of different kinds of honeycomb sandwich panels under loading.

It was not possible to obtain MOR and MOE values for the open cell honeycomb types because they had no continuous top or bottom surface. These samples deformed easily by hand with essentially no resistance to bending and therefore the physical properties of only the paper-laminated honeycomb core were measured.

2.2.2 Expansion of open cell honeycomb core material

The unexpanded Kraft paper honeycomb units were 1295.4 mm long and comprised of 100 strips of paper glued together at regular intervals. Before expansion, the top and bottom edges to which the face panels were later glued were roughened with a sand block using 80 grit sandpaper to increase the surface area exposed to the adhesive. Shallow incisions (about 2 mm deep) at spaced intervals along the length of the honeycomb strip were made using a band saw to create pathways for air flow and moisture migration during and after pressing. The core material was then evenly expanded by hooking (lengthwise) the cells on each end to nails spaced at intervals of 44.5 mm on a 1219.2 x 2438.4 mm (4 x 8 ft) oriented strand board. To set the honeycomb in its expanded form the boards were placed in a walk-in oven (8 x 6 x 4.5 ft) for 3 hours at 80 C. The core materials were allowed to cool over night before removal from the boards since they tend to return to an under expanded hexagonal state as they reabsorb moisture if removed immediately.

2.2.3 Sandwich fabrication

The face sheets and expanded honeycomb core material were cut to dimensions of 457.2 x 1219.2 mm (1.5 x 4 ft). Prior to gluing and assembly, the components of each sandwich – two face sheets and the honeycomb core were each weighed. The Duro-lok glue was applied to the undersides of the sheets using a stippled carpet coated roller. Each sheet was then re-weighed prior to sandwich assembly to check the consistency of the glue mass applied to all panels. On the whole an average of 133 g of glue was applied to each 457.2 x 1219.2 mm face material.

The honeycomb core was carefully placed onto the bottom sheet and kept in place with the aid of flat wooden sticks, the top sheet was then glued on and the stack weighed down with 50 kg of weight while the next sandwich was assembled. The stacks were left to cure for two days before removing the weights.

2.3 Experimental designs

2.3.1 Experiment 2.1: shelling ratios (effect of different face and core height ratios)

Open cell expanded honeycomb of three different cell wall heights – 12.7 mm (0.5 inches), 25.4 mm (1 inch) and 38 mm (1.5 inches) – were used in conjunction with smooth surfaced MDF face sheets, 3 and 6 mm in thickness. This created six different ‘shelling ratios’ shown schematically in Figure 2.3. The factors of interest were the thickness of the face sheet and the honeycomb cell wall height. All panels were made up with the honeycomb core material oriented in the core ribbon or *x*-direction (i.e., the direction of continuous sheets running parallel to the long axis of the sandwich panel) shown in Figure 2.2. For each shelling ratio two replicate panels were fabricated, for a total of 12 panels.

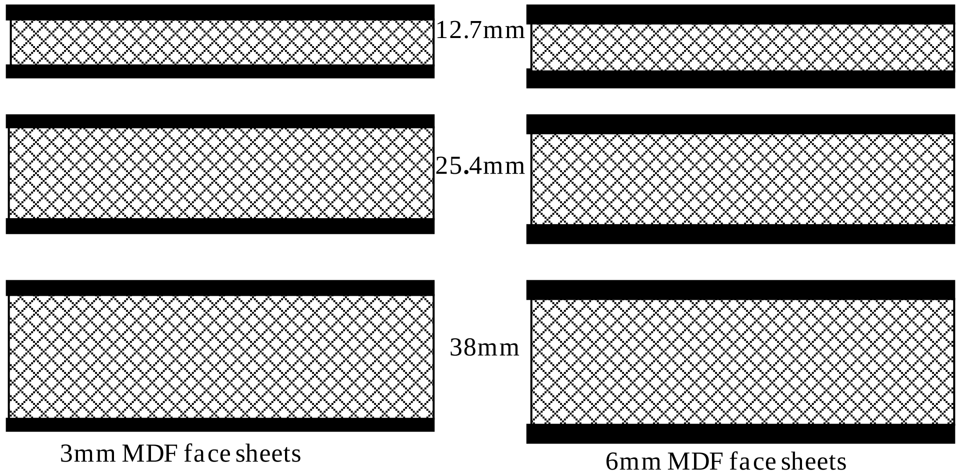

Figure 2.3: Face thickness-to-core height ratios using 3 and 6 mm MDF face sheets and open cell expanded honeycomb.

2.3.2 Experiment 2.2: effect of different types of honeycomb cores and orientation

A set of sandwich panels consisting of 3 mm hardboard faces and four different types of honeycomb core materials with a constant cell wall height of 25.4 mm were fabricated. The honeycomb type and orientation were the two fixed factors tested in this experiment. The sandwich panel dimensions were the same as in Experiment 2.1.

The top side of the hardboard used in this experiment was smooth while the bottom side was rough with a mesh screen imprint on it; this is a result of the manufacturing process for hardboard and presents a very different surface for gluing than the MDF used in Experiment 2.1. The sandwich panels were made with the screen imprinted side in contact with the cores. In this experiment the effect of honeycomb orientation in the *x* and *y*-direction (see Figure 2.2) along the long axis of the panel was evaluated. For each orientation and honeycomb type two replicate panels were fabricated, for a total of 16 panels.

2.3.3 Experiment 2.3: effect of different types of face sheets

Sandwich panels were fabricated using seven different types of face materials and standard 25.4 mm open cell expanded honeycomb; with 'face sheet type' being the only factor tested. For each face sheet type two replicate panels were fabricated with the honeycomb running in the *x*-direction (see Figure 2.2); a total of 14 panels.

2.4 Sandwich properties measured

Due to the limited quantity of stock on hand honeycomb sandwich panels were fabricated to a standard size of 457.2 x 1219.2 mm. Note that the main properties of interest for this experiment were the behaviour of the honeycomb panels under bending load, creep and shear. In accordance with the ASTM standards the span length of the test samples for the six shelling ratios (six different panel thicknesses) were of different sizes. To ensure the consistency of test samples, cutting patterns (Figure 2.4) were designed to help obtain the maximum number of samples from each board with consideration for the main properties of interest. The creep, shear, linear expansion (LE) and edgewise compressive (EC) samples were sent to FPInnovations – Forintek Eastern Division in Quebec to be tested; results of which will be used in establishing an FE model.

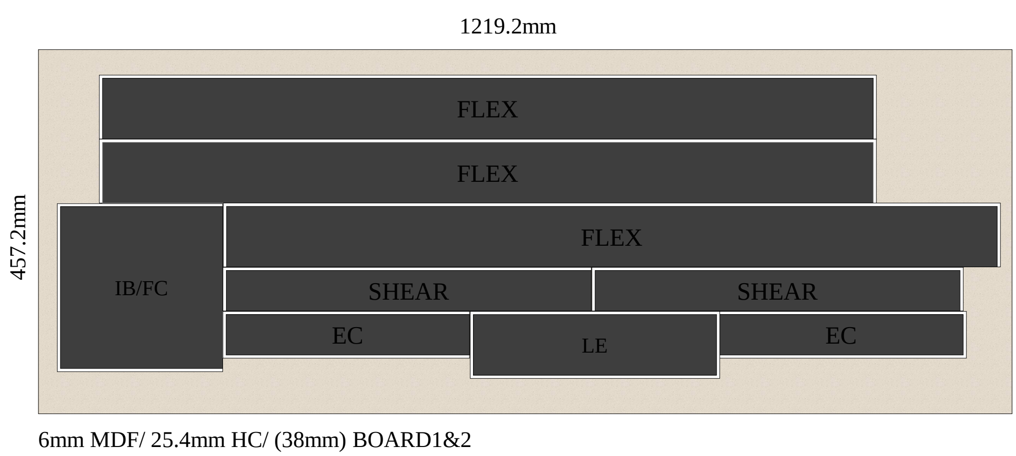

Figure 2.4: Cutting pattern for the 6 mm MDF sandwich panel containing the 25.4 mm open cell expanded honeycomb.

For each experiment the panel's shear modulus, compressive strength (FC), flexure strength and internal bond strength (IB) were measured. The maximum bending moment (M), bending stiffness (D) and shear rigidity (U) properties for each panel were then computed. Samples were cut from each panel and tested in accordance with the appropriate ASTM standards. The number of samples cut from each panel and the relevant standard testing procedures were: 2 flexure samples (ASTM C393-00), 1 IB sample (ASTM C297/C 297M-04), 1 FC sample (ASTM C365/C 365M-05) and 2 shear samples (ASTM C273-00). The specified span length for the sandwich panels with the 38 mm core height limited the total number of flexure samples from the two replicates to 3 test specimens.

The results for the IB and FC samples are from a very limited number of samples, i.e., a single IB or FC sample per panel, and as such does not permit statistically inferences to be drawn, thus those results are not included.

2.5 Statistical analysis

A statistical software package (SAS version 9.1) was used in the analysis of the experimental data obtained using a 5% significance level. All three experiments were designed using a Completely Randomised Design fixed effects model. Experiments 2.1 and 2.2 were analysed using a two-way ANOVA and Experiment 2.3 a one-way classification ANOVA. Scheffé's multiple comparison method was used to identify significant differences between means.

2.6 Results and discussion

2.6.1 Constituent material properties

The physical properties of the paper laminate honeycomb of different cell sizes and honeycomb orientation are shown in Figure 2.5. The mode of failure for the paper laminated honeycomb core was the crushing of the tops of the honeycomb cell walls due to deformation of the face paper directly below the loading nose. In practice, non-laminated open cell honeycomb is almost always used for sandwich panel construction for its lower material cost and flexibility.

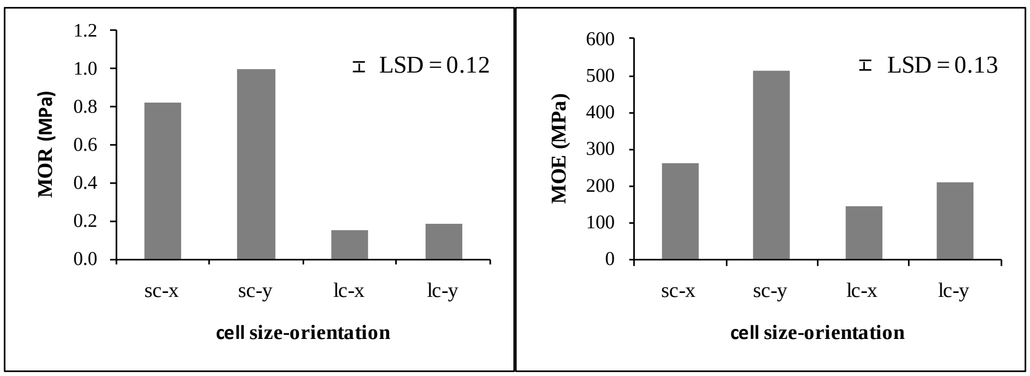

Figure 2.5: MOR and MOE of small cell (sc) and large cell (lc) paper laminated honeycomb oriented in the x (core ribbon) and y-directions. n=4 for each mean. Error bars represent the least significant difference between means.

The most significant factor affecting the MOR (i.e., the maximum amount of load that a member can bear in bending) and MOE (i.e., the tendency of a member to deform elastically when load is applied) of paper laminated honeycomb was the honeycomb core cell size. The smaller 16 mm cell size (sc) core material was much stronger and stiffer than the larger 32 mm cell size (lc), consistent with the smaller cell size honeycomb having more cell wall material over which the load was dispersed. The MOE of paper laminated honeycomb was greatest in the *y*-oriented core which was consistent with the experience of manually bending a piece of expanded honeycomb parallel to the paper strips; bending it across the paper strips as was done in the *x*-oriented core material was substantially harder.

The average density (in descending order), MOR and MOE of the different face sheets are given in Table 2.1. From the table, though the plywood face sheets (4.5 mm meranti and 6 mm Douglas-fir) recorded the lowest density values in comparison to the hardboard materials, the 6 mm Douglas-fir plywood had the highest load carrying capacity (MOR) and elastic modulus (MOE). The lowest value for both MOR and MOE was observed in the 6 mm medium density fiberboard (MDF). For both the hardboard and MDF materials, the 3 mm sheets had consistently higher MOR and MOE when compared to the 6 mm sheets.

The results of the physical properties of the face and core materials were used for the design of experiments. In order to identify the exact effect of different cell wall heights on honeycomb sandwich panels, the open cell expanded honeycomb and the MDF face sheets (with relatively low MOR and MOE) was chosen for Experiment 2.1. The second experiment, 2.2, combined a frequently used face sheet, the 3 mm hardboard (second highest MOR and third highest MOE), with the different honeycomb types oriented in the *x* and *y*-directions. Experiment 2.3 then compared the performance of the various face sheets when used as honeycomb sandwich panels.

Table 2.1: The physical properties of the candidate face sheets.

Face sheet material	Density* (kg/m^3)	MOR** (MPa)	MOE** (GPa)
6 mm hardboard	974.6	37.99	3.77
3 mm hardboard	972.7	45.80	4.56
3 mm masonite	926.0	32.29	3.07
3 mm MDF	845.9	31.26	3.40
6 mm MDF	749.3	24.14	2.86
6 mm plywood	463.0	70.55	9.28
4.5 mm plywood	357.2	39.65	5.43

* mean of 8 specimens; ** mean of 12 specimens

2.6.2 Experiment 2.1

The average maximum bending moment (M) and panel deflection (y) for each shelling ratio are shown in Figure 2.6. The panel shear modulus and rigidity values are given in Table 2.2. The core shear modulus data for the sandwich panels were obtained from lap shear tests conducted by FPInnovations (Forintek Eastern Division) and the shear rigidity values were calculated from these.

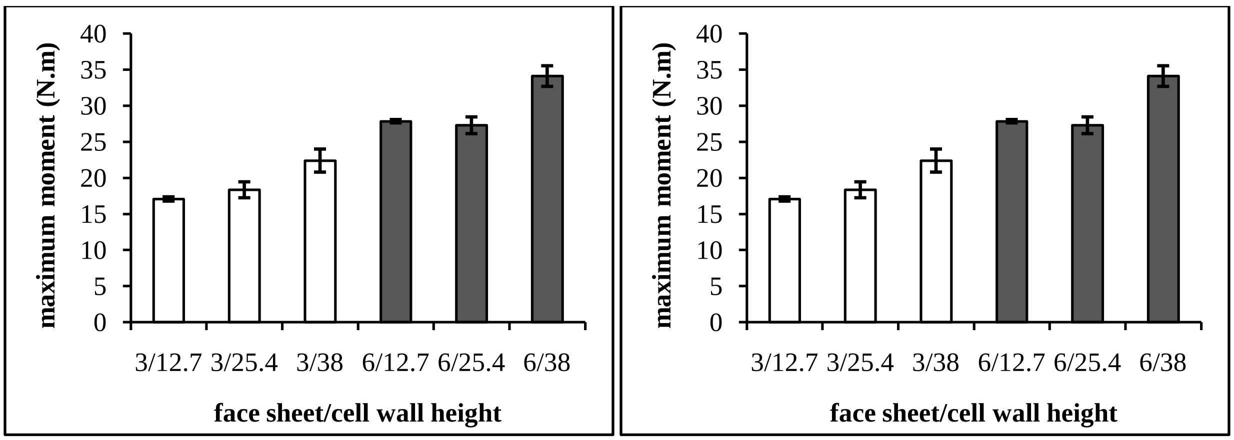

Figure 2.6: The different face-to-core height ratios in terms of the maximum bending moment and deflection values for panels with honeycomb oriented in the ribbon or x-direction. n=4 for each mean except for the 38 mm core height where n=3. Error bars represent standard deviation of the mean.

Table 2.2: Face -to-core cell wall height sandwich properties. n= 4 for each mean. Standard deviation is given in parenthesis.

Face /core height (mm)	Shear modulus (N/mm^2)	Shear rigidity (kN)
3/12.7	2.66 (*0.99*)	4.00
3/25.4	2.30 (*1.45*)	5.67
3/38	1.56 (*0.82*)	5.25
6/12.7	2.77 (*0.53*)	5.89
6/25.4	1.76 (*1.09*)	5.22
6/38	1.59 (*0.75*)	6.20

Significant differences ($p \leq 0.0001$) were observed in maximum bending moment for both face thicknesses and honeycomb core materials, with no significant interaction recorded between these factors. Honeycomb sandwich panels with the 6 mm thick MDF faces recorded the highest load bearing capacity in comparison to the 3 mm MDF faces. The results of the effect of face sheet thickness on sandwich panel maximum moment significantly differ from the face sheet properties measured (Table 2.1), where the 3 mm thick MDF had a relatively greater elastic modulus and load bearing capacity in comparison with the 6 mm MDF partly due to the differences in density. The presence of the honeycomb core material and the mode of failure of the sandwich panels contributed to the current differences.

In the case of the sandwich, the resulting panel was a composite structure whose bending performance was evaluated not only on the strength properties of the constituent materials but also on the geometry of the panel's cross-section (i.e., the moment of inertia of the panel's cross-section with respect to the neutral axis). For sandwich panels of the same material, it has been shown that panels with a larger distance between the centers of the top and bottom face sheets tend to resist bending stresses more effectively (Hibbeler, 2008), hence the larger bending moments recorded for the 6 mm MDF sandwich panels.

Generally, the honeycomb sandwich panels failed by shear stresses in the core and crushing (compressive stress) of the paper honeycomb core under the loading noses (Figure 2.7). In most cases there was also delamination between the face and core materials at the support edges as the panel failed. This mode of failure was attributed to the low resistance offered by the Kraft paper core to bending loads and the high shear stress in the glue line between the face and core – a mode of failure that has been reported by Bryan (1957), Thomsen (1998), Hassinen *et al.* (1997), Petras and Sutcliffe (1999) and Zok *et.al.* (2003), for a wide variety of different core and face materials such as Nomex, aluminum honeycomb cores, textile cores, metallic and fiber reinforced plastic face sheets.

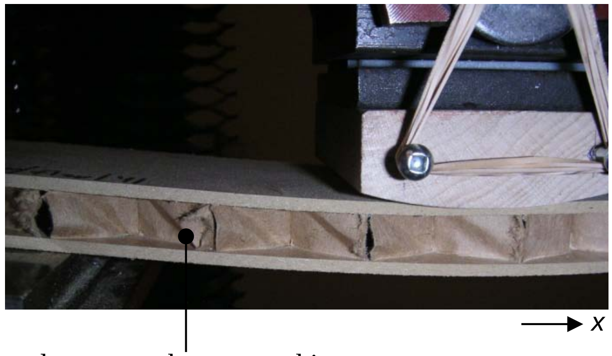

Figure 2.7: Failure mode of Kraft paper honeycomb panel indicating core shear and crushing (6mm MDF sandwich panel under one loading nose in a four point bending test).

During loading, the sandwich panels with 3 mm MDF face sheets flexed more readily under the applied load creating a greater stress concentration on the honeycomb cell walls and the face-to-core interfaces. This phenomenon resulted in the early crushing of the cell walls directly beneath the loading nose (particularly the free walls of the honeycomb shown in Figure 2.8) which in turn spread gradually to surrounding cells crushing them and finally causing failure of the sample.

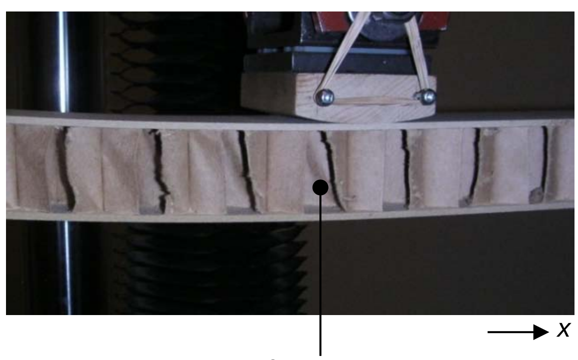

Figure 2.8: Shear in the honeycomb cells (oriented in the ribbon direction) of the 3mm MDF sandwich panel under one loading nose in a four point bending test; note the shear deformation in the free wall of the honeycomb.

In the case of the honeycomb core material irrespective of the face sheet thickness (3 or 6 mm), the maximum bending moment of the sandwich panels generally increased with increasing cell wall height. Significant differences were however observed between only the 38 and 25.4 mm ($p = 0.0003$), and 38 and 12.7 mm ($p < 0.0001$) core materials; no difference was observed between the 25.4 and 12.7 mm cores.

It should be noted that failure in the honeycomb sandwich panels was mainly due to buckling of the Kraft paper honeycomb material and not localised bending failure of the face materials. From Figure 2.9, the peak load for the sandwich panels decreases almost linearly with an increase in cell wall height from 12.7 to 38 mm. (Note: For the 6 mm MDF panels, variability in core density and assembly imperfections could have contributed to the slight differences in peak load values for the 25.4 and 38 mm cell wall heights). The peak load values can be explained by column theory where shorter columns (12.7 mm cell wall height) are more stable and carry higher compressive loads in comparison to taller columns (38 mm cell wall height). One would expect this to reflect in the maximum bending moment (maximum load at failure) of these sandwich panels, however, this is not the case since the moment calculations also depends on the span length, which increases with increasing cell wall height/ sandwich thickness according to the ASTM standards D1037-06a (the span length for each test specimen shall be 24 times the nominal depth of the specimen). In effect, sandwich panels with a higher cell wall height (38 mm) and long spans will record higher failure loads.

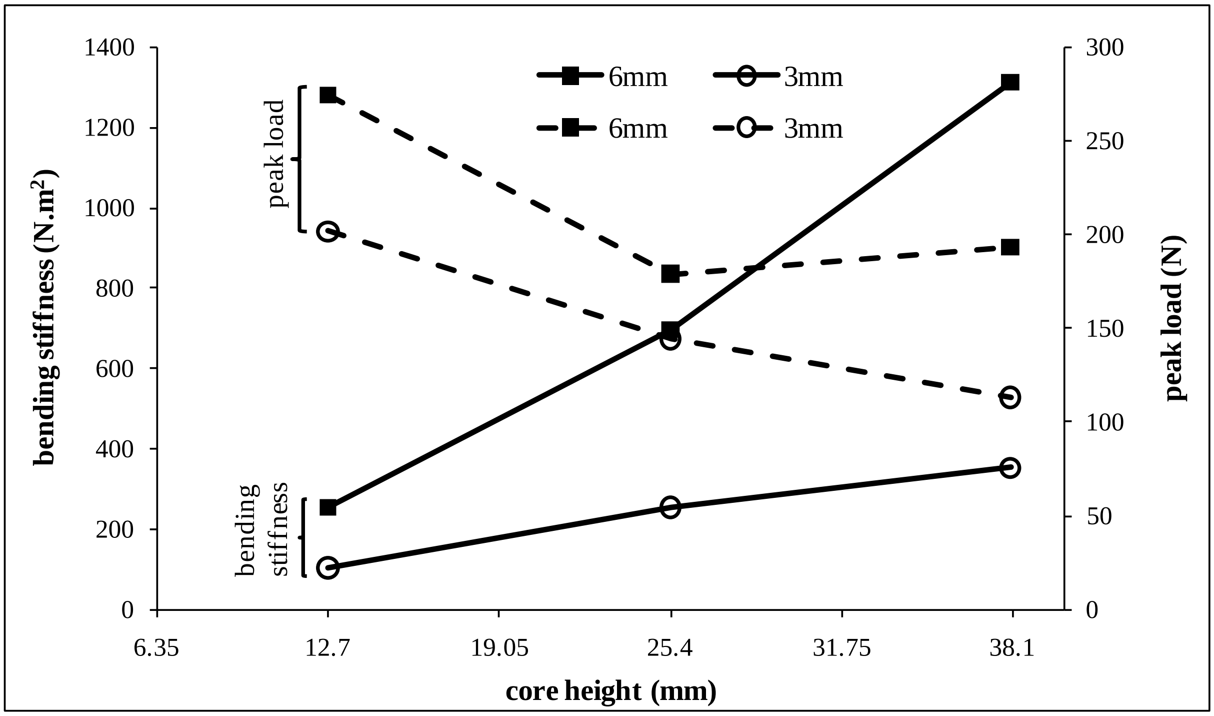

Figure 2.9: Bending stiffness and peak load values for the different honeycomb cell wall height.

The bending stiffness (D) of a sandwich panel helps predict the panel's ability to resist bending and deflection. There was a general increase in panel bending stiffness with increasing cell wall height for both the 3 mm and 6 mm MDF panels.. This trend observed for the bending stiffness of the paper honeycomb panels with different cell wall heights are in agreement with those of Lingaiah and Suryanarayana (1991) who worked with polyurethane foam cores sandwiched between fiber-glass reinforced plastic and aluminum alloy faces materials.

Our results suggest that, the flexural rigidity (bending stiffness) of the honeycomb sandwich panels were largely provided by a combination of the core height and the thickness of the face sheet material. Based on our findings, if thin face sheets (3 mm) are to be used for sandwich panels, their strength properties over a long span (> 508 mm) must be high so as to minimize the deflection of the face sheet material and deformation of the honeycomb core at the maximum required service load.

The results for the sandwich panel deflection indicated an interaction ($p = 0.0169$) between the face sheet thickness and core height. This result was anticipated since the total panel deflection of a sandwich panel is the sum of the panel's bending and shear deflections, where the bending stiffness of the sandwich panel influences the bending deflection and the core shear rigidity the shear deflection (Bitzer, 1997; Moody *et al.*, 2007). Note that the shear rigidity of a core is a function of its shear modulus which is related to its deformation in the plane perpendicular to the face sheets and parallel to the sandwich panel length. Normally, a low core shear modulus results in higher panel deflection in comparison to a core with high shear modulus (Moody *et al.*, 2007). A multiple comparison of the treatment means indicated only sandwich panels made from a combination of the 3 mm MDF and the 25.4 mm high core material (with the lowest panel deflection) were significantly different from all other sandwich panels.

The results suggest that in the production of Kraft paper honeycomb sandwich panels, the choice of a honeycomb core height should be based on the shear modulus of the paper honeycomb. Within the boundaries of this study, it appears the use of a stiffer and thicker (6 mm) MDF face sheet material with a honeycomb material of cell wall height 38 mm in the manufacture of Kraft paper sandwich panels would be advantageous, confirming the initial hypothesis about thicker face sheets producing panels with greater bending strength properties. Much thinner (3 mm) and flexible MDF face sheets will however work best with a 25.4 mm honeycomb cell wall height in shorter spans.

2.6.3 Experiment 2.2

Figure 2.10 shows the average maximum bending moment (M) and total panel deflections (y) of the different types of honeycomb grouped by ribbon orientation. Other panel properties are given in Table 2.3. Analysis of the sandwich panel strength results indicated a significant interaction between honeycomb core type and orientation, implying that depending on the type of Kraft paper honeycomb the orientation of the hexagonal honeycomb cells would significantly affect the panel's deflection and load bearing capacity.

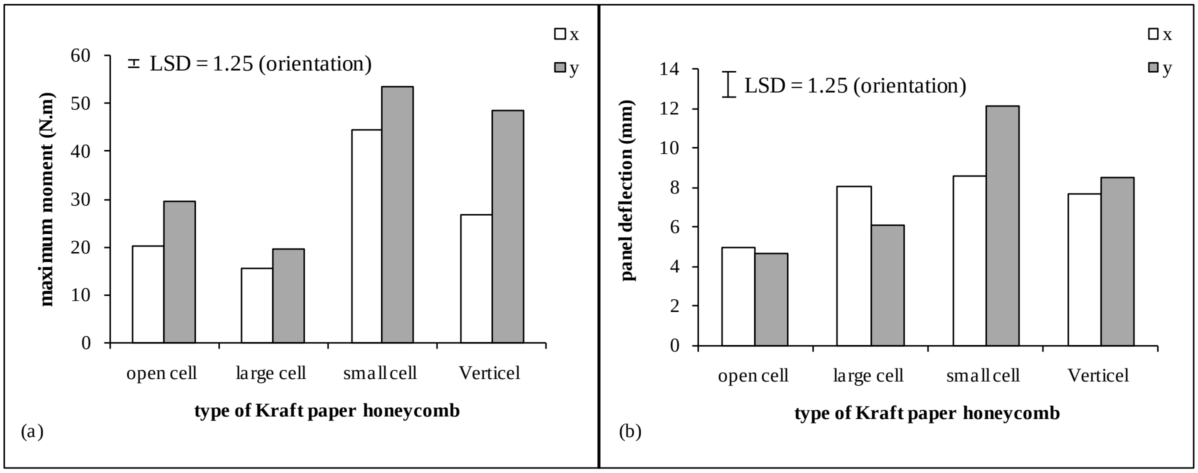

Figure 2.10: The maximum bending moment and deflection of panels with different honeycomb types oriented in the x and y-directions respectively. n=4 for each mean. Error bars represent the least significant difference between means.

The results show that both honeycomb core type and cell orientation significantly affected ($p < 0.0001$) sandwich properties, with panels oriented in the *y*-direction and containing the small cell size core materials (the 16 mm small cell paper laminated and 13 mm Verticel™ honeycombs) recording higher loads. Generally, for each core material, honeycomb cells oriented in the ribbon/*x*-direction failed at significantly lower loads compared with those oriented in the *y*-direction.

Table 2.3: Shear modulus and rigidity values for the different honeycomb sandwich panels. n=4 for each mean. Standard deviation is given in parenthesis.

Honeycomb type	Peak load (N)	Shear modulus[1] (N/mm^2)	Shear rigidity (kN)
Open cell-x	159.6	3.12 (*1.02*)	7.69
Open cell-y	232.3	8.88 (*11.83*)	21.89
Large cell-x	123.9	1.02 (*1.21*)	2.51
Large cell-y	155.5	2.06 (*0.86*)	5.08
Small cell-x	350.1	5.13 (*5.19*)	12.64
Small cell-y	420.6	3.59 (*1.61*)	8.85
Verticel™-x	210.5	2.33 (*0.68*)	5.74
Verticel™-y	382.0	6.61 (*1.66*)	16.29

[1] Shear modulus values were obtained from shear lap tests conducted on sandwich panels by FPInnovations (Forintek Eastern Division).

Our results for the directional effect (*y*-direction) on the load carrying ability of sandwich panels with different honeycomb materials also confirmed those of Petras and Sutcliffe (1999) for Nomex™ honeycomb sandwich panels of cell size 13 mm. According to Petras and Sutcliffe, sandwich panels (made of glass fibre reinforced plastic laminate faces and Nomex™ honeycomb core) of core cell size 3 mm and oriented with the ribbon or *x*-direction parallel to the long axis of the panel failed at significantly higher loads compared to those oriented in the *y*-direction. However, the opposite result was reported for a core material of cell size 13 mm, this difference was attributed to intra-cell buckling which at higher loads resulted in the crushing of the honeycomb core. The different honeycomb core materials used in our study were of size 13 mm, 16 mm and 32 mm, all of which are well above 13 mm hence our observation that sandwich panels oriented in the *y*-direction had higher load carrying properties than those in the core ribbon direction.

With regard to honeycomb cell size, it was observed from Figure 2.10 that the 32 mm cell size core materials (large cell paper laminate and open cell expanded honeycomb) carried less load compared with the 13 mm corrugated and 16 mm small cell paper laminated core material. This observation could be related to the smaller cell core materials being more stable and possessing more cell walls over which to distribute the applied load from the point of application. The results were also consistent with the observations from the flexure tests on paper laminated cores themselves. This finding supports the hypothesis on cell size effect and suggests that honeycomb cell size was one of the major factors affecting honeycomb sandwich performance.

The method of construction for hexagonal honeycomb cores results in some cell walls having double layers of paper, i.e., a node in Figure 2.2, compared with a free wall that has only a single wall, making the honeycomb highly anisotropic and producing major differences in its shear rigidity. The shear rigidity values (Table 2.3) for the different core materials indicated that with the exception of the small cell paper laminated core, all other core materials oriented in the *y*-direction resulted in panels with higher shear rigidity. The honeycomb directional effects observed for the sandwich panel shear rigidity were contrary to those of Kollman *et al.*, 1975 and

Bitzer, 1997 who stated that the shear properties for the hexagonal cell honeycomb itself was greater in the core ribbon or *x*-direction than in the *y*-direction.

A closer look at the behaviour of the honeycomb core sandwich panels under bending loads helps to explain the differences in results. When a panel with the core ribbon oriented parallel to the long axis of the panel is loaded in bending, the honeycomb core experiences more compressive stresses than shear before deformation of the nodes occurs because the moments at the support ends causes rotation (Figure 2.11a). However under the same loading conditions, a sandwich panel with its core ribbon oriented perpendicular (*y*-direction) to the long axis of the panel from the onset of loading experiences greater shear stresses as the core material in this configuration is more flexible with no deformation of the nodes occurring at the early stages (Figure 2.11b).

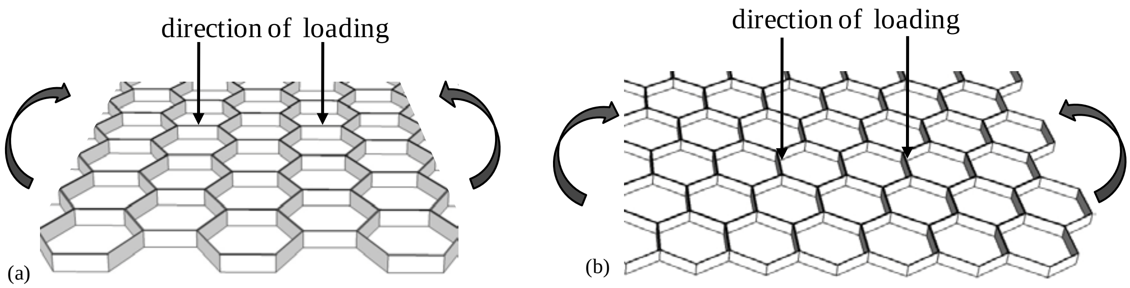

Figure 2.11: Effect of honeycomb orientation (core ribbon and x-direction respectively) on sandwich properties.

Statistically, panel deformation like maximum bending moment recorded a significant interaction ($p = 0.0015$) between the type of honeycomb core material and its cell orientation. On a factor basis however, significant differences were observed for only the honeycomb types ($p < 0.0001$) and not the cell orientation ($p = 0.6409$). The interaction between the factors therefore implies depending on the type of honeycomb, the cell orientation would significantly affect the resulting panel deflection. Further analysis of the combination of factors revealed that only the paper laminated honeycomb materials (small cell and large cell) registered significant differences with the different cell orientations.

The differences observed could be explained in terms of the panel's shear rigidity where panels containing honeycomb cores with relatively higher shear rigidity values had correspondingly lower deflection values in comparison to panels with low shear rigidity values. Other variations in the core density or sample assembly could have also contributed to this difference. Further research is therefore necessary in order to fully understand the directional effect of honeycomb cells on panel deflection.

Based on these findings it is recommended that in the choice of honeycomb type for furniture applications the open cell and Verticel™ honeycomb materials oriented in the *y*-direction be used, with the Verticel™ core material employed in applications requiring higher load carrying capacities.

2.6.4 Experiment 2.3

Statistical analysis of the results from this experiment revealed significant differences ($p < 0.0001$) in the load carrying capacity and deflection values for sandwich panels with different face sheets. From the average maximum bending moment and panel deflection values shown in Figure 2.12, the 6 mm Douglas-fir plywood face sheet in bending carried the highest load. For the 3 mm face sheet types (hardboard, Masonite and MDF) there were no significant differences in their maximum bending moment and stiffness values (Table 2.4); similarly the 4.5 mm meranti plywood and 6 mm MDF face sheets recorded no significant differences between their maximum bending moments. For the most part the 3 mm face sheets recorded lower load carrying abilities when compared with the 6 mm face sheet types, just as it was detected in Experiment 2.1. For the hardboard the thicker face sheet panels had higher maximum bending moments than the thinner face sheets, but not significantly so, whereas the 6 mm MDF panels were significantly stronger than their 3 mm counterpart.

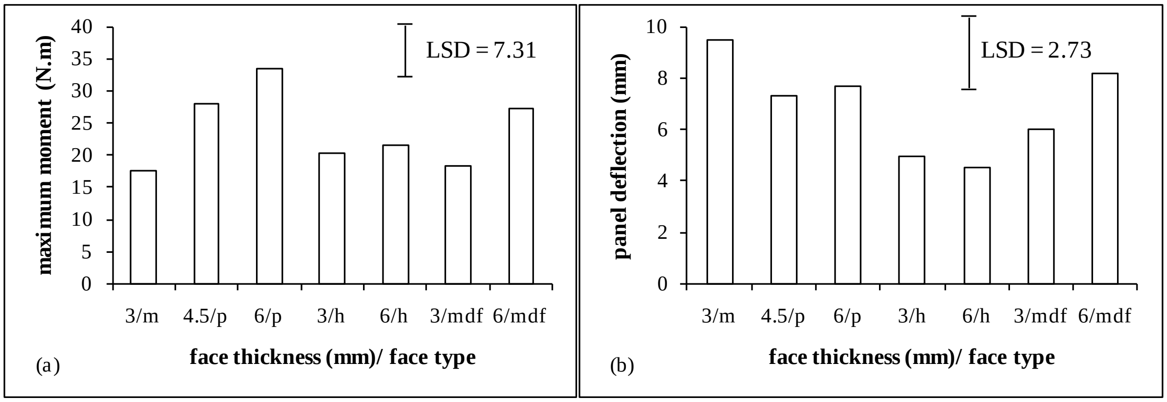

Figure 2.12: Maximum moment and deflection values for sandwich panels with different face materials. 'm' indicates Masonite, 'p' for plywood, 'h' for hardboard, and 'mdf' for medium density fiberboard. n=4 for each mean. Error bars represent the least significant difference between means.

Table 2.4: Panel properties for sandwich panels with different face materials. n=4 for each mean. Standard deviation is given in parenthesis.

Face material (mm)	Peak load (N)	Shear modulus[1] (N/mm^2)	Shear rigidity (N)	Bending stiffness ($N.m^2$)
3mm masonite	138.5	1.26 (*0.89*)	2998	260.6
4.5mm plywood	200.7	1.93 (*1.67*)	5267	910.9
6mm plywood	226.0	1.69 (*1.00*)	5081	2262
3mm hardboard	159.6	3.12 (*1.02*)	7690	473.1
6mm hardboard	150.7	3.16 (*0.85*)	8911	722.7
3mm MDF	144.4	2.30 (*1.45*)	5669	352.7
6mm MDF	179.0	1.76 (*1.09*)	5292	697.1

As mentioned earlier the panel shear rigidity (a function of the core shear modulus) influences the honeycomb sandwich panel deflection under applied load. From Table 2.4 and Figure 2.12b, it was observed that panels with higher shear rigidity values, for example the hardboard sandwich panels, had correspondingly lower deflection values in comparison to panels with low shear rigidity such as the 3 mm Masonite panels. Irrespective of their face thicknesses, a comparison of the mean deflection values for sandwich panels made of either the hardboard (3 and 6 mm) or 6 mm Douglas-fir and 4.5 mm meranti plywood materials revealed no statistical

[1] Shear modulus values were obtained from shear lap tests conducted on sandwich panels by FPInnovations (Forintek Eastern Division).

differences. The deflection results for the different face sheet show that the face sheets play an important role in delaying the transfer of applied loads to the core in the form of shear and buckling stresses; the stiffer and more stable face sheets resulted in sandwich panels which bore high loads.

These results imply that depending on the specific application, the 6 mm Douglas-fir plywood face sheet and with high load bearing abilities would best suite RTA furniture applications. However, the uneven under surface (i.e., holes and cracks) of the bottom veneer and warp in the 6 mm Douglas-fir plywood available made it a less suitable candidate for the manufacture of sandwich panels because in most cases it affected the contact zone between the honeycomb and the face sheet. Therefore, the hardboard (3 and 6 mm) materials with average load carrying and deflection values would be a better face material for honeycomb sandwich panels.

The adoption of paper honeycomb sandwich technology in the furniture industry is extensively dependent on the costs of the constituent materials – the face sheets and honeycomb core relative to conventional composite board (i.e., particleboard). Based on square foot price of a standard 25.4 mm expanded core ($0.6) there is a significant cost increase of 65-75% for the small cell core (13 mm) compared to the large cell core (32 mm). This is due to the smaller cell honeycomb containing twice as much paper and glue per unit area compared to the large cell form. The price differences between different types of composite board face sheets of the same thickness were found to be minimal. Major price differences only exist between the different face sheet thicknesses – a 1219.2 x 2438.4 mm (4 x 8 ft) long 6 mm MDF ($13.25) is approximately twice as expensive as the 3 mm MDF ($7.82). Therefore a relatively expensive face sheet could be combined with a less expensive (in comparison to the face material) core material to produce a sandwich panel whose weight would be well below that of solid wood components of similar size.

The sandwich panels in this study were assembled manually and pressed by way of a flat board (26 mm thick) evenly loaded with 50 kg of dead weights. It would be expected that sandwich panels from an automated assembly line will have consistent glue application, even core expansion and uniform pressure application during pressing. The variability in the manually assembled sandwich panels is expected to be slightly higher than that for panels from an automated assembly line, but the mean values of the properties are expected to be the same.

2.7 Conclusions

This study has shown the factors that require greatest consideration in the manufacture of paper honeycomb sandwich panels are the strength properties (bending stiffness and maximum bending moment) of the face sheet, the shear modulus of the core material, the cell size and cell wall height of the honeycomb core material, and its orientation relative to the long axis of the sandwich structure.

Consequently to garner the maximum advantage from Kraft paper honeycomb sandwich panels, a honeycomb core of cell size 13 mm, cell wall height 38 mm and oriented with its paper strips perpendicular to the long axis of the sandwich panel is recommended. This core combined with a face sheet thickness of at least 6 mm possessing high flexural properties will result in a product that is light weight with less material content compared to solid composite boards.

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3 Edge reinforcement of honeycomb sandwich panels[1]

3.1 Background

The use of light weight honeycomb sandwich panels in the furniture industry faces a number of challenges including how to effectively seal and reinforce the edges of the honeycomb panel. The edges must be sealed to protect the face and core materials from damage (liquids, moisture, and impact), provide support for conventional hardware to be inserted and permit the panels to be fastened to other structures (Bitzer, 1997; Moody *et al.*, 2007).

Strips of solid wood veneer, Polyvinyl Chloride (PVC), or composite materials (medium density fiberboard, particleboard and oriented strand board) have been employed as reinforcements for the edges of honeycomb panels during panel manufacture. Industry typically uses edge reinforcements that are large enough to bear a panel's loading requirement (Eurolight, 2007). Common edge banding techniques for honeycomb panels include direct coating, stabilizer edge and surface folding (Stosch, 2008). The edge band runs along the long edges of the honeycomb panels sometimes over a strip of edge reinforcement termed the 'stile'. It serves to seal panel edges with a decorative finish and improve panel bending strength and stiffness.

There is a dearth of published information directly comparing the load bearing capacity of honeycomb core panels' edged using different edge banding techniques, edge rail material types and widths. To address these deficiencies two experiments were designed to quantify the load bearing properties of honeycomb core shelves made with different rail materials (i.e., solid wood or composite) using the three different edge banding techniques mentioned above. The information obtained was used to fabricate prototype honeycomb core book shelves from different types of face sheet materials, fastening systems, and different methods of edge band application.

Experiment 3.1 focused on edge rail type and rail width for honeycomb shelves as these edge materials stabilize and reinforce the panel as well as provide the substrate required to fasten the

[1] A version of this chapter has been submitted for publication. Sam-Brew, S., Semple, K. and Smith, G.D. (2009). Edge reinforcement of honeycomb sandwich panels.

shelves to the gables of the book cases. The hypothesis for this experiment was that increasing rail width will increase the load bearing capacity of honeycomb shelves.

Experiment 3.2 investigated the effect of different edge banding techniques on shelf strength. Three different techniques for edge band application were investigated with the hypothesis that a technique which maximizes the adhesive contact area between the edge band and the panel will increase overall panel stiffness.

3.2 Design of honeycomb shelves

A survey of local furniture companies that fabricate and use honeycomb core sandwich panels showed yellow poplar wood (*Liriodendron tulipifera)* and M2 grade particleboard to be the most commonly used materials for rails (short edge reinforcement), with screws and brackets as the predominant fastener systems for bookshelf assemblies. Research on sandwich construction (Zenkert 1997; Moody *et al.*, 2007) has suggested that the strength properties of a sandwich panel are very much determined by the properties of the face material. Preliminary experiments (Chapter 2) conducted on sandwich panels with different face materials indicated the load carrying capacities of the hardboard and medium density fiberboards (MDF) faces (commonly used RTA furniture materials) to be between those of the Masonite sheets (the lowest) and the plywood, the best performing materials.

Based on these preliminary results and to easily identify the exact edge rail effects on sandwich panels, the 3 mm hardboard and 6 mm MDF were used as face sheets for the sandwich construction with open cell expandable honeycomb (cell size 32 mm) as the core material. Rail widths of 10 and 38 mm were chosen so that differences in bending stiffness, maximum bending moment and deflection of the sandwich panels could be detected; the 65 mm width would likely be so strong as to mask the effects we were looking to examine and were not in keeping with the light weight theme of this research.

In both Experiments 3.1 and 3.2, a common book shelf size of 1067 x 305 mm (42 x 12 inches) with a thickness of 38 mm was chosen for the construction of the honeycomb shelves as illustrated in Figure 3.1. To ensure a common sandwich thickness of 38 mm for both the 3 mm hardboard and 6 mm MDF face materials, honeycombs with cell wall heights 32 and 26 mm were used respectively. Limitations on the width of the edge band material normally available for purchase led to the reduction of the shelf thickness in Experiment 3.2 to 32 mm. As a result the experimental design included control shelf samples which were fabricated in the same way as shelves in Experiment 3.1 but with a 32 mm thickness. Note that the guidelines (Architecture Woodwork Quality Standards, 1999) for furniture construction states shelf thickness shall be a minimum of 19- 27 mm (¾ - $1^{1}/_{16}$ inch).

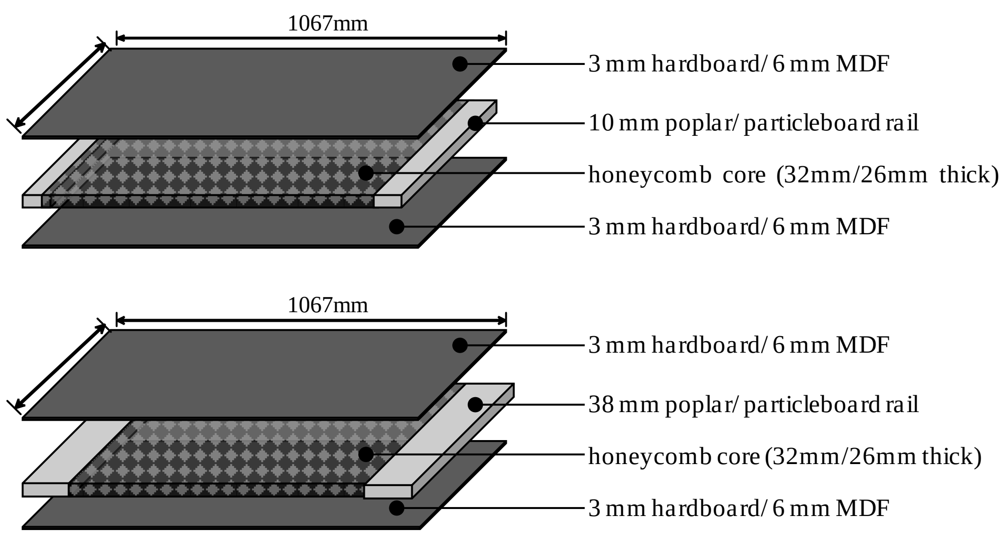


Figure 3.1: Exploded view of two honeycomb core shelves (total sandwich thickness is 38mm).

3.3 Sandwich panel assembly

The edges of the unexpanded Kraft paper honeycomb strips were first roughened with sandpaper to increase the surface area exposed to the adhesive. Before expansion incisions 2 mm deep were made at spaced intervals along the length of the paper honeycomb to create pathways for air flow during and after sandwich panel fabrication. The honeycomb strip was then evenly expanded on a nailed 1219 x 2438 mm (4 x 8 ft) oriented strand board and placed in a walk in oven at 80ºC for 3 hours to set.

The face sheet materials were cut to dimensions 1067 x 305 mm, and the honeycomb core material to 1047 x 305 mm. The particleboard and yellow poplar rails (edge reinforcements) were cut to a length of 305 mm and to two different widths, 10 mm and 38 mm. DURO-LOK 422150 glue (a cross linked PVA with phenolic resins, no catalyst required for interior purposes) was applied to the bottom face sheet and the rails and honeycomb core were carefully placed onto it. On average 127 g of glue was applied to each face sheet. The rails and honeycomb material were kept in place with the aid of flat wooden sticks, and the top sheet was then glued in place. The sandwich panels were weighed down with a 26 mm thick medium density board evenly loaded with 50 kg of weight while the next sandwich was assembled. The stacks were left to cure for two days before removing the weights.

3.4 Edge reinforcement design

3.4.1 Experiment 3.1

Experiment 3.1 focused mainly on the edge rail material (type and width) and comprised of 2 phases based on the fastener type used for assembling the shelf components. The first phase had 3 factors of interest being compared:

1. face sheets (3mm hardboard and 6mm MDF),
2. rail type (particleboard and yellow poplar)
3. rail width (10 mm and 38 mm)

The honeycomb shelves were fixed to 305 x 178 mm particleboard gables using 25.4 mm and 38 mm no.8 fully threaded sheet metal screws (with 14 tpi) according to System 32 (Architecture Woodwork Quality Standards, 1999) as illustrated in Figure 3.2a. The resulting treatment combinations were replicated 3 times for a total of 24 panels.

The second phase allowed for a contrast between shelf fastening systems: no.8 fully threaded sheet metal screws or standard shelving brackets (Figure 3.2b). Honeycomb shelves were made of 3 mm hardboard faces and particleboard rails in widths of 10 and 38 mm. Three replicate panels were fabricated for rail width and fastener combination, for a total of 6 panels.

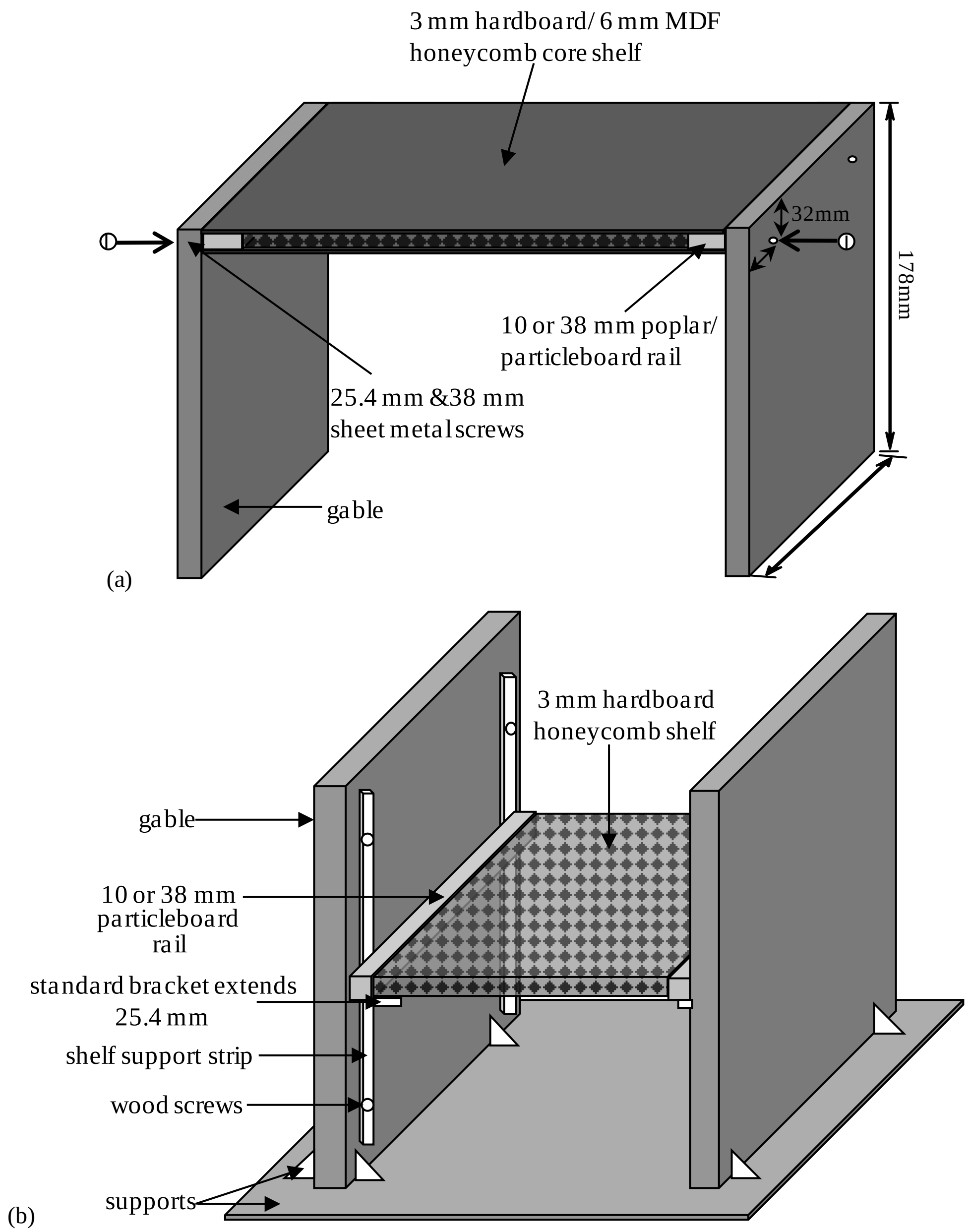


Figure 3.2: Testing of (a) screw-fastened and (b) bracket-fastened honeycomb shelf assemblies.

3.4.2 Experiment 3.2

This experiment was designed to isolate the true effect of edge banding on the bending stiffness and load carrying capacity of honeycomb core shelves. The rail width needed to be as small as possible to minimize any masking effects of wider rails; 10 mm particleboard rails were therefore selected as the smallest practical width. The honeycomb core shelves were fabricated using 3 mm hardboard faces and open cell expanded honeycomb. Shelves were attached to the particleboard gables using the standard shelf bracket system (Figure 3.2b). Three different edge banding techniques were evaluated: direct coating, stabilizer edge and surface folding. Each technique was replicated 6 times for a total of 18 panels.

3.5 Edge band application

For all three techniques, a PVC edge band of thickness 3 mm and width 32 mm was glued to sandwich panels using an automated SCM (Olimpic K 1000) edge banding machine.

3.5.1 Direct coating technique

In this process the PVC edge band was glued directly onto the edges of the sandwich panels as shown in Figure 3.3.

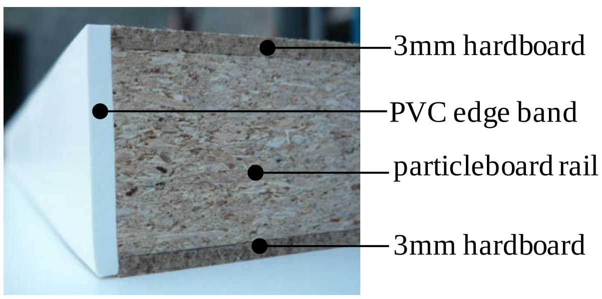


Figure 3.3: Side view of a sandwich panel directly coated with a PVC edge band.

3.5.2 Stabilizer edge technique

For this process each face layer had a 3 mm recess cut from its inside edge (Figure 3.4a). These recesses allowed for a vertical support edge in the form of a strip of 3 mm thick hardboard material to be manually inserted along both long edges of the honeycomb shelves using DURO-LOK glue. After the support edge had been inserted, the PVC edge band was glued to the outside (Figure 3.4b).

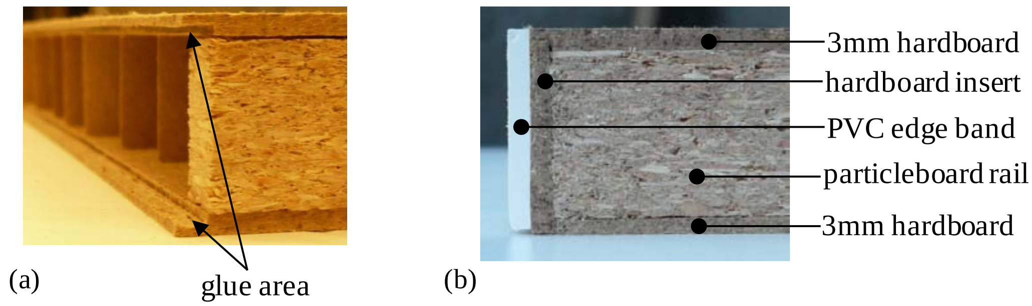
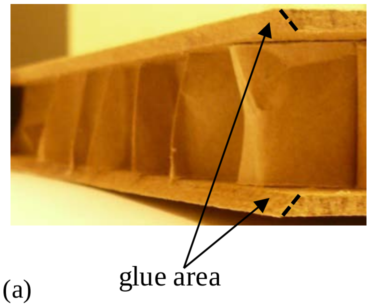


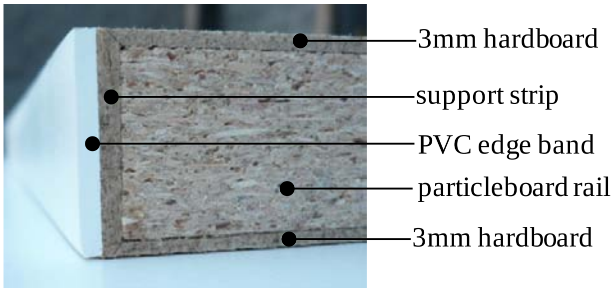
Figure 3.4: Honeycomb shelf showing (a) top and bottom recesses for support edge insert and (b) inserted hardboard support edge attached to a PVC edge band material.

3.5.3 Surface folding technique

This process uses a vertical support strip similar to the stabilizer edge technique except that the top and bottom face sheets were cut in at a 45° angle (Figure 3.5a). The hardboard insert (support strip) was also cut at a 45° angle along its edges to fit between the face sheets (Figure 3.5b). The PVC edge band was then subsequently applied.



(a)



(b)

Figure 3.5: Honeycomb shelf with (a) 45° beveled edges - the dashed line shows the edge of the 45° bevels and (b) inserted support strip and PVC edge band material.

3.6 Testing honeycomb shelf properties

For each experiment the peak load, deflection values (y) and failure modes of the sandwich panels were measured and the bending stiffness (D) and maximum moment (M) computed in accordance with the ASTM standard C393-00 for hollow core sandwiches. A four point bending test (third point loading) was conducted using the screw and standard bracket shelf assemblies (Figure 3.6) at a loading rate of 4mm/min on a Sintech 30D testing machine. As per the ASTM standard rubber pads (102 x 305 x 25.4 mm) and a 3 mm thick steel sheet were located directly beneath the loading noses to help dissipate the load and prevent localised crushing of the core directly beneath the loading noses.


(a) screws


(b) brackets

Figure 3.6: Four point bending (third point loading) test using (a) screws and (b) brackets.

The ASTM standard used in this study to test for flexure properties was issued under the fixed designation C393-00 and covered the determination of sandwich properties when subjected to flatwise flexure. In this standard, it was recommended that the speed of testing be set to ensure maximum failure occurred between 3 to 6 minutes after the test began. This standard also allowed for separate tests to be conducted for the core shear strength and modulus in accordance with test method C273-00.

The standard ASTM C393-00 has since been superseded by ASTM C393/C393M-06 that requires the use of ASTM D7250/D7250M-06 to determine the flexural and transverse shear stiffness of sandwich panels. Generally, the test specimen configuration remained the same. Major differences in testing procedure occur with the speed of testing which has been set at a suggested standard rate of 6 mm/min, and the ability to test and calculate the flexural stiffness, shear rigidity and core shear modulus on a single specimen with two loading configurations.

3.7 Results and discussion

All experiments were designed using a Completely Randomised Design fixed effects model and analysed using a two-way ANOVA. SAS version 9.1 was used in the analysis of the experimental data using a 5% significance level. Scheffé’s multiple comparison method was used to identify significant differences between means.

To simplify the discussion of the experimental data being presented in the Figures and Tables, abbreviations were created for the experimental parameters edge rail material, rail width and fastener type. The list below defines these abbreviations.

- PB = particleboard rails
- Poplar = yellow poplar rails
- 10s or 38s = shelves with 10 or 38 mm particleboard rails fixed to gables with screws
- 10b or 38b = shelves with 10 or 38 mm particleboard rails fixed to gables with brackets

3.7.1 Experiment 3.1

During testing failure in the honeycomb shelves generally occurred as follows:

1. The shelves flexed under load and the honeycomb cells directly beneath the loading noses were crushed, this crushing gradually spread to surrounding cells.
2. During loading, there was delamination of the honeycomb core from the face sheets (mostly the bottom faces) at the ends of the shelves where it was fixed to the gables. The debonding was attributed to the failure of the glue joint between the face and core materials due to the high shear stresses at this point.
3. The rails separated from the face sheets, mainly the bottom first then the top sheet; this was more pronounced for the narrower 10 mm particleboard rail than the 38 mm particleboard or yellow poplar rails. These separations indicate a failure in the glue joint between the rails and face material as a result of over loading.
4. Finally, the combination of crushing of the core and delamination of the core material and rails from the face lead ultimately to failure of the sandwich structure.

During loading the joints between the gables and the shelves (hardboard and MDF) with 10 mm rails were greatly stressed resulting in a 2-3 mm gap between the edge of the shelf and the gable face. This observation indicates the substrate (rail) provided for the fastener was not sufficient enough to support the shear forces produced during loading. Most of the 10 mm particleboard rails cracked and split at the points where the 25.4 mm screws were inserted, some rails then broke off above the glue bond between the rail and the face sheet (Figure 3.7a); only cracks were observed in the 38 mm particleboard rails (Figure 3.7b). For the 6 mm MDF shelves delamination of the MDF face sheet occurred at the ends adjacent to the gables (Figure 3.7c) — in two samples as core failure progressed the face sheet broke right where the support from the 38 mm poplar rail ended (Figure 3.7d). The failure modes observed in c and d indicate the yielding of the face sheet material caused by the high bending moments at the panel edges. The highest loads (an average of 984.55 N) were recorded for shelves with the 38 mm rails.

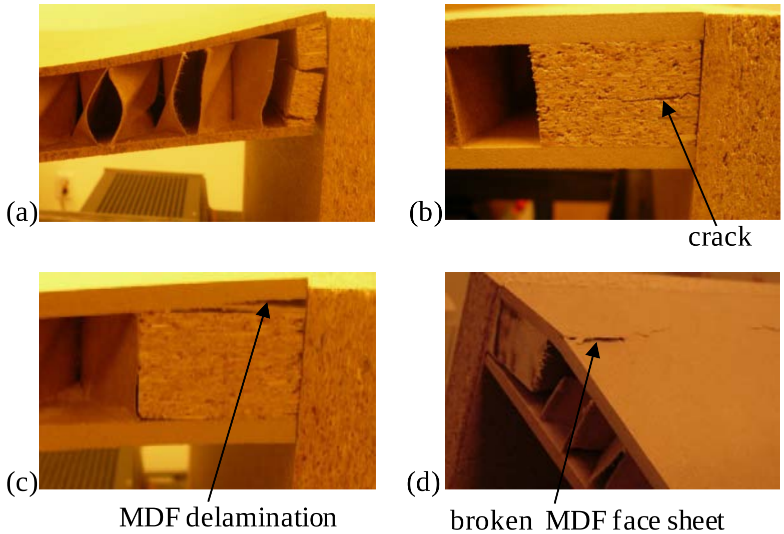


Figure 3.7: Honeycomb shelf failure modes; (a) broken 10 mm particleboard rail, (b) cracked 38 mm particleboard rail, (c) delaminated MDF face sheet and (d) broken MDF face sheet.

3.7.1.1 Relationship between rail type and rail width

The maximum bending moment for the shelf assemblies (fixed to gables) occurred at the ends of the honeycomb shelves reinforced with rail materials because these fixed ends resisted the bending moments created and thus restricted the resulting rotations. Statistical analysis for the shelves indicated significant differences ($p = 0.0156$) between only the types of edge rail materials (particleboard and yellow poplar) used, but no differences in the widths (10 and 38 mm). From Figure 3.8a, the 3 mm hardboard honeycomb shelves reinforced with the yellow poplar rails recorded higher maximum moment values compared with those containing the particleboard rails – an observation consistent with the bending stiffness values (Table 3.1) for the respective shelves.

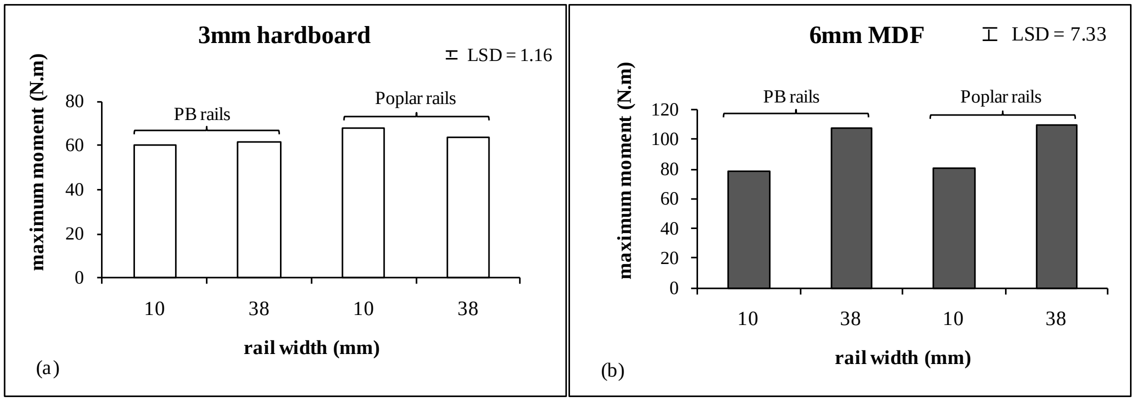


Figure 3.8: Maximum bending moment of 3 mm hardboard and 6 mm medium density fiberboard (MDF) honeycomb shelves with combinations of different rail width and rail materials. n=3 for each mean. Error bars represent the least significant difference between means.

In contrast, the 6 mm MDF honeycomb shelves recorded significant ($p < 0.0001$) rail width effect on the maximum bending moment of the shelves. Shelves with the 38 mm wide rails (whether particleboard or yellow poplar) recorded higher strength values than the 10 mm rails. It is important to also note the differences in maximum bending moment values between the 3 mm hardboard and 6 mm MDF honeycomb shelves. The higher moment values obtained for the 6 mm honeycomb shelves could be attributed to its greater stiffness under bending load.

Table 3.1: Cross-sectional properties of honeycomb shelves with different combinations of face, rail width and rail materials.

Shelf type	Rail width (mm) and material	Bending stiffness middle ($N.m^2$)	Bending stiffness rail section($N.m^2$)
3 mm Hardboard	10 PB 38 PB	2562	4415
	10 Poplar 38 Poplar		11640
6 mm MDF	10 PB 38 PB	2798	4075
	10 Poplar 38 Poplar		7667

The cross-sectional properties (bending stiffness) of the honeycomb shelves are presented in Table 3.1 and these can be used to predict a panel's ability to resist bending moments and deflection. The ends of the honeycomb shelves fixed to the gables during loading turn not to restrict rotation only but also displacement. Therefore, the maximum deflection in the honeycomb shelves occurred in the section of the sandwich panel between the two loading noses; a section with a weak paper core and no rail material. The cross-sectional properties given in Table 3.1 are grouped according to the types of honeycomb shelves, 3 mm hardboard or 6 mm MDF.

For each honeycomb shelf there are two cross-sections of importance, the ends of the shelves with the edge rail materials (particleboard or yellow poplar) and the middle section consisting of the paper honeycomb core. Irrespective of the combination of edge rail material and width, the middle sections of the hardboard and MDF shelves have the same bending stiffness value, 2562 and 2798 N.m^2 respectively. For any shelf type, the bending stiffness values for the particleboard or poplar rail section were equal because, the cross-sectional area remained the same regardless of rail width (10 or 38 mm). These cross-sectional properties suggest that shelves with particleboard rails would record relatively higher deflection values compared to those edged with poplar rails. As observed from the maximum bending moment results (Figure 3.8) it would generally be expected that for each rail material (particleboard or yellow poplar) honeycomb shelves with the 10 mm rail width would experience comparatively more deflection than the 38 mm rails.

The deflection values measured for the 3 mm hardboard shelves (Figure 3.9) indicated a significant interaction (p = 0.0023) between the type of rail material and its width used for edge reinforcement. Statistically only the honeycomb shelf reinforced with the 10 mm particleboard with the lowest deflection value was significantly different from the other shelves. This was due to the split which occurred during loading in the rather thin particleboard rail at the point where the screws were inserted (as shown in Figure 3.7a). The results therefore imply 3 mm hardboard shelves reinforced with edge rail materials (with exception of a 10 mm particleboard rail) and subjected to bending loads would most likely have similar deflection values.

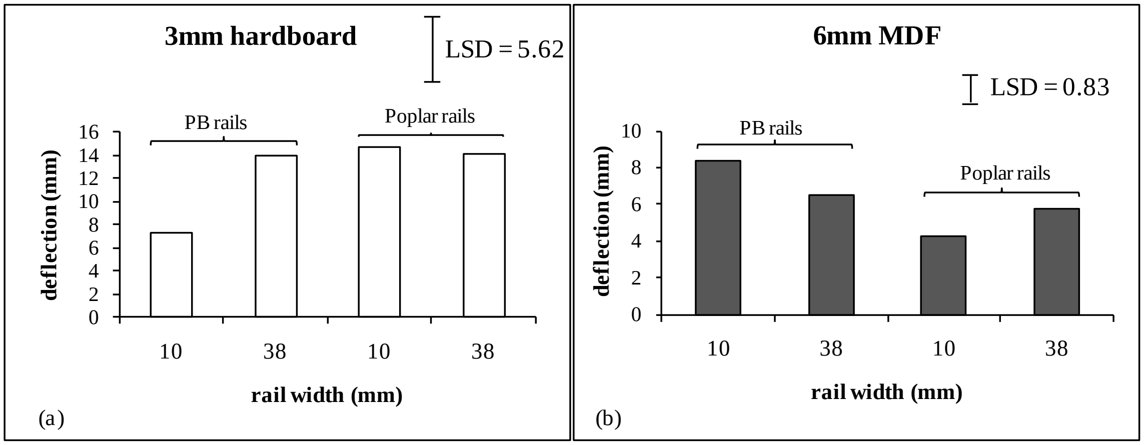


Figure 3.9: Panel deflection values for 3mm hardboard and 6mm MDF honeycomb shelves. n=3 for each mean. Error bars represent the least significant difference between means.

The deflection values for the 6 mm MDF shelves also indicated an interaction ($p = 0.0047$) between the type of rail material and its width. As was expected shelves reinforced with particleboard rails recorded higher deflection values – those edged with the 10 mm rails having significantly higher values than the 38 mm rails. However, the same was not the case in the yellow poplar reinforced honeycomb shelves, where the 38 mm rails recorded greater deflection values. This was attributed to the failure that occurred in the compressive face of the honeycomb shelves because the bending stresses in the face had reached the maximum yield stress of the face material.

A comparison of the deflection values for the two types of honeycomb shelves indicates the 6 mm MDF shelves recorded lower deflection values than the 3 mm hardboard shelves. This was largely due to the differences in their ability to resist bending moments (Table 3.1).

3.7.1.2 Effect of fastener system on shelf assemblies

The effect of fastener type (screws or brackets) on the load bearing properties of honeycomb shelves is shown in Figure 3.10a. The results indicate that the bending moment properties of honeycomb shelves were significantly (p = 0.0090) affected by the type of fastener used for its assembly – shelves fastened with brackets (b) irrespective of the rail widths carried significantly higher loads compared with those fastened with screws (s).

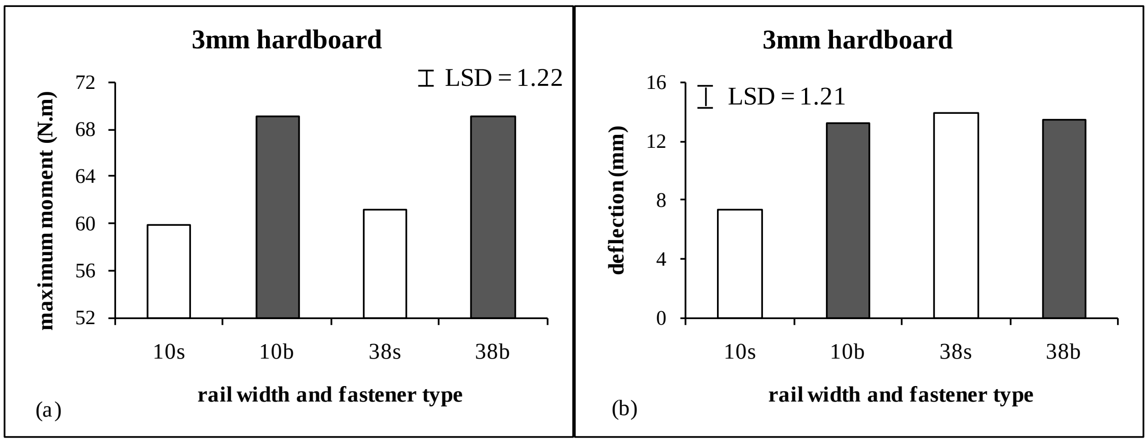


Figure 3.10: Maximum moment and deflection properties of 3mm hardboard honeycomb shelves with screw and bracket assemblies. n=3 for each mean. Error bars represent the least significant difference between means

Figure 3.10b illustrates the effect the different fastener types had on the deflection of the honeycomb shelves. From the results the honeycomb shelves assembled with the screws experienced less resistance to displacement during loading than shelves held in place by brackets. Further analysis of the bracket assembled shelves revealed no significant differences in deflection between panels with the 10 mm or 38 mm rails, unlike those for the screw assembly system.

3.7.2 Experiment 3.2

Three honeycomb shelves with no edge rails were run through the edge banding machine to identify any effect that the rollers of the machine might have on the panels. Afterwards, the PVC edge band was removed to examine the honeycomb core within the shelf (Figure 3.11a). Examination of the honeycomb core material showed that it had been crushed vertically along the outer edges of the panel where it had been run though the edge banding machine. Measurements of the panel thickness before and after edge banding revealed a decrease in panel thickness of 1 mm or more after edge banding.

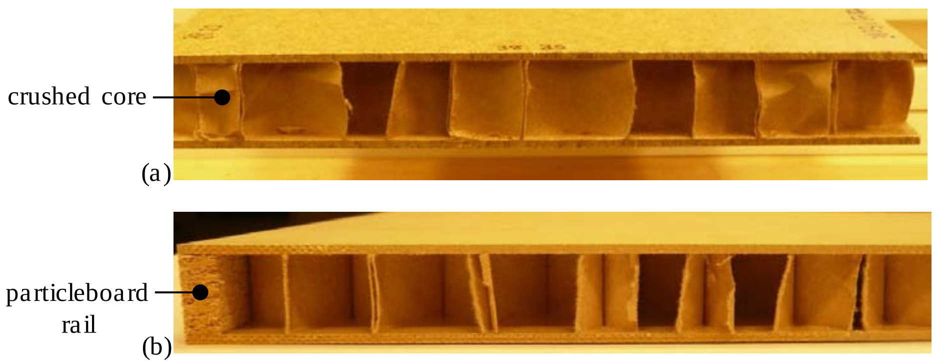


Figure 3.11: Effect of edge banding on (a) honeycomb panel without rails, showing crushed core material and (b) honeycomb panel with edge rail material.

A second set of honeycomb shelves this time with 10 mm particleboard rails (the short edge) were also edge banded. The shelves in this case showed no crushing of the honeycomb core along the outer edges when the PVC edge band was peeled off (Figure 3.11b). This difference showed that, even though the panels were only supported along the short edges of the shelf, the presence of the 10 mm rails resisted the pressure of the rollers on the honeycomb shelves preventing the deformation of the core. Making the rails a necessary component for paper honeycomb sandwich panels destined for finishing by edge banding.

Figure 3.12 shows the average maximum bending moment and deflection values for honeycomb shelves finished with the three different edge banding techniques. The method of edge band application significantly affected the load carrying capacity ($p < 0.0001$) and deflection

(p = 0.0012) properties of the honeycomb shelves. Shelves edge banded with the surface folding (SF) technique carried the greatest bending moments compared to shelves edge banded with the direct coating (DC) and stabilizer edge (ES) techniques. This result subsequently reflected in the deflection values for each edge banding technique where the surface folding (SF) method recorded the greatest resistance to deflection (lowest deflection values). A comparison of means indicated significant differences between the load carrying capacity for each edge banding technique. In the case of the honeycomb shelf deflection data there was no statistical difference between the direct coating (DC) and stabilizer edge (ES) techniques.

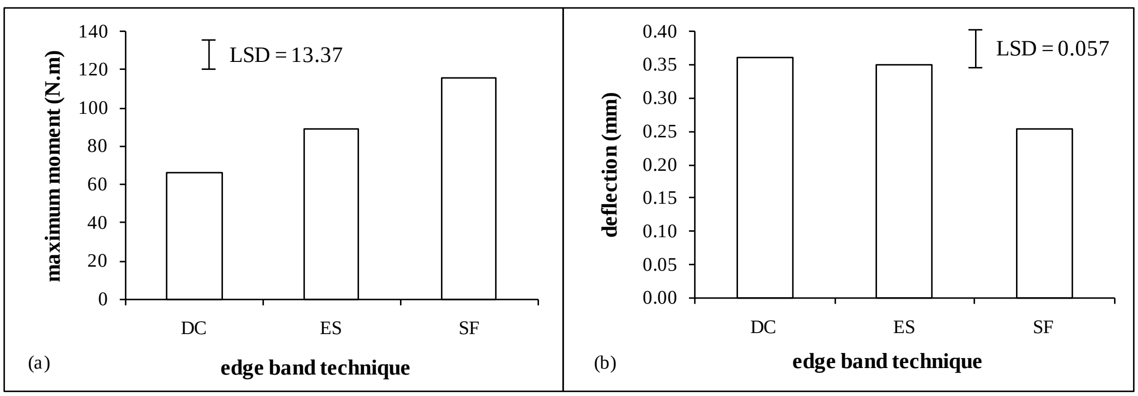


Figure 3.12: Panel properties for honeycomb shelves edge banded with different techniques. n=6 for each mean. Error bars represent the least significant difference between means.

For all 3 methods of edge band application failure during testing ultimately came about by debonding of the PVC edge band from the honeycomb shelf as shown in Figure 3.13a, followed by the crushing of the Kraft paper honeycomb core directly beneath the loading noses and the subsequent delamination of the rails from the face sheet, Figure 3.13b. Note the delamination within the 10 mm particleboard rail.

(a)  (b) 

Figure 3.13: Failure modes in edge banded honeycomb shelves during testing (a) direct coating and (b) stabilizer edge techniques.

The effects of applying edge banding either as PVC edge band material itself (direct coating technique) or with hardboard insert (stabilizer edge and surface folding techniques) on the strength and stiffness of honeycomb shelves are compared in Table 3.2. The values for no-edge band in the table were obtained from the 38 mm honeycomb shelves tested with the bracket configuration in the second phase of Experiment 3.1. Also included in the table are values of the control honeycomb shelves (32 mm) fabricated and tested in a similar way as the “no-edge band” shelves (38 mm), the only difference being their total panel thickness.

Table 3.2: Comparison of the average maximum moment and deflection values for the frameless and edge banded honeycomb shelves. n=3. Data in italics represent standard deviation of the mean.

Shelf type (bracket assembly)	Maximum moment (N.m)	Deflection (at mid-point) (mm)	Adhesive contact area (mm^2)
No-edge band (38 mm)	69.05 (*1.64*)	13.26 (*0.54*)	—
Control shelf (32 mm)	41.35 (*0.97*)	0.59 (*0.03*)	—
DC shelf (32 mm)	66.04 (*10.30*)	0.36 (*0.03*)	6402
ES shelf (32 mm)	88.91 (*2.84*)	0.35 (*0.02*)	9603
SF shelf (32 mm)	1158 (4.83)	0.25 (*0.03*)	10670

It can be seen from Table 3.2 that honeycomb shelves which were 38 mm thick carried more load in bending with high deflection values than the 32 mm shelves. A comparison of the maximum bending moment of the 32 mm thick shelves, i.e., the control and the edge banded shelves, shows a great increase in the load carrying capacity of the honeycomb shelves with the application of edge band material. The bending strength (maximum moment) values were significantly higher for honeycomb shelves edge banded with the surface folding technique (more than 3 times higher compared with the frameless control shelves). The resistance of the honeycomb shelves to deflection also increased with the application of edge band.

The differences observed between frameless and edge banded shelves could be attributed to the increase in edge support for the edge banded honeycomb shelves, while the variations recorded within the edge banding techniques maybe attributed to the differences in the total adhesive contact area provided by each technique for the edge band material. From Table 3.2, shelves banded using the direct coating technique recorded lower bending strength because of the limited contact area; a total glued edge area of 6402 mm^2 compared with greater than 9500 mm^2 for the stabilizer edge and surface folding techniques. For the stabilizer edge technique (Figure 3.4a) the 3 mm hardboard edge inserts had an adhesive contact area of 9603 mm^2 with the two face sheets (top and bottom) while the surface folding technique (Figure 3.5a) had an adhesive contact area of 10670 mm^2 (Table 3.2). Given the greatly increased contact area for the stabilizer edge technique compared to the direct coating, its load bearing ability were expected to be higher. Despite this difference in adhesive contact area between the two techniques, the stabilizer edge recorded no significant difference in deflection from the direct coating.

The findings support the idea that applying edge banding to frameless honeycomb shelves is not merely cosmetic but with the right design can greatly improve panel strength and stiffness properties. Our observations showed that in the case of the stabilizer edge and surface folding techniques the joints between the hardboard inserts and the honeycomb shelves were the weak point in the construction since the PVC edge band was still firmly attached to the outer surface of the inserts after those panels failed. To redress this issue the use of narrow stiles (10 mm) between the face sheets (behind the edge band and running along the long edges of the shelf as shown in Figure 3.14) needs to be considered. These stiles will provide additional support to the edge inserts (ES and SF) and in the case of the DC technique increase the adhesive contact area for the edge band material.

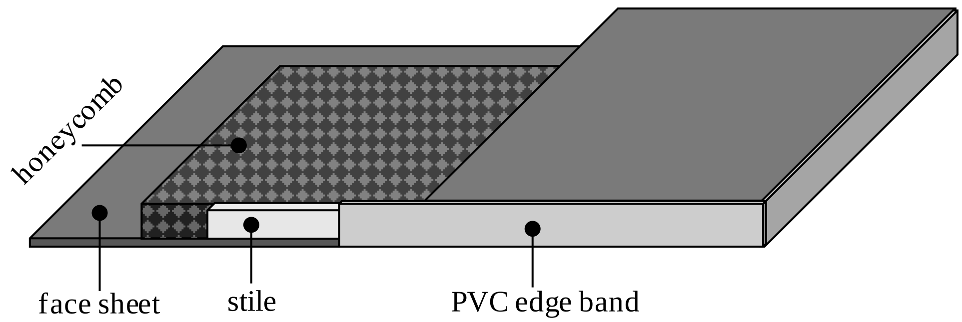


Figure 3.14: Exploded view of a honeycomb shelf with 10mm stile and PVC edge band.

This design (Figure 3.14) is expected to further increase the strength and stiffness of the paper honeycomb shelves. This internal bracing would also be expected to enable honeycomb panels to be fabricated from thinner face sheet materials without compromising strength and stiffness properties.

3.8 Conclusions

For improved quality and performance of a simple shelving unit constructed from Kraft paper honeycomb core panels it is preferable to use thicker face sheets reinforced with an edge rail material of width 38 mm. This study also identified the presence of rails in honeycomb core shelves as essential members to avoid crushing of the honeycomb core material during the application of edge band material.

Finally, the application of edge banding to honeycomb sandwich panels contributes significantly to their load bearing abilities and resistance to deflection. Of the three edge banding techniques tested (direct coating, stabilizer edge and surface folding), shelves edged with the surface folding technique had a 3 fold increase in strength when compared to frameless honeycomb panels.

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4 Summary, limitations and future work

4.1 Summary

Particleboard plants are struggling with higher wood fibre costs due to its short supply and increased transportation costs. Coupled with this is the reduced ability of the panel users (i.e., furniture manufacturers) to incur additional cost as they must compete with the cheaper furniture substitutes imported from overseas. In the design community there is a definite trend towards thicker furniture components, especially for higher-end furniture. This presents an opportunity for manufacturers to provide those customers with higher value-added furniture.

The development of thick, but light weight sandwich panels for use in furniture is anticipated to help the wood industry through its present predicament. This thesis focused on the design and manufacture of light weight hollow core sandwich panels for use in furniture applications; the panels were constructed from Kraft paper honeycomb cores, veneer and fiberboard face sheets. The first study aimed at investigating and understanding the mechanical properties of various Kraft paper honeycomb types, face material types, and face-to-core height ratios in relation to the paper sandwich panel. The second study built on the knowledge gained from the first and concentrated on sealing the panel edges to prevent damage to the core and provide a frame for the insertion of hardware, while improving panel strength.

The first round of investigations conducted revealed that paper honeycomb sandwich panels generally failed due to buckling of the honeycomb cell walls directly beneath the loading points; a failure mode which was also observed by Hassinen *et al.* (1997), Petras and Sutcliffe (1999) and Zok *et.al.* (2003). As a panel was loaded, the compressive and shear stresses under the loading points would increase until the honeycomb cell walls would crush ultimately resulting in panel failure. A simple way of delaying panel failure and improving the honeycomb panel strength was to orient the honeycomb core in such a way that the core ribbon or *x*-direction run perpendicular to the long axis of the panel and/or the direction of loading.

In the shelling ratio experiments, characteristics of the Kraft paper honeycomb (cell size and cell wall height) and the face materials were found to significantly affect sandwich properties. Panels fabricated with honeycomb materials having smaller cell sizes, 13 and 16 mm, (Petras and Sutcliffe 1999, Pflug *et al.* 2002 and Barboutis and Vassiliou 2005), and taller cell wall heights (38 mm), and sandwiched between thicker and stiffer face sheets (6 mm medium density fiberboard) produced sandwich panels with the highest load carrying capacities. The face sheet effect on sandwich panels was further investigated by fabricating honeycomb panels with different face materials in two thicknesses – hardboard (3 and 6 mm), medium density fiberboard (3 and 6 mm), 3 ply 4.5 mm meranti and 6 mm Douglas-fir plywood. Sandwich panels made with the plywood were significantly higher in bending strength and stiffness properties compared to those made with either the hardboard or medium density fiberboard. However, the warped under surface of the plywood materials made it less suitable for panel assembly. The hardboard materials on the other hand with average bending strength and deflection values were therefore selected as an ideal face materials for honeycomb sandwich panels.

Further experiments on larger size paper sandwich panels (such as shelves) identified rail materials of width 38 mm as the optimum edge supports for the insertion of fittings and hardware into honeycomb panels. The simple incorporation of rails (preferably solid wood) between the face materials of the sandwich panels, at both ends, also significantly reduced the compressive damage (crushing) of the paper honeycomb core during the application of PVC edge band to the long edges of the panel. The edge band applied to the honeycomb sandwich panels was found to improve the panels overall strength properties. The extent to which panels were strengthened was strongly linked to the adhesive contact area (support edge inserts or thickness of face sheet edges) available for the application of the edge band material. The surface folding technique which had the edges of both face materials and support edge insert bevelled inwards at a 45º angle, was the strongest of three edge banding configurations tested.

This thesis research provided an insight into the behavior of Kraft paper honeycomb when used as core materials of sandwich panels. The research findings are important for furniture companies that seek to adopt and incorporate the light weight sandwich concept into their production lines. The experimental data provides a basis for comparison of the strength properties of traditional slab construction with paper sandwich panel and introduces a product that offers the company the opportunity to differentiate itself from its competitors. The study also sheds light on the major concern most furniture manufactures have contemplated in relation to providing frames for paper sandwich panels without adding excessive weight.

4.2 Limitations

For this study, quantitative inferences could not be drawn on the internal bond and compressive strength properties of the honeycomb sandwich panels because of the limited number of test samples. The reason being, the limited quantity and dimension of the secured paper core material restricted fabricated sandwich panels to a standard size of 457.2 x 1219.2 mm (1.5 x 4 ft); which further influenced the number of test samples obtained in accordance with the ASTM standards. Consequently, precedence was given to the main properties of interest — the honeycomb panel flexure, creep and shear properties to maximize the number of test samples.

4.3 Future work

From this study, buckling of the honeycomb core was identified as the major cause of failure of the paper honeycomb sandwich panels. It will therefore be useful to investigate ways to reduce the buckling stresses in the core, by examining the effect of variations in the thicknesses of the paper used in the manufacture of honeycombs. To increase the mechanical strength properties of the sandwich panels, it is recommended to identify a balance between honeycomb cell sizes and cell wall thicknesses. The knowledge acquired here can help understand and improve the design of Kraft paper honeycomb panels for furniture applications.

4.4 References

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Appendices

Appendix A: Properties of the Kraft paper honeycomb material

The first table represents the properties of the Kraft paper (as obtained from the paper manufacturer) used in the manufacture of the open cell expanded honeycomb core. The second table presents the physical properties measured for each of the four types of honeycomb core materials used for fabricating honeycomb sandwich panels in Experiment 2.2.

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BASIS WEIGHT		g/m2	125	140	150	161	165	171	175	186	200	225	250
		lb/1000ft2	26	29	31	33	34	35	36	38	41	46	51
CALIPER		mm	0.18	0.20	0.22	0.23	0.24	0.25	0.25	0.27	0.29	0.32	0.36
MOISTURE		%	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
BURST		kPa	630	700	740	790	800	830	840	880	930	1010	1090
STFI	CD	kN/m	2.8	3.0	3.2	3.4	3.4	3.5	3.6	3.8	4.0	4.4	4.8
RING CRUSH	CD	N	180	220	240	260	270	290	290	320	350	400	440
INTERNAL BOND		J/m2	280	280	280	280	280	280	270	270	270	270	270
COBB TS	2 min	g/m2	38	38	38	38	38	38	38	38	38	38	38
COBB WS	2 min	g/m2	46	46	46	46	46	46	46	46	46	46	46
POROSITY		sec/100ml	60	60	60	60	60	60	60	60	60	60	60
SCUFF	(G-H)	dbl str	50	50	50	50	50	50	50	50	50	50	50
COLOR		green filter	34	34	34	34	34	34	34	34	34	34	34
ROUGHNESS		μ H-20	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8

Typical values tested at 23 ° C and 50 % RH
Ring Crush calculated from STFI values

Source: Caswell Products

Honeycomb core type	Honeycomb density (kg/m^3)	Cell size (mm)	Paper thickness (mm)
Open cell expanded	10.03	32	0.13
Paper laminated (large cell)	24.00	32	0.15 x 015
Paper laminated (small cell)	47.41	16	0.30 x 0.15
Verticel™	24.88	13	0.13

Source: UBC, Wood Composites laboratory

Appendix B: Survey of some Canadian furniture manufacturers

Surveys began with general questions about each company's panel usage. Most questions focused on the quality, dimensions, and inherit properties of the panel products used within each company. Other questions were related to the specific types of face materials, edge bands, and fasteners frequently used. The final set of questions was related to each company's interest, experience, and knowledge of hollow-core panels.

Since no two furniture manufacturers dealt with equivalent scales of panel usage, a statistical comparison of the survey results from different companies was not undertaken. The statements below are therefore generalized to represent what holds mostly true.

General Information:

All of the companies surveyed dealt with particleboard, or a pre-laminated equivalent, for the majority of their panel based furniture.

The common types of panel based furniture were office desks and workstations, as well as some tables, bookshelves, and other case goods. Most companies produced a standard line of products rather than customer specific orders.

Most companies had their particleboard supplied from within Canada; some, however, had started importing as much as 30% of their supply from Asia. One company imported as much as 2/3rd's of their particleboard from the US.

Majority of the companies surveyed use either an MS or M2 grade particleboard. Only one company used an M1 grade, and another an M3 grade.

Approximately half of the companies laminate or veneer all of their own particleboard, while the others order pre-surfaced Melamine particleboard.

PVC was the most prominent type of edge band, followed by veneer, and then hardwood.

All of the companies' surveyed edge banded their panels immediately after a fresh cut, without any intermediate step.

The most common types of fasteners used are wood screws and glued dowels, followed by ready-to-assemble (RTA) type fasteners like cam-locks, cam and dowels, and pins and casings.

Only one of the surveyed companies does regular quality control tests on their received panels. Most of the companies relied on their panel producers to meet the grade standards, and only test at their discretion; for example, if a new product is being developed and it is important that a component meet specified performance criteria, then a set of relevant properties are measured on a batch of products.

Dimensional Information:

The most common thicknesses of particleboard used are 13 mm, 16 mm, and 25.4 mm, respectively. Some companies used 19 mm, 38 mm, or other denominations in excess of 25.4 mm (mostly for desk or table tops).

All Canadian producers of hollow-core panels produce a panel of 38 mm or thicker. The few companies that produce their own hollow-core panels produce individual framed panels rather than sheets for breakup.

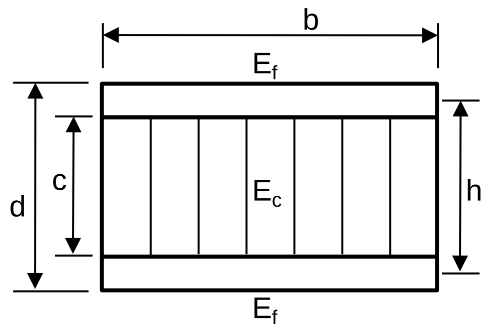
Current Issues with Particleboard:

The largest concerns expressed by the companies' with regards to particleboard included:

1. surface quality: flat and smooth panels for surfacing, and scratch resistance faces
2. density/ weight: transport cost, deflection, ease of assembly
3. Internal bond strength: poor screw holding, and poor edge banding properties
4. green issues/ Formaldehyde: using recycled, environmentally safe materials

Appendix C: Standard honeycomb sandwich formulae

The panel nomenclature used in the analysis of honeycomb sandwich panels is given below:



Where

a= distance between the support and the loading nose (⅓ L for third point loading)

b= width of sandwich panel (mm)

d= sandwich panel thickness (mm)

c= honeycomb core thickness (mm)

h= the distance from the center of the top face sheet to the center of the bottom face sheet (mm)

E_f= Modulus of Elasticity of the face sheet (N/mm^2)

E_c= Modulus of Elasticity of the honeycomb core (N/mm^2)

D= panel bending stiffness ($N.mm^2$)

U= panel shear rigidity (N)

G= core shear modulus (N/mm^2)

y= sandwich panel deflection (mm)

P= load (N)

L= span length (mm)

M= moment ($N.mm^2$)

k_s and k_b= constants dependent on the loading condition

The bending stiffness of a sandwich panel is defined as the ability of the panel to resist applied forces/loads that creates rotation. Generally the calculations for the bending stiffness of sandwich panels neglects the contribution of the core because of its low bending modulus (it does not resist bending), hence E_c=0 and the stresses in the face sheet are uniformly distributed (Zenkert, 1997). The calculations however include the sandwich cross section properties (second moment of area, I) which help predict the panel's ability to resist bending and deflection. Therefore the bending stiffness (D) of a sandwich panel having faces of equal thickness and material is given as:

$$D = \frac{E_f(d^3 - c^3)b}{12} \quad C.1$$

In most cases, the panel shear rigidity (stiffness) also assumes the core shear modulus to be equal to 0, implying a constant shear stress throughout the honeycomb core (Moody *et al.*, 2007). Thus the panel shear rigidity (U) of a sandwich panel is given by:

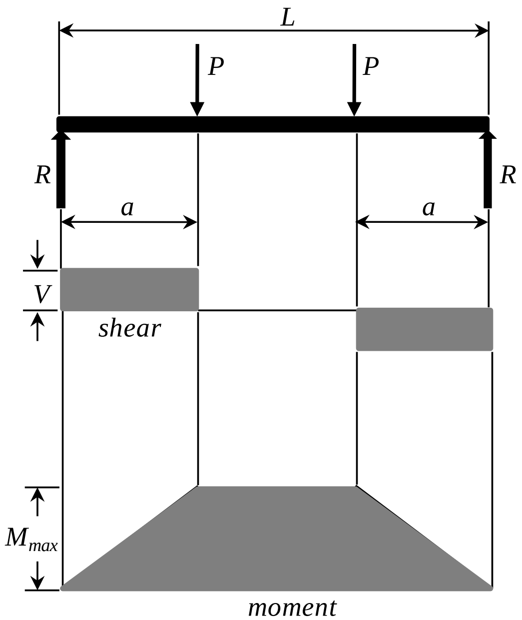
$$U = \frac{G(d+c)^2 b}{4c} \quad C.2$$

In a four point loading, the total panel deflection for a sandwich panel is the sum of the panel bending deflection and the shear deflection. The bending stiffness of the sandwich panel influences the bending deflection whiles the core shear modulus influences the shear deflection (Bitzer, 1997). The total deflection of a sandwich panel (y) is given as:

$$y = \frac{k_b P L^3}{D} + \frac{k_s P L}{U} \quad C.3$$

Beam formulas with shear and moment diagrams

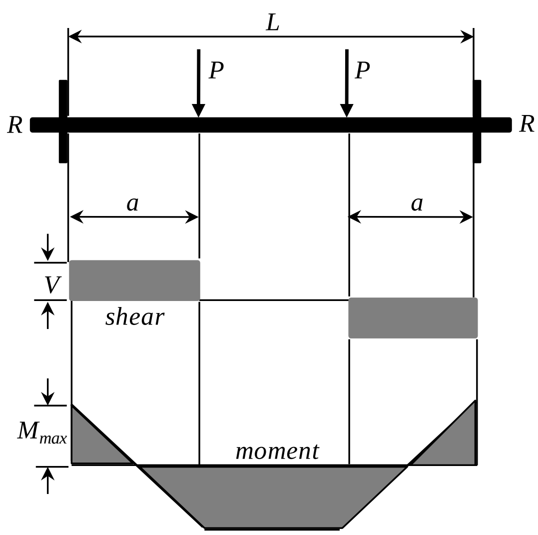
Simply supported beam with two equally concentrated loads symmetrically placed



M_{max} *(between loads)*.......= Pa

y_{max} *(at center)*.......= $\frac{P.L^3}{D}.\frac{5}{162} + \frac{P.L}{U}.\frac{1}{3}$

Beam fixed at both ends with two equally concentrated loads symmetrically placed



M_{max} *(ends)*...............= $\frac{P.L}{9}$

M_{middle}.......................= $\frac{P.L}{18}$

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