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Face checking in decorative maple veneered plywood panels is a significant problem for hardwood plywood manufacturers, furniture makers, cabinetmakers, and consumers. Efforts made by panel producers and researchers to minimize checking conducted to-date have been limited, and produced contradictory results. In this study the impact of four manufacturing factors believed to contribute to check development in decorative maple veneer panels were determined. The factors investigated were face veneer thickness and preparation, lathe-check orientation, adhesive and core type. An efficient, automated, optical technique based on digital image correlation principles was developed and used to detect and measure checks as they develop.

The novel new method for characterizing check severity and development was effective in efficiently measuring checking for a substantial number of samples. The results of the factor screening analysis reveal intricate four way interactions between factor levels contribute to check development, and that some combinations are likely to exhibit much more checking than others.

Key Factors Influencing Checking in Maple Veneered Decorative Hardwood Plywood

by
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Michael D. Burnard, Author

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1. Introduction

1.1 Decorative hardwood plywood

Decorative hardwood plywood is a wood-based composite panel comprised of hardwood veneers on the faces, adhesively bonded to center layers (or "the core") which may be veneer, plywood, lumber, particleboard, medium density fiberboard, or hardboard (Forest Products Laboratory, 2010). These panels are primarily used for appearance applications (i.e., non-structural).

Decorative hardwood plywood panels are commonly used where quality appearance is critical. Applications in cabinetry and furniture are commonly cited examples. Fixtures, wall and ceiling panels may also utilize decorative hardwood plywood. In uses where appearance is most critical, any defects in the face veneer can lead to complaints by the customer. For many years, checking in the face veneer has been a common customer complaint (Holcombe, 1952; Yan & Lang, 1958; Cassens & Leng, 2003).

The center layer of a decorative hardwood plywood panel is commonly and interchangeably referred to as the, “core,” or, “substrate.”

The face of a decorative hardwood panel is, “the better side of any plywood panel in which the outer plies are of different veneer grade,” or either side of a panel where both sides are of equal veneer grades (Hardwood Plywood & Veneer

Association, 2004). Face veneers, therefore, are the veneers used on the face of the decorative plywood panel, while back veneers are the veneers used on the opposite side if the veneers are of different grades.

Veneers are thin sheets of wood produced from flitches, half-rounds or logs (Hardwood Plywood & Veneer Association, 2004). Flitches are portions of a log cut specifically for slicing (Schramm, 2003). Decorative veneers are sorted for appearance quality, the best of which are used for face veneers on highly exposed products, such as cabinet doors or paneling. Lesser quality appearance grade veneer is often used in situations where visual appeal is less critical, but still important such as the interior components of cabinetry.

Sugar maple (*Acer saccharum*, a hard maple) is a common choice for face veneers in decorative plywood panels. Though no industrially utilized sugar maple is grown in Oregon, it is of particular importance to regional producers as nearly 50% of North American hardwood plywood panels are produced in Oregon, including a significant percentage of decorative maple plywood panels (Hardwood Plywood & Veneer Association, 2010). Sugar maple used for producing veneers for decorative plywood panels is typically harvested from forests growing in the Midwest and Northeastern United States, as well as Southeastern Canada (Hardwood Plywood & Veneer Assocation, 2006).

1.2 Veneer checking in decorative plywood

A wood veneer check is, “a separation of the wood along the fiber direction that usually extends across the rings of annual growth, commonly resulting from stresses set up in the wood during seasoning,” (ASTM International, 1999). Seasoning, in this sense, means drying that occurs naturally or through mechanical means (e.g. kiln-drying) (ASTM International, 1999). No threshold for length or width was found that would limit what is considered to be a check. The appearance of checks may vary from panel to panel and may range from a collection of minute checks to longer, extended checks (Figure 1) (Holcombe, 1952). This defect, which often results in customer complaints to manufacturers, can be costly to veneer and panel producers as well as furniture and cabinet manufacturers. Though manufacturers have been reluctant to share actual costs, they have expressed mounting concerns with this problem.

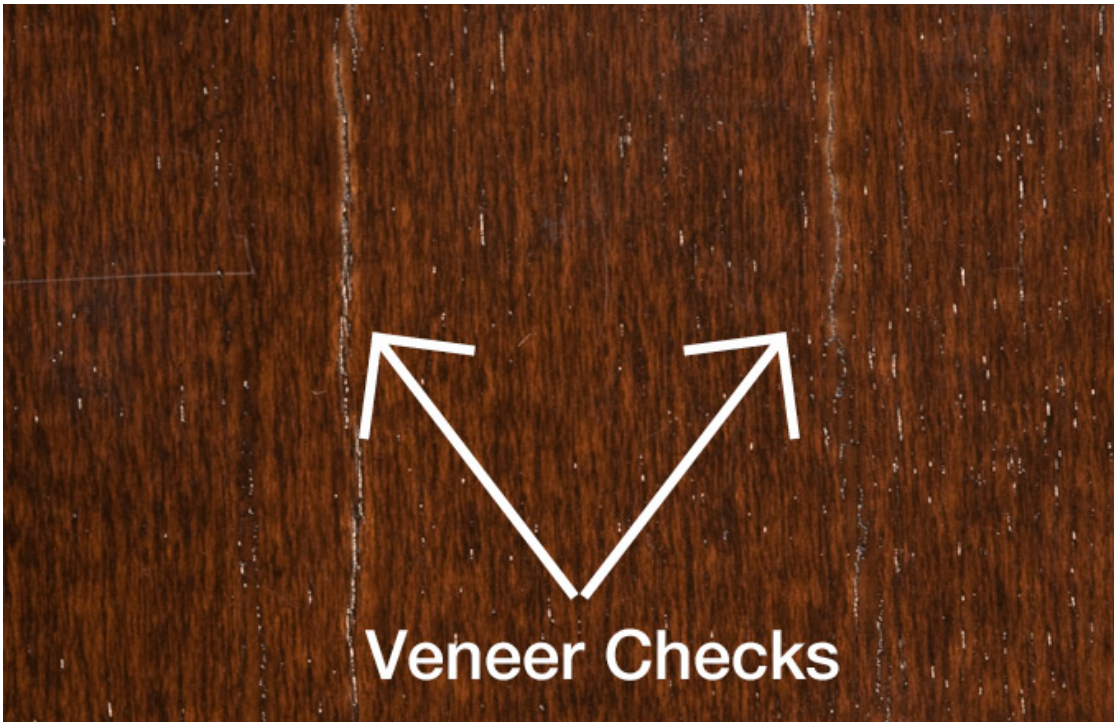

Figure 1 Typical checks in maple veneered decorative hardwood plywood

Checks may occur anytime within a few hours of manufacture to several years after installation (Holcombe, 1952). Addressing checking can be difficult and costly because checks may not develop until after a panel has been put into service. Consider a case where a highly visible check appears in the cabinetry in a kitchen. If the check is in a door panel, the cost and time to replace it may be fairly low. However, if the check is in a part of the cabinetry that is more difficult to remove and replace than a door panel, repair may include removing and rebuilding or replacing the entire cabinet system. The cost is far more than the value of the actual plywood needed for the repair, and the inconvenience to the cabinet (home) owner is also great. Similarly wall panels and furniture made from decorative hardwood plywood will have replacement or repair costs much greater than the value of the faulty panel itself. In these situations, considerations must be made regarding matching the style, colors and patterns of the replaced panels which also adds costs.

Current manufacturing processes are designed to create the highest quality panel while keeping costs acceptably low and managing environmental concerns. Following best practice guidelines, such as those found in Yan and Lang (1958) and Christiansen and Knaebe (2004) and embracing the results of recent studies such as those by Cassens and Leng (2003) and Leavengood, et al. (2011) may have reduced incidents of checking, but the problem continues to be a burden to the industry.

Effectively addressing the issue of veneer checking requires examining a comprehensive set of factors, which may require testing a large number of samples. Overcoming the vast time investment required to manually observe checks in many samples will require a new, automatable method for analyzing check severity and development.

1.3 Detecting and measuring checks

Current methods for detecting and measuring checks in scientific studies are problematic due to their labor intensity and inherent lack of reproducibility. The time consuming nature of existing methods limit the quantity of panels than can effectively be examined in any one study, and therefore limit the scope of factors that can be examined.

Furthermore existing methods only capture check measurements at an isolated point in time and provide little information about how checks develop and when they occur. Indeed, check characteristics may change during inspection if panels are not equilibrated to their environment when examined.

No standards were discovered that describe a method for measuring checks, conditions for measurements and a common metric for quantifying check intensity. New methods are sough to achieve greater efficiency, detail, and reproducibility for check characterization. Automated methods are expected to provide the opportunity to examine more test specimens, and therefore examine more factors that may contribute to check development.

1.4 Objectives

Therefore, the overall goal of this study is to determine which manufacturing factors are mostly likely to contribute to check development. Specific objectives to achieve this goal are: (1) develop a comprehensive matrix of test factor that may affect checking in maple plywood, (2) develop an automated, efficient check detection and analysis method capable of characterizing check development and severity, (3) measure intensity of checking for combinations of identified factors, and (4) identify critical variables and interactions.

2. Background

Veneer checking is a visible outcome of a complex process occurring in composite wood products, most commonly as a result of drying stress (ASTM International, 1999; Hardwood Plywood & Veneer Association, 2004). Wood is a natural material used world wide to produce energy, and a great diversity of products. Variations are expected in any natural material, and wood is no exception. Though any single species of tree may produce wood that is suitable for a variety of purposes there are often many manufacturing techniques and choices that impact the quality of a final product. The same applies to decorative hardwood panels. To best understand the impact of manufacturing decisions on the quality of decorative hardwood panels, especially with respect to check development, it is necessary to understand how panels are prepared, how the production methods and components may vary between manufacturers.

The complexities make correlating check development to any one component of the process or product difficult.

This study was, in its most basic form, a factor screening study designed to examine the effect that manufacturing decisions, applied at varying levels have on check development in the face veneer of decorative hardwood plywood panels. Throughout this study, the term factor is used to refer to components of manufacturing decorative hardwood plywood panels considered in this study. For example, in a study examining how the core material and adhesive affect checking “core” and “adhesive” would be factors. Similarly, when multiple “cores” are to be examined, for example, particleboard and veneer core, these would each be levels of the factor “core”.

2.1 Hardwood veneer manufacturing

Hardwood veneer to be used for face veneer on decorative panels is produced from the highest quality logs. Logs producing veneer of high appearance quality receive a considerable price premium (Mercker & Hopper, 2004). Once logs are received at the veneer mill they are typically sorted by grade and stored so they readily accessible to meet the demands of the production schedule). Stored logs received in the green condition are kept wet to minimize premature drying and associated defects such as splitting at the end or along the length of the log.

Log preparation varies depending on how the veneer is to be cut. Logs are either peeled into wide sheets of veneer or sliced into narrow strips that will later be spliced together to make full-size veneer sheets.

2.1.1 Sugar maple veneer used for decorative hardwood panels

North American maple is a diffuse porous hardwood often categorized into two groups: hard maple and soft maple. *Acer Saccharum*, or sugar maple, the species being investigated in this study is often referred to as a hard maple. In the U.S., sugar maple is principally harvested in the Great Lakes and Middle Atlantic regions (Schramm, 2003). According to the Hardwood Plywood and Veneer

Association, nearly 50% of all maple veneered plywood panels are produced west of the Rocky Mountains, though no maple from that region is used; of the 50% produced west of the Rockies, more than 90% of these panels are produced in Oregon (Hardwood Plywood & Veneer Association, 2010). U.S. manufacturers also use sugar maple harvested in Canada. Sugar maple sapwood is often white with light reddish-brown tones, has a fine texture and a uniform grain pattern. Some isolated regions of distinct grain patterns occur and are selected for specific uses in furniture and novelty items (Forest Products Laboratory, 2010).

The following table (Table 1) summarizes pertinent physical and higromechanical properties of sugar maple:

Table 1 Pertinent physical and mechanical properties of *Acer saccharum* (Forest Products Laboratory, 2010).

Property	**Value**
Average green moisture content (heartwood)	65 %
Average green moisture content (sapwood)	72 %
Shrinkage, radial (green to ovendry)	4.9 %
Shrinkage, tangential (green to ovendry)	9.9 %
Shrinkage, volumetric (green to ovendry)	14.7 %
Specific gravity (green)	0.56
Specific gravity (12%)	0.63

Maple veneer tends to be produced near to where the trees are harvested to keep costs down, and to maintain the green conditions of the logs until they can be properly stored at the mill; however, decorative maple veneered plywood panels are produced across the nation.

2.1.2 Rotary Peeling veneer

Rotary peeling is the most common method for manufacturing veneer (Baldwin, 1995; Schramm, 2003). According to Schramm (2003) all veneer cut for core material in decorative hardwood plywood panels and for non-decorative veneer used in structural plywood panels is prepared this way. In addition, some decorative veneer is also manufactured by rotary peeling (Schramm, 2003).

To produce rotary peeled veneer, logs are first debarked and cut to lengths known as blocks that are between approximately 1.2 m and approximately 3.7m; the blocks are then placed into a steaming chamber or soaked in vats to soften the wood and facilitate the peeling process (Schramm, 2003). Heating wood and adding moisture act as a two-part system to soften the wood; indeed, the softening temperature of wood is greatly affected by moisture content (Placet, Passard, & Perre, 2008). Introducing water acts as a plasticizing agent by replacing hydrogen bonds in the amorphous regions of wood's cellular structure with water-carbohydrate bonds, which increases the flexibility of the polymer network. Temperature also breaks inter-molecular bonds in the cellular structure increasing the flexibility of the network and softening the wood (Placet, Passard, & Perre, 2008).

The softened blocks are often passed through a metal detector to look for metal objects such as bullets or nails, which may damage the knife blade, in the block before they are loaded into a lathe. The logs enter the lathe through a device called a charger, which analyzes the log geometry and orients ("centers") it to maximize the veneer yield (Baldwin, 1995; Schramm, 2003). The log is then rotated against the lathe blade to produce sheets of veneer that, in effect, peel off the log as paper towels peel from the roll (Figure 2). A pressure bar is sometimes used to apply pressure to the veneer on the side opposite the knife, which helps ensure a consistent and tight cut is achieved (Baldwin, 1995; Schramm, 2003). Attention to detail at this stage is paramount. During the author's visit to one rotary mill, two individuals were examining both the knife and the veneer as it was peeled. They were looking for small knicks, grooves or protrusions in the veneer, which may indicate a flaw in the blade. If problems were found the process was stopped and the knife repaired. Knives are also replaced on regular schedules to ensure a veneer is tightly cut.

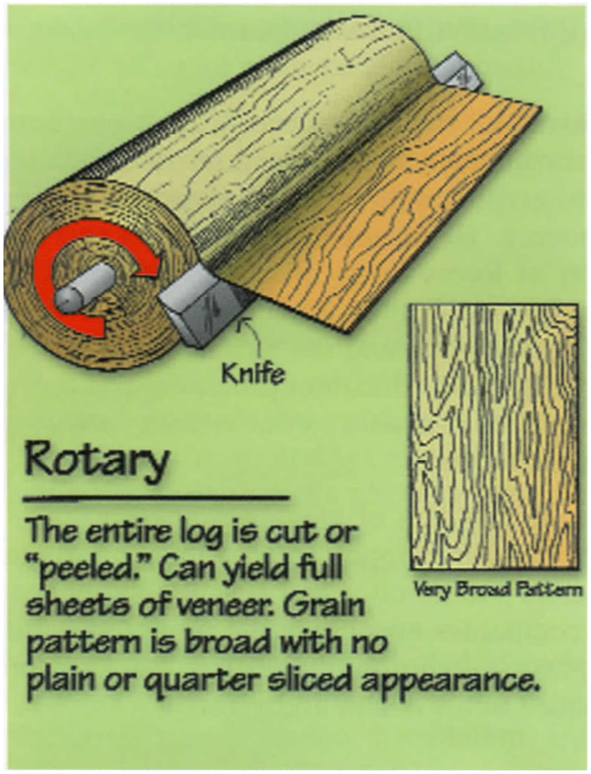

Figure 2 Rotary peeling (Hardwood Plywood & Veneer Association, 2004)

Next, the peeled veneer is fed onto a clipping line where it is cut ('clipped') to specific widths. In this process sections with defects are removed (Baldwin, 1995). The veneer is then dried to around 6-12% moisture content (Schramm, 2003).

Yields for the highest-grade veneers are very low for full sized face grade veneers. The clipping process will only occasionally yield full sized face grade veneers. Consequently these full sized sheets – often referred to as "whole piece," (Hardwood Plywood & Veneer Association, 2004) – earn premium prices. Narrower pieces are often spliced together to form full sized sheets of high-grade veneer (Schramm, 2003).

2.1.3 Slicing veneer

Sliced veneer is manufactured by taking flitches ("a log sawn on two or more sides from which veneer is sliced" (Evans, 2000)) and moving them obliquely, either on a plane or in partial rotation, against a stationary knife.

As with the rotary peeling method, logs are first debarked, then cut to length. Slicing flitches are then produced by sawing logs into rectangular sections similar to timber or by roughly squaring up a log and cutting it longitudinally to produce log halves or quarters. These segments are then steamed or soaked, as in the rotary peeling method, to soften the wood fibers and facilitate slicing (Schramm, 2003).

Veneer can be produced by plain slicing (half-log slicing), quarter slicing (quarter-log slicing) or rift-cutting (quarter-log slicing on a rotating head) (Hardwood Plywood & Veneer Assocation, 2006). Each method produces different grain patterns to meet a variety of customer tastes.

Plain-sliced veneer is produced, typically, by placing a half-round segment with its widest face (near the center of the log) against the slicing plate so its narrowest face will be cut first. The segment is then pushed against a lathe knife and very gradually moved toward the knife after each slice so that increasingly wider strips are produced as the knife moves nearer the center of the log. The veneer produced is the product of tangential cuts producing what is called a cathedral grain pattern. Each veneer strip will usually resemble the wide face of flat-sawn lumber, with repeating peaks in the grain pattern along the length of the strip (Schramm, 2003) (Figure 3).

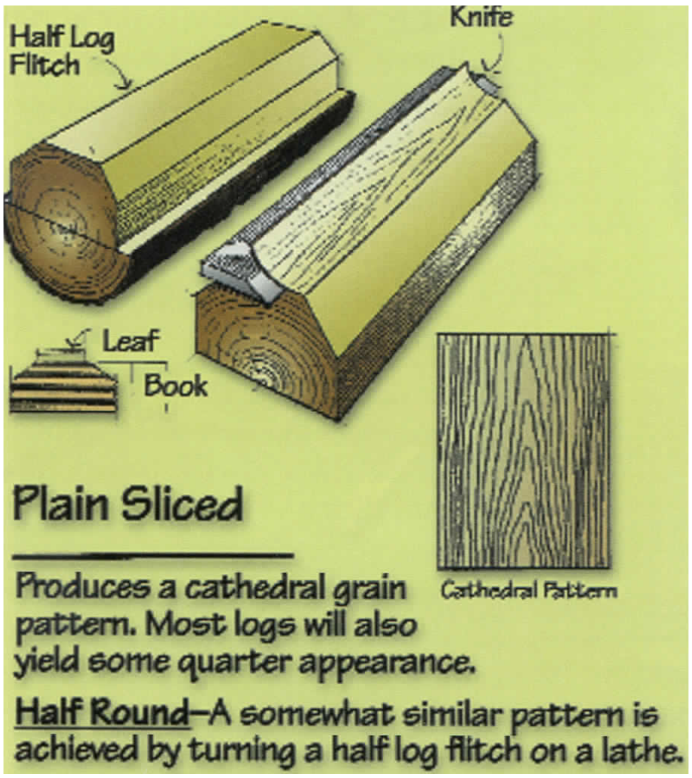

Figure 3 Plain slicing (Hardwood Plywood & Veneer Association, 2004)

Quarter-sliced veneer is produced similarly, but, instead of being produced from half-rounds, the flitch is produced by quartering the log (Figure 4). The process is similar to plain slicing, except the flitch is oriented so it is cut radially to the center of the log. This produces straight-grained veneer, which resembles the wide-face of vertical-grain lumber (Schramm, 2003). This method exposes the rays in many species of tree and produces a figure known as ray fleck that is desirable for some end uses.

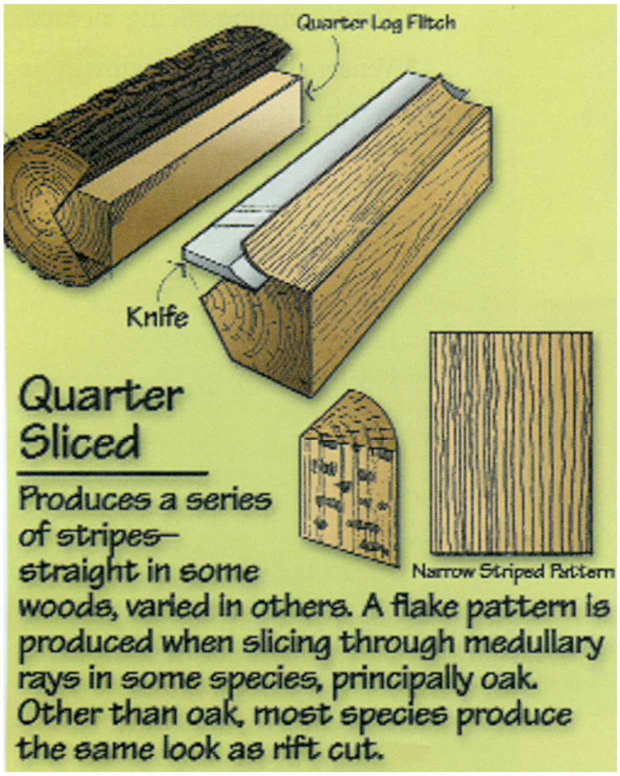

Figure 4 Quarter Slicing (Hardwood Plywood & Veneer Association, 2004)

Rift-cut veneer is produced by placing a log quarter on a rotating head, and moving it against a knife during its rotation (Schramm, 2003) (Figure 5). The quarter flitch is positioned so it is only in contact with the knife for a small portion of each revolution, which tends to produce straight grain veneer, with less ray fleck than quarter slicing.

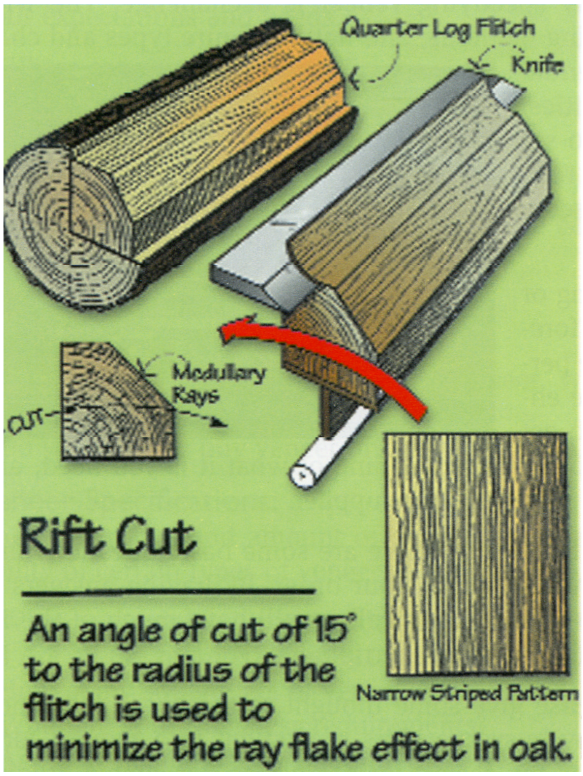

Figure 5 Rift slicing (Hardwood Plywood & Veneer Association, 2004)

It is important to note that grain pattern does not necessarily correlate to a specific method of cutting. Patterns can vary within veneers produced by a single cutting method, and veneer produced by one method may appear as though it was produced by another (Schramm, 2003).

Face veneers are graded for appearance according to grade rules defined in a voluntary American National Standards Institute (ANSI) grade standard, and producers are accredited through the Hardwood Plywood & Veneer Association (HPVA). Face veneer grades range from AA, the highest quality through E, while grades for backs are numbered from the highest quality, designated 1, through 4 (Hardwood Plywood & Veneer Association, 2004). The highest-grade face veneers are rare and expensive. An average veneer log may only yield only 2% AA grade veneer (Table 2).

Table 2 An average veneer log yield by grade/use (Hardwood Plywood & Veneer Association, 2004).

Hardwood Veneer Face Grades	**Approximate Yield**
AA	2%
A	10%
B	13%
C	33%
D	13%
E	8%
Reject/Other Use	21%

It is important to note that any of the methods for producing veneer may produce veneer that checks. Indeed, all cutting methods induce checks during the manufacturing process. These checks are called lathe checks, and are present to some degree on all veneer (Schramm, 2003). Tightness of cut references to the presence of lathe checks – tightly cut veneer has fewer and/or smaller lathe checks than loosely cut veneer.

The most important aspects of veneer production methods, as it pertains to checking, are the tightness of the cut and the thickness of the veneer (Yan & Lang, 1958; Schramm, 2003; Christiansen & Knaebe, 2004). Tightly cut veneer is thought to be able to resist checking more than loosely cut veneer (Cassens &

Leng, 2003). Veneer thickness is understood to contribute to the characteristics of any checking that may occur (Yan & Lang, 1958; Christiansen & Knaebe, 2004).

Thickness is determined by customer demand, and by the price of quality veneer logs. The expense of high quality logs causes manufacturers to maximize their yield by producing thinner veneers.

2.1.4 Tight-side and Loose-side of veneer

Regardless of the production method, small fissures develop in the surface of the veneer as it flexes and peels away from the knife during manufacturing. They are known as lathe checks (Schramm, 2003). Veneer sides are designated "tight" (without lathe checks) and "loose" to indicate the side of the veneer containing lathe-checks (Figure 6). The presence of the lathe checks is thought to be a crucial factor in plywood panel manufacturing related to check development (Yan & Lang, 1958; Cassens & Leng, 2003; Schramm, 2003; Christiansen & Knaebe, 2004; Leavengood, Funck, & Reeb, 2011).

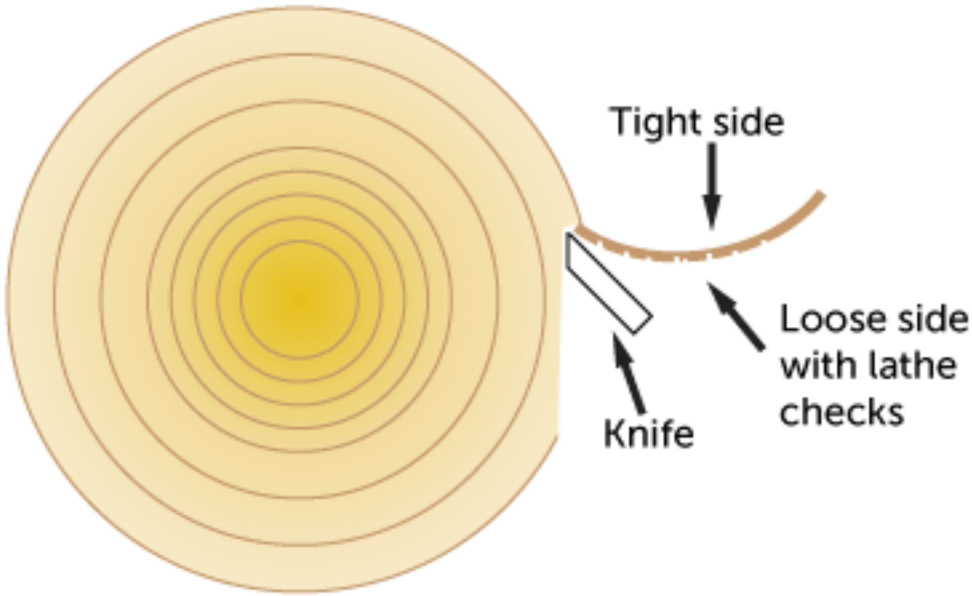

Figure 6 Diagram of tight and loose side of the veneer as it peeled, including the presence of lathe checks on the loose side

2.1.5 Veneer thickness

Veneer thickness varies between production methods and from mill to mill. However, most purchasers request specific thicknesses for panel production (Schramm, 2003). Decorative veneers tend to be thinner than veneers used for core material. Schramm (2003) notes that before 1980 it was generally accepted that decorative rotary cut veneer was 1/24” (1.00 mm) to 1/30” (0.82 mm) and plain sliced veneer was 1/28” (0.88 mm) to 1/32” (0.77 mm). Currently produced thicknesses, according to a survey performed for this study, range from 1/36” (0.68 mm) to 1/50” (0.49 mm) (see section 3.1 Factor). The logic behind producing thinner veneers is clear: it increases yields for the veneer producer.

Given that veneer thickness has decreased over the years, early tests on veneered plywood panels used thicker veneer than are readily available today. Blackwell (1952) used 1/28" face veneer for his study, while Cassens (2003) used 1/38" (0.65 mm) face veneer. Another recent study by Leavengood et al. (2011) used 1/36" face veneer. The authors of previous studies do not state a reason for selecting the veneer thicknesses utilized in their studies.

Yen and Leng (1958) state that thicker veneers tend to check more readily than their thinner counterparts. At the time, 1/28", according to the researchers, was a reasonable compromise (Yan & Lang, 1958). However, Christiansen and Knaebe (2004) relate the opposite notion: because thinner veneers offer less resistance to the dimensional changes of the substrate, they are more prone to check, but that larger checks occur in thicker veneer, than in thinner veneer (Christiansen & Knaebe, 2004). The discrepancy between reports may be due to the differences in materials in use at the time of the studies, especially thickness.

2.1.6 Splicing methods

All slicing methods produce strips of veneer, which are later matched and spliced together, side by side, to produce wider sheets. Rotary peeled veneer also produces narrow strips as producers clip defects from the sheets; these strips are also matched and jointed together to create full-width sheets (Schramm, 2003). Spliced veneer sheets allow narrow strips to be used to make full-sized sheets after they have been jointed. It is possible for joints to separate during or after panel production. These separations may resemble checks, and will have similarly detrimental effects on a decorative hardwood panel.

During the jointing process, small bundles of veneer sheets are gathered, sometimes pressed to flatten the strips, clipped, sprayed on their edges with adhesive, then arranged according to matching preference before being fed into a splicing machine (Figure 7). Matching describes the process and criteria used for the arrangement of the veneer strips in a full sheet. These methods include book matching, slip matching, random matching, pleasing or color matching and plank matching (Schramm, 2003).

Figure 7 Peeled, clipped veneer with adhesive sprayed on its edges being fed into a veneer jointer to be spliced into full-size sheets.

Book Matching: Most common among the matching methods is book matching, where veneers are turned over so adjacent strips appear symmetric and opened like the pages of a book, then laid next to one another and are jointed together

(Figure 8) (Hardwood Plywood & Veneer Association, 2004).

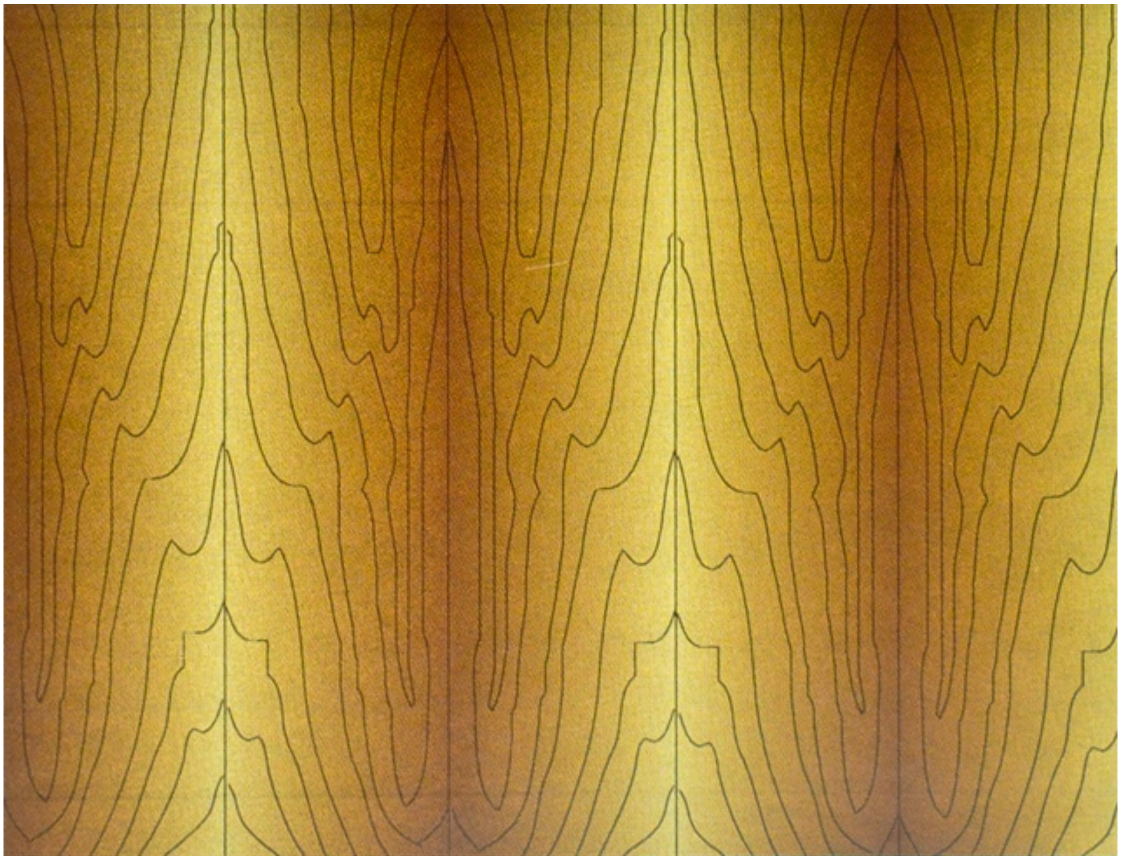

Figure 8 Book match pattern (Hardwood Plywood & Veneer Assocation, 2006)

While best practices often suggest orienting face veneers tight-side out to minimize check development (Yan & Lang, 1958; Schramm, 2003; Christiansen & Knaebe, 2004), strips in a book matched veneer sheet will necessarily alternate lathe-check orientation exposing both the tight and loose side to the surface on the same veneer sheet.

Slip Matching: Another, though less common, method is slip matching. To create slip matched veneer sheets, strips of sliced veneer are laid out in sequence, without turning any strips over then spliced (Figure 9) (Hardwood Plywood & Veneer Association, 2004). Consequently, and in contrast to book matching, slip matching produces veneer sheets with distinct tight and loose sides.

Figure 9 Slip matched veneer (Hardwood Plywood & Veneer Assocation, 2006)

Other Matching patterns: Pleasing, random and plank matched veneer sheets are also made; their descriptions can be found in Table 3 (Hardwood Plywood & Veneer Association, 2004).

The highest grades of veneers require specific types of matching. For example, AA and A grade face veneers limit matching patterns to book or slip match, or whole piece (by specification), while pleasing match and others are excluded (Hardwood Plywood & Veneer Association, 2004).

Veneer grades limit the minimum strip width based on whether the veneer was sliced or peeled (Hardwood Plywood & Veneer Association, 2004). For example, AA grade veneer limits plain-sliced and rotary cut veneer strips to no less than 152 mm and quarter-sliced strips to no less 76 mm (Hardwood Plywood & Veneer Association, 2004).

Table 3 Common matching methods for spliced veneer (Hardwood Plywood & Veneer Association, 2004). * Because of this subjective definition, pleasing matches may vary from one mill to the next as any given mill may have their own standard for "pleasing overall."

Method	Description
Book match	Adjacent pieces of veneer from a flitch or log are opened like a book and spliced to make the face with matching occurring at the spliced joints. The fibers of the wood, slanting in opposite directions in the adjacent sheets, create a characteristic light and dark effect when the surface is seen from an angle.
Slip match	A sheet from a flitch is slid across the sheet beneath it and, without turning, is spliced at the edges.
Pleasing match	A face containing components which provides a pleasing overall* appearance. The grain of the various components need not be matched at the joints. Sharp color contrasts at the joints of the components are not permitted.
Random match	A panel having a face made up of veneer strips of the same species which are selected and assembled without regard to color or grain, resulting in variations, contrasts and patterns of color and grain. Pleasing appearance is not required.
Plank match	A panel having the face made up of specially selected and assembled dissimilar (in color, grain, or width) veneer strips of the same species, and sometimes grooved at the joints between strips to simulate lumber planking.

2.1.7 Grade reducing characteristics, repairs and other common issues

Natural inhomogeneities such as knots, worm tracks and bark pockets, and defects, like rot, cracks, timber break (wind break) are present in most logs and will be revealed in the veneers produced from them during slicing or peeling. When these grade-reducing characteristics are revealed during veneer production, they are often clipped around by removing full width strips of the material that contain the defect (Schramm, 2003). Unappealing characteristics small enough to be "punched-out" can be replaced by a patch (Schramm, 2003;

Hardwood Plywood & Veneer Association, 2004; Hardwood Plywood & Veneer Assocation, 2006). The degree to which defects, repaired or not, are allowed in veneer sheets is dependent upon the grades specified in the ANSI Standard for Hardwood and Decorative Plywood (Hardwood Plywood & Veneer Association, 2004) and other similar guidelines. The highest grades of face veneers are very restrictive.

2.2 Hardwood plywood manufacturing

Hardwood plywood is a wood-based composite made by adhering thin hardwood veneers to the front and back of a core material. Most hardwood plywood is used for decorative purposes, and the face and back veneers are prepared and selected for their high quality appearance.

There are many steps to manufacturing hardwood plywood, each with various options and strategies for making the best panel for a specific purpose (e.g., a cabinet door versus an interior component of the cabinet). Indeed, the ANSI standard for decorative hardwood plywood recommends a checklist of 16 items to help buyers ensure they order the product they desire (see 1. Recommended decorative hardwood plywood ordering checklist). Four of the items are specific to decorative face veneers: thickness, species, color, grade, pattern or type of cut and matching requirements (Hardwood Plywood & Veneer Association, 2004). The other listed items include quantity, substrate type, backs and finish.

Decorative hardwood plywood panels are produced by overlaying decorative veneers on the front and back of a core material and bonding them with an adhesive. After this process, panels may be finished by sanding and staining to achieve appearance specifications by the panel manufacturer or shipped to the customer unfinished.

Manufacturing hardwood plywood begins with decorative veneer selection. Decorative veneer mills are most often separate from plywood manufacturing facilities, so veneers are produced in one location and sold then transported to another, often distant location (e.g. veneer produced in Michigan is often sent to Oregon to be produced into decorative hardwood panels). Veneers are selected by grade and species to fulfill customer needs concerning appearance. Substrates (cores) best fitting the purpose and price point of the final product are then chosen followed by adhesive selection. Adhesives are selected based on a variety of concerns, including price, emissions (i.e., for indoor air quality concerns) and end use. Pressing procedures vary based on adhesive type, core type and manufacturer discretion. After pressing, panels are repaired (e.g., to patch voids on the edge or knots on the face or back) to grade standards and sorted according to their fitness for a particular use before being sanded and finished to specifications determined by customer needs. Each step is discussed in more detail below.

2.2.1 Selecting face and back veneer

Selecting face veneers begins with understanding customer desires, and the suitability of the veneer to the final product. Species variations in color and grain characteristics play an important role; indeed even within-species variations may greatly differentiate the appearance of a veneer. Additional selection criteria may include specifying whole piece veneer, thickness, or matching type (i.e., book-matched, slip matched, etc.).

Sugar maple (*Acer saccharum*), selected for this study, varies greatly in color and grain pattern. Color descriptions for maple range from creamy-white in the sapwood to heartwood that has a pinkish tint to light reddish-brown (Hardwood Plywood & Veneer Assocation, 2006). Because of this variation in color, the HPVA *Hardwood Plywood Handbook* (2004) warns plywood manufacturers to "clearly communicate" color preferences to suppliers at the time of order.

Patterns in veneer appearance resulting from "growth rings, rays, knots, deviations from natural grain such as interlocked, curly and wavy grain, and irregular coloration" are referred to as *figure* (Hardwood Plywood & Veneer Association, 2004). Species with more *figure* have been connected with greater degrees of checking (Yan & Lang, 1958).

Veneer thickness varies according to cutting method (Hardwood Plywood & Veneer Association, 2004) and today is generally 1/32nd inch (0.80 mm) and thinner. Common thickness used currently for plain sliced and rotary peeled maple veneers were determined by surveying both veneer producers and plywood manufacturers (see section 3.1 Factor. Some common thicknesses are listed in Table 4.

Table 4 Common maple veneer thicknesses by preparation method as found in authors' survey.

Veneer preparation method	**Common Thicknesses**
Sliced	1/42nd inch, 1/45th inch, 1/48th inch, 1/50th inch, (0.58 mm, 0.54 mm, 0.51 mm, 0.49 mm)
Rotary peeled	1/32nd inch, 1/36th inch, 1/38th inch, 1/42nd inch, (0.77 mm, 0.68 mm, 0.65 mm, 0.58mm)

Because there is no specified thickness for grades or use in decorative veneer, customers and suppliers must agree upon the thickness at the time of order (Hardwood Plywood & Veneer Association, 2004). Thicknesses produced by a veneer mill are most likely determined by technological capabilities, cost, and customer demand.

2.2.2 Selection of Substrates

Core material can be divided into four categories: veneer, lumber, reconstituted panels (such as MDF and particleboard), and combination cores which typically contain layered veneer cores with thin MDF cross bands (Schramm, 2003; Architectural Woodwork Institute, 1994).

Substrates, or core materials, are selected based on a variety of concerns, which include appearance, strength, machinability, unit weight, and fastener withdrawal strength (Schramm, 2003). The appearance of the cores becomes important when the edges are left exposed and influence the appearance of the edges of a decorative panel. Additionally, and especially in panels with veneer core, features from the core (including texture, defects and even color) can telegraph through the thin veneer overlays and mar the overall appearance of the decorative panel (Schramm, 2003; Christiansen & Knaebe, 2004).

For example, veneer and lumber core offer superior screw withdrawal when compared to reconstituted panels; veneer and lumber core, however, are harder to machine and have inferior edge appearance when compared to reconstituted panels, especially MDF (Architectural Woodwork Institute, 1994).

Table 5 Core type descriptions

Core Type	**Characteristics**
Veneer	Typically three to five plies of thicker (e.g., 1/10”-1/7” (2.54 – 3.63 mm)) veneer arranged with the grain pattern perpendicular to each other. Can be softwood or hardwood. Good fastener withdrawal and strength properties. Lighter than reconstituted panels.
Lumber	Thin boards arranged side-by-side covered with veneer cross-bands. Good fastener withdrawal and strength properties. Lighter than reconstituted panels. No longer in common use.
Reconstituted panels	Examples are fiberboard and particleboard. Often simply termed ‘board core’ in the industry. Core material produced from small particles (e.g., sawdust, chips, and planer shavings) and fibers, which are then covered in adhesive and formed into a mat. The mat is then pressed to make a panel. Smooth surfaces won’t telegraph through thin veneer overlays. Can be heavy.
Combination Core	Typically multiple plies of veneer most commonly with thin MDF as cross bands. Fastener withdrawal properties approach veneer and lumber core panels. Better strength properties than reconstituted panels. Little to no telegraphing of core defects through the face or back veneer.

2.2.3 Selection of Adhesives

Adhesives come in a myriad of distinct types and formulations. In addition to the principal purpose of bonding the components of a panel to one another, adhesives are used for jointing matched veneer. Adhesive choices affect many aspects of a panel including pressing cycles (e.g. time, temperature, and pressure), emissions, bond strength, and water resistance. Common adhesives used in decorative hardwood plywood manufacturing include those derived from vegetable proteins such as soy-based adhesives, urea formaldehyde (UF) based adhesives (e.g. ultra low-emitting urea formaldehyde (ULEF)), polyvinyl acetate (PVA) adhesives and some isocyanate adhesives.

Adhesives are applied to panel components by two principle means: glue spreader and curtain coater, though the glue spreader is the most commonly used device (Schramm, 2003). Glue spreaders typically have two rollers coated with adhesive, which apply the adhesive to both sides of a panel component that is passed through rollers. Glue spreaders ensure the right amount of adhesive is applied and that it is spread evenly.

The amount of adhesive spread on a panel component is referred to as the spread rate is and is a ratio of the weight of the wet glue to the one thousand square feet of panel surface area (Schramm, 2003). When the weight of adhesive applied to two sides of the panel is used in the measurement the spread rate is referred to as *double glue line* (dgl). When only one side is used in the measurement the spread rate is referred to as *single glue line* (sgl).

Quality and strength of the adhesive-wood interface depend on the presence of lathe checks because they increase surface roughness. Increased surface roughness on loose-side interfaces reduces bond performance compared to tight-side interfaces (Koch, 1965; Neese, Reeb, & Funck, 2004). As a consequence, performance concerns must be weighed against potential appearance concerns.

2.2.3.1 Principal purposes and concerns with adhesives in decorative hardwood plywood panels

The primary purpose of an adhesive is to bond the constituent parts into one piece. In decorative hardwood plywood this goal is met primarily in two ways:

1) Bonding core to face veneer and core to back veneer, veneer plies for veneer core panels
2) Jointing matched veneers

Though there are many concerns that govern the choice of adhesive utilized in a product, those relating to the requirements of the grade standard and environmental concerns including formaldehyde emissions are chief amongst them (Schramm, 2003; California Air Resource Board, 2012). Other concerns often relate to cost, appearance, and performance issues, such as dark adhesive colors bleeding through thin veneers and water resistance.

With regards to exposure (e.g. to moisture) most decorative hardwood plywood panels are considered Type II under the HPVA/ANSI standards (Schramm, 2003). Type II is designated for interior use and has relaxed standards concerning bond line requirements and durability test performance compared to technical and Type I, which are rated for exterior uses. Water resistance and delamination are the primary concerns with regards to adhesives within the standard (Hardwood Plywood & Veneer Association, 2004). The standard requires samples taken from production panels to pass a three-cycle soak test, which specifies conditions for soaking, drying and testing (see details in Appendix 2 Three-cycle soak test).

Concerns over air quality are also addressed within the ANSI standard; however they are trumped by the much more stringent California Air Resource Board (CARB) standard for formaldehyde emissions. The CARB regulations limit hardwood plywood formaldehyde emissions to 0.05 parts per million (effective for veneer core products in January 2010 and composite core products in July 2012) (California Air Resource Board, 2012). These regulations have led to increased use of formaldehyde free (e.g., soy-based) adhesives and ultra-low emitting formaldehyde based adhesives.

2.2.3.3 Adhesive properties

Modern adhesives used in wood products are largely synthetic organic polymers based on petrochemicals or natural gas systems. However, polymers extracted from natural proteins – especially those from soybeans – are still in use (Forest Products Laboratory, 2010). Soy based adhesives have recently seen a resurgence in popularity because of advances in the bonding ability and their limited ecological impact due to reduced reliance on petrochemicals and formaldehyde regulations.

Wood adhesives are often categorized into groups based on how they react to heat. Thermoset adhesives undergo a chemical change when they are cured and do not soften and flow when reheated. Thermoplastic adhesives will undergo repeated cycles of softening and hardening when exposed to heating and cooling. Thermoplastic adhesives are also less resistant to moisture (Forest Products Laboratory, 2010).

One limitation of adhesives is their "pot life." This term refers to how long they remain useful and useable after being prepared. The use of catalysts to increase bonding performance of adhesives limits their pot life. Pot life is a concern for panel producers because it impacts when an adhesive can be prepared and how it is stored. In production environments, components of adhesives with short pot lives are stored separately then combined just before being applied to the panel components. Similarly, in a laboratory setting, adhesives with short pot lives must be prepared from their components prior to each use, while those with longer pot lives can be mixed once and used as needed throughout a project.

2.2.4. Pressing panels

All plywood panels require pressing in order to properly bond the core material to the surface and back veneer. There are often two stages to pressing cycles: pre-pressing and hot-pressing (Schramm, 2003).

Panels made with veneer core are typically laid up with the face veneer grain oriented perpendicular to the topmost layer of veneer in the core (Hardwood Plywood & Veneer Association, 2004). Orienting face veneers parallel to the grain is allowed (Hardwood Plywood & Veneer Association, 2004), however alternating grain orientation of veneer plies produces a balanced panel, which is less likely to check or warp (Christiansen & Knaebe, 2004).

Once panel components have been assembled, the panel is allowed to stand for a short time (e.g. five to 20 minutes) before being pressed to give the adhesive the opportunity to give off moisture and convert to a gel or “tacky” state (Schramm, 2003). The panel is then placed under pressure, without heat (this is sometimes referred to as “cold-pressing” or “pre-pressing”). This process serves to begin the bonding process by partially transferring adhesive between surfaces (e.g. from the core to the face veneer) by forcing it into the pores of the wood. If panels are not allowed enough stand time, adhesive transfer may be insufficient leading to poor adhesive bonds (Schramm, 2003).

After pre-pressing, panels are placed into a heated press, which serves to finalize the adhesive bond. Panels are pressed individually within steel platens in hot-presses, though a single press may contain many openings and therefore be able to press up to 60 panels at once (Schramm, 2003). Hot press pressures are typically near 1 GPa, and temperatures are near 115 °C. Hot press times vary based on the depth of the innermost glue line to be cured (i.e. panel thickness). The modern practice of using pre-made cores allows for very short press times – 2 minutes or less – because heat need only be transferred to the glue interface between the thin face and back veneers and the core.

When panels go through both pre-press and hot-press cycles, the process is referred to as a “two-step” process (Schramm, 2003).

2.2.5. Cutting to size and repairs

After pressing, panels are cut to size. Most commonly, panels are sawn to 1.22 m x 2.44 m (Schramm, 2003). Straightness of cut, and quality of the edge made are particularly important for decorative plywood panels.

After panels are properly sized they are inspected for defects and repaired (or, “patched”). During this phase of production open splits that may have occurred before or during manufacturing and knotholes are filled with synthetic filler colored to resemble wood called “putty”. Panels requiring greater amounts of repair must be downgraded according to the HPVA standard (Hardwood Plywood & Veneer Association, 2004). Panels may be inspected for checks at this point, dependent upon manufacturer preference. Once panels have been repaired they are staged before moving on to the final phases of production. This allows time for the putty to dry (Schramm, 2003).

2.2.6. Sanding and finishing

Panels are sanded to create a smooth, even surface on the panel. Sanding grits range between 100 and 220 and vary based on equipment and manufacturer needs (Schramm, 2003). For mills without finish lines, this is the last stage of production before panels are packaged and delivered to customers. In mills with finish lines, panels are coated with a variety of finishes or stains and allowed to cure before packaging. Finishes depend on customer request, and manufacturer capabilities. Water based finishes are believed to increase the likelihood of check development because they may contribute moisture to the face veneer (Yan & Lang, 1958; Forbes, 1997; Christiansen & Knaebe, 2004; Schramm, 2003; Gilmore & Hanover, 1990). Finishes and finishing techniques were not examined in this study, but are logical factors to examine in a future study.

2.3 Physics of checking

Veneer checks are small cracks that appear in the surface of the veneer. Veneer checking is a costly problem to manufacturers and customers of decorative hardwood panels. Sugar maple seems to be particularly troublesome because this defect appears inconsistently (Cassens & Leng, 2003). Checks in maple may be more prominent than other species due to the lack of figure in the more popular grades of maple. Highly figured species such as oak or walnut are considered more sensitive to checking than maple and other less intricately figured species (Yan & Lang, 1958), yet the figure may make checks harder to see.

Checks most often occur as many fine longitudinal splits in the visible face of the veneer, but may also appear as a larger, more prominent split in the veneer (Figure 1, Figure 10 and Figure 11) (Holcombe, 1952; Feihl & Godin, 1970). Diffuse porous hardwoods, such as sugar maple, are more likely to check along the grain, while ring porous hardwoods may check either across or along the grain (Schramm, 2003). They may extend partially or completely through the veneer, and tend to expand and contract with changes in moisture content (Figure 10 and Figure 11). Face checks can occur at various stages of manufacturing, but may not occur until years later after the panel has been put in service (Holcombe, 1952; Jayne, 1953).

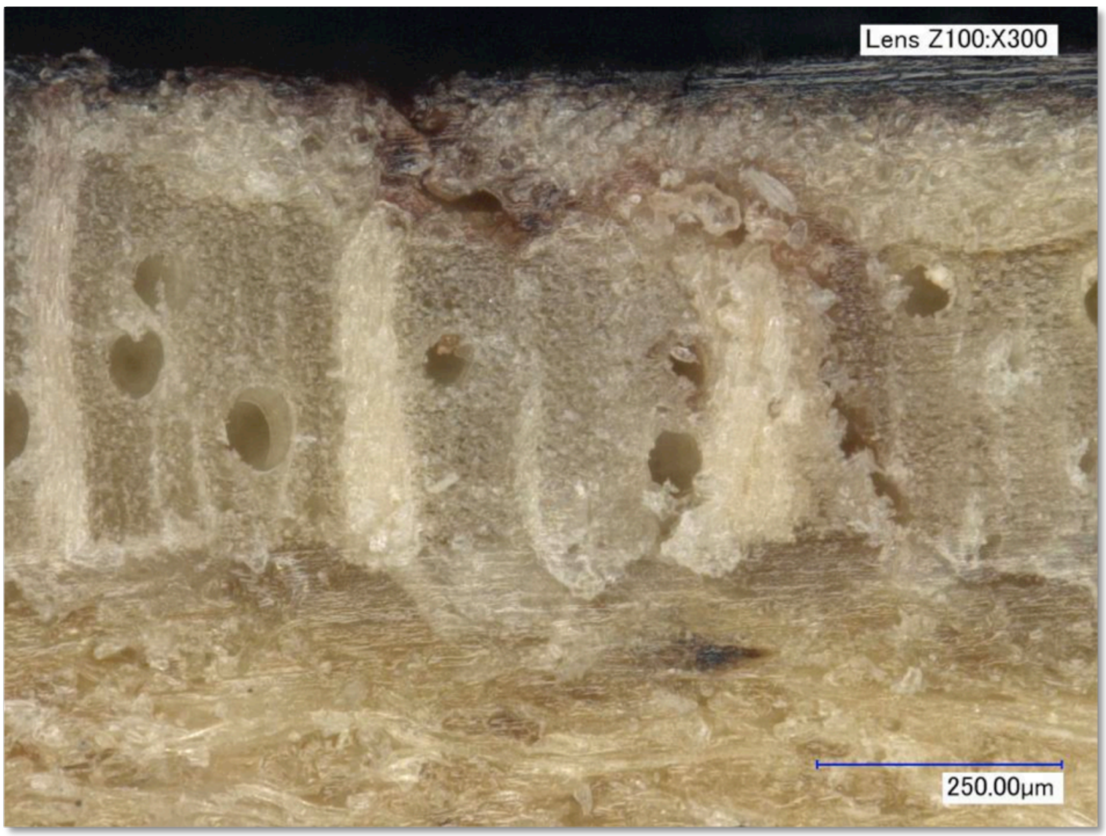

Figure 10 Image of cross section of a maple veneered panel with a check present. Dark discoloration within check is stain that entered the check during finishing.

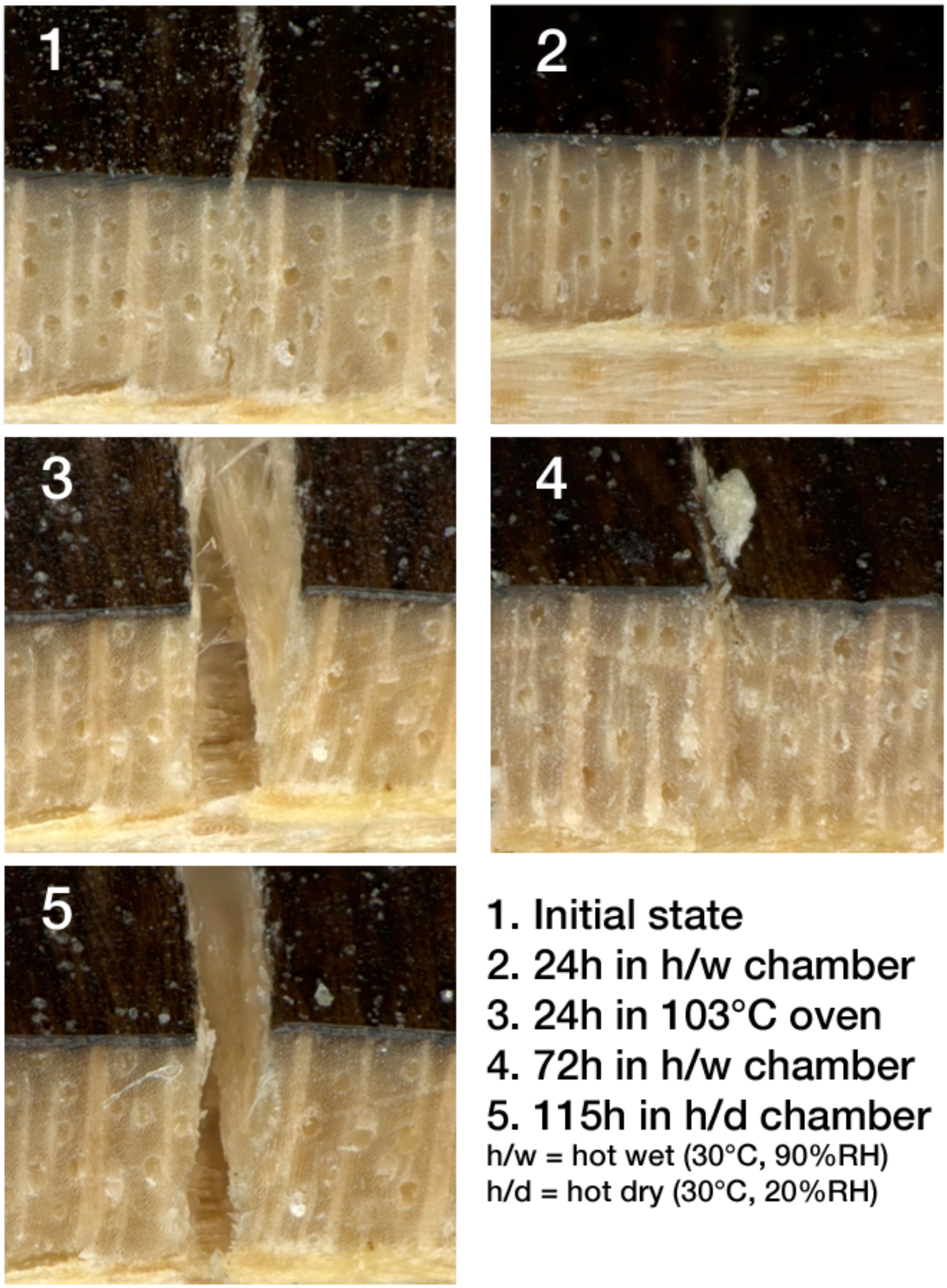

Figure 11 Progressive check size changes after exposure to different moisture and heat conditions

2.3.1 Checking mechanism

The cause for veneer checking is the differential moisture content between the veneer and substrate it is adhered to, which leads to shrinking and swelling of the component materials at different rates (Cassens & Leng, 2003; Christiansen & Knaebe, 2004). As the components dry, they shrink to different degrees, and at different rates resulting in a moisture gradient across the thickness of the panel (Figure 12).

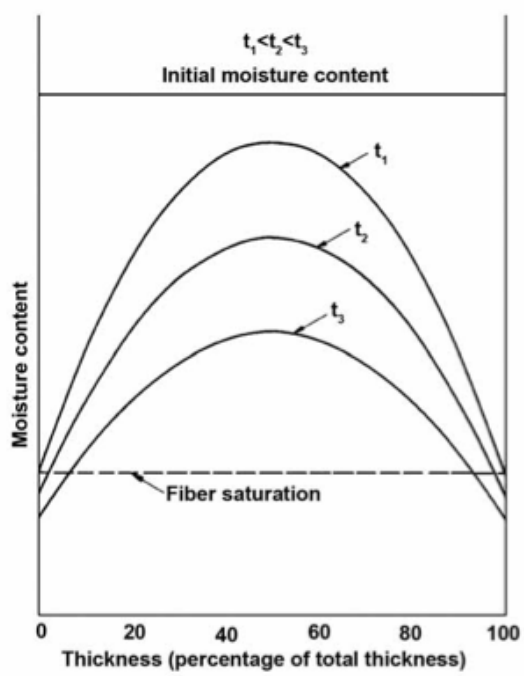

Figure 12 Moisture gradients at different times (t1, t2, t3) across the thickness of a piece of solid wood (Forest Products Laboratory, 2010).

The difference in rate and degree causes drying stresses to build up. The drying stress build up occurs in up to three generalized stages:

1) Panel components have approximately equal MC and drying stress is approximately zero.
2) Face veneer begins to lose MC, while the core component remains at a higher MC (face veneer MC < core component MC). Face veneer is in *tension* – face veneer is shrinking but prevented from doing so fully because it is adhered to the core, which is not yet shrinking (Figure 13 a).
    a. Checking occurs if the tension at this stage increases beyond the ultimate tensile strength of the veneer (perpendicular to the grain of the veneer)
3) Core component begins to lose MC, face veneer approaches EMC. Face veneer is in *compression* – core is shrinking (Figure 13 b).

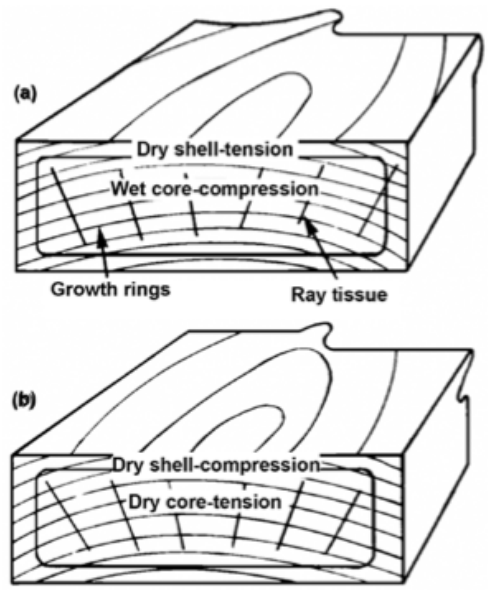

Figure 13 Compression/tension gradient across the thickness of solid wood (Forest Products Laboratory, 2010)

As an example, a panel may be made with a medium density fiberboard (MDF) core and maple face and back veneers. MDF shrinks and swells much less than the face veneer. The incompatibility of dimensional changes between the core and the surface veneers due to drying leads to stress build-up and, in some cases, can result in check development in the surface veneer (Yan & Lang, 1958). Tension in the surface veneer will be greatest when the face veneer has dried much more quickly than the core (Figure 14).

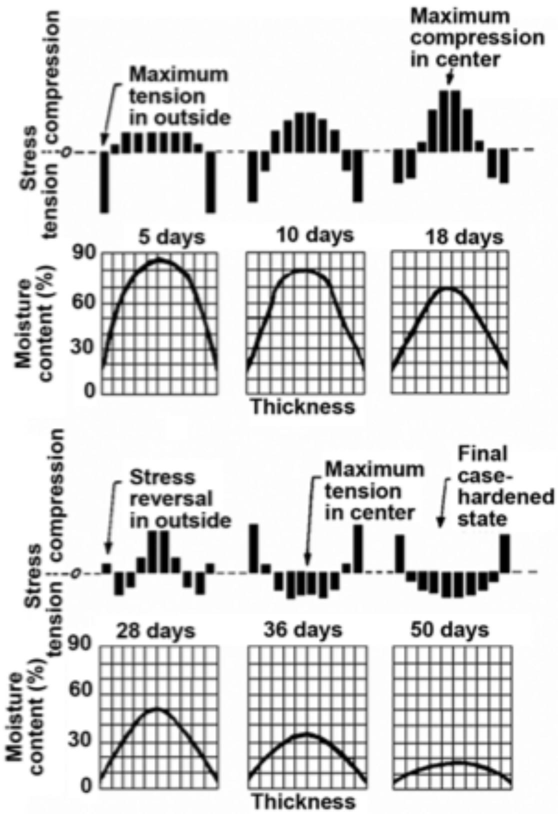

Figure 14 Tension and compression states with moisture gradients at different times during drying (Forest Products Laboratory, 2010)

2.3.2 Moisture content and dimensional change

Wood, as most natural materials, exchanges moisture with its surrounding environment. Materials with this property are referred to as hygroscopic. The exchange of moisture between a hygroscopic material and its environment depends on the relative humidity and temperature of the environment and current amount of moisture in the material (Forest Products Laboratory, 2010). The amount of moisture in a material can be quantitatively expressed as moisture content (MC), which in wood, is typically expressed as dry-base percentage and is determined by the following equation (Eq. 1):

$$MC = \frac{m_{water}}{m_{wood}} * (100\%) \qquad \text{Eq. 1}$$

The moisture content of wood has an impact on many physical and material properties. Most important to this study are the relationships between dimensional changes (shrinking and swelling) and Equilibrium Moisture Content (EMC) between wood and ambient air.

2.3.3 Equilibrium moisture content of wood

EMC is the moisture content wood reaches when it is no longer exchanging moisture with its environment (Forest Products Laboratory, 2010). EMC, therefore, changes as environmental conditions change. Moisture content in wood changes according to the sorption isotherm for a given temperature. The sorption isotherm is a curve that describes the relationship between wood moisture content and relative humidity for a constant temperature (Suchsland, 2004). A typical sorption isotherm for solid wood is shown in Figure 15. In service, decorative panels are typically used in climate controlled environments where relative humidity is low, and temperatures can be high, such as an air conditioned home. Consider an indoor environment where relative humidity is 20% and the temperature is 21.1°C; the moisture content of solid wood in this environment could reach 4.5% if the environmental conditions are maintained for a sufficiently long time (Forest Products Laboratory, 2010). Sorption isotherms for many wood-based composites may vary substantially from those determined for solid wood. No sorption isotherm specific to the wood based composites used as core material in this study could be identified in the literature.

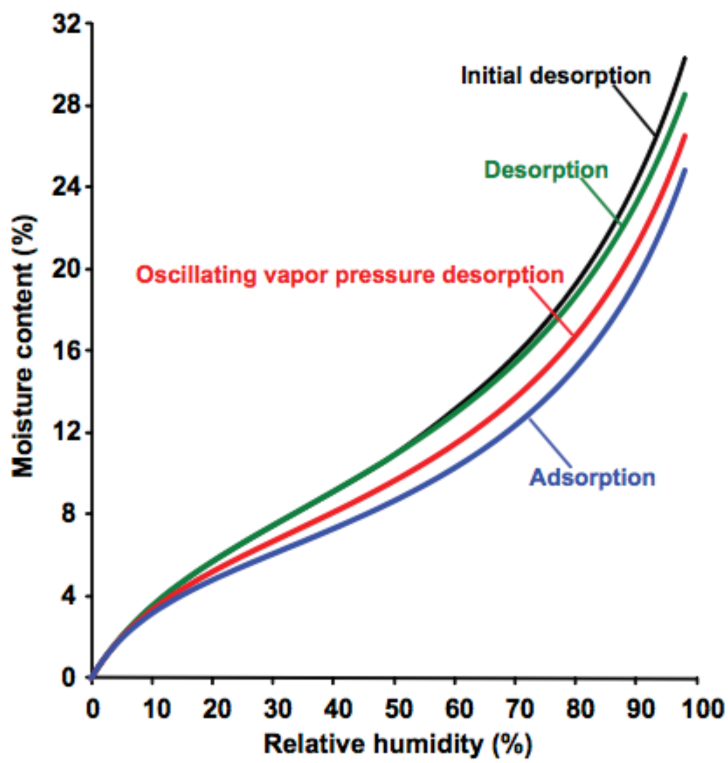

Figure 15 Typical sorption isotherms for wood (Forest Products Laboratory, 2010)

To estimate the EMC of wood in an environment given temperature and relative humidity an empirical equation was proposed by Simpson (1998) (Appendix 9. Wood equilibrium moisture content equation). This formula was used extensively for estimating the EMC of panels and environmental conditions in this study.

Indoor EMC in the United States is estimated to be approximately 8% for most of the country, 6% in the warm dry climates (southwestern interior region), and 11% in the warm damp climates (southeastern coastal region) (Forest Products Laboratory, 2010). These values are subject to seasonal change, though to a lesser degree than outdoor EMC values.

2.3.4 Dimensional stability

Dimensional stability, as it pertains to wood products, is the extent to which the product resists the natural swelling, shrinking and out of plane changes in dimension and shape caused by moisture content changes. It is a prime concern for any manufacturer or end user of plywood products because of the effect size and shape changes have on in-service products. This is especially true of highly visible products, such as those that utilize decorative veneered plywood panels. In composite products the dimensional stability of components may vary from one another. While warping and other out of plane deformations can be a concern for manufacturers and users of decorative plywood, these changes aren't the primary cause of checking in decorative veneered panels. Differences in dimensional rates of change between the core and decorative veneer are the primary cause of surface checking in decorative plywood (Cassens & Leng, 2003; Christiansen & Knaebe, 2004).

As wood adjusts to its surrounding environment towards its EMC, its physical and mechanical properties change. When these moisture content adjustments are below the fiber saturation point, dimensional changes occur. Fiber saturation point is the level of moisture content at which the cell walls are saturated, but no water is present in the cell lumen. The fiber saturation point, in most species, is between 25% and 30% moisture content (Forest Products Laboratory, 2010).

When moisture content changes occur below the fiber saturation point, changes in dimension for solid wood can be calculated using the following equations (Forest Products Laboratory, 2010):

1) If initial and final moisture contents are between 6% and 14% (within the linear region of dimensional change):

$$\Delta D = D_I[C_T(MC_F - MC_I)] \qquad \text{Eq. 2}$$

2) When one, or both, of the moisture content values are outside of the 6% to 14% range:

$$\Delta D = \frac{D_I(MC_F - MC_I)}{30(100)/S_T - 30 + MC_I} \qquad \text{Eq. 3}$$

In both of these equations, the tangential shrinkage coefficient (C_T) and the tangential shrinkage (as a percent value) (S_T) were used. ΔD and D_I refer to change in dimension and initial dimension, respectively. MC_F and MC_I refer to final moisture content and initial moisture content, respectively. To calculate dimensional changes in the radial direction, the corresponding radial values (C_R, S_R) may be used in their place.

To illustrate the effect of moisture content changes on dimensional stability, consider a maple panel produced in a hot and humid climate without moisture control during production and shipped to a hot, dry climate and installed in an air conditioned home. If the panel were produced in Louisiana in August its estimated MC would be 14.7% based on the average outdoor EMC for Louisiana in August (Simpson, 1998). If that panel were then shipped to and installed in a home in Utah, the panel would, with time, equilibrate to approximately 6% moisture content (Forest Products Laboratory, 2010). The 8.7% change in moisture content would cause a standard 122 cm by 244 cm panel to shrink to 118.3 cm by 236.6 cm. Though the panel will not actually shrink this much, the resulting stress will build up and likely cause defects such as checking or warping to occur.

These equations are sufficient for estimating dimensional changes in solid wood products, including veneer. However, estimating dimensional stability in plywood, reconstituted particle and fiber based panels often used as core materials in decorative plywood is more complex, because they are a blend of wood and adhesives. Species may vary within core materials, as well as grain orientation, further increasing the complexity of estimating shrink and swell values for general types of core materials. In general, wood composites offer superior properties with regards to shrinking and swelling (they shrink and swell less than their solid-wood counterparts) (Suchsland, 2004). Within the family of reconstituted wood products, fiberboard shrinks and swells less than particleboard (Suchsland, 2004).

Linear expansion is one measure of dimensional change associated with moisture content changes. This value estimates expansion along or across the grain orientation of a wood composite from a low humidity point to a higher humidity point. Estimated linear expansion values are presented for core types used in this study in Table 6. These values are considerably lower than the shrinkage rates for solid wood (values for maple presented in Table 1).

Table 6 Estimated linear expansion values for core types used in this study.[1]

Core type	**Linear expansion estimate (0-80%MC)**
Particleboard	0.28%[a]
MDF	0.17%[a]
Combicore	0.20%[b]
Veneer	0.22%[c]

Manufacturing decisions, techniques and component properties all may influence check development.

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[1] [a] Values from Heroux & Dopico, 2004
[b] Estimated based on veneer core value and MDF value
[c] Estimate derived from Douglas-fir plywood values paralell to the grain of the outermost layer presented in table 6-4a in Suchsland, 2004

2.4 Manufacturing decisions and check development

2.4.1 Adhesive use

Moisture content differences and variable shrinkage rates between the face veneer and the core material are the principal cause of checking in hardwood plywood products (Yan & Lang, 1958; Gilmore & Hanover, 1990; Forbes, 1997; Schramm, 2003; Cassens & Leng, 2003; Christiansen & Knaebe, 2004; Leavengood, Funck, & Reeb, 2011). Many adhesives contribute moisture to plywood panels, as they are often more than 50% water, and potentially contribute to moisture content differentials between the face veneer and the core. However, while previous research findings have determined adhesives can contribute to increased check development (Yan & Lang, 1958; Gilmore & Hanover, 1990; Forbes, 1997), studies detailing the impact of adhesive choice on check development were lacking until recently. In their study examining the effect of adhesive choice (PVA and urea formaldehyde), veneer MC at time of pressing (12% and 7%), panel assembly time (1 and 10 minutes), and lathe-check orientation (tight-side out and loose-side out) Cassens and Leng (2003) found strong evidence adhesive choice was part of multiple two way interactions that influenced check development. Cassens and Leng (2003) found strong evidence indicating the two-level interaction between adhesive choice and lathe-check orientation jointly contribute to veneer checking. Furthermore, strong evidence was discovered indicating adhesive choice and veneer moisture content at the time of pressing cause increased checking in maple veneered decorative hardwood panels. The study demonstrated maple panels constructed using PVA (as opposed to urea formaldehyde), with the loose-side of the veneer facing out, a higher veneer MC at the time of pressing (12% compared to 7%) and a longer assembly time (10 minutes compared to 1 minute) checked most of the 16 combinations examined (Cassens & Leng, 2003).

2.4.2 Veneer properties and lathe-check orientation

Veneer properties including moisture content at time of pressing, thickness, and cutting method (e.g., sliced or peeled) are all considered to play a role in check development of decorative hardwood panels (Yan & Lang, 1958; Forbes, 1997; Schramm, 2003; Christiansen & Knaebe, 2004).

Controlling the moisture content of the face and back veneers at time of pressing is thought to be one effective method of controlling check development (Yan & Lang, 1958; Christiansen & Knaebe, 2004; Schramm, 2003; Cassens & Leng, 2003).

Veneer thickness also contributes to check development as thinner veneers provide less resistance to dimensional changes in the substrate (Christiansen & Knaebe, 2004). Thicker veneers are expected to have larger checks, while thinner veneers are expected to have more, smaller checks (Christiansen & Knaebe, 2004).

Cutting method affects checking because different cutting methods expose tangential and radial faces of the wood. Plain slicing and rotary peeling most commonly produce veneers with tangential faces, while rift slicing and quarter slicing most commonly produce veneers with radial faces. Tangential shrinkage rates are higher than radial shrinkage rates (9.9% compared to 4.9% in sugar maple, Table 1). Therefore, depending on cutting method face veneers may experience differing shrinkage values, and correspondingly may have more stress built up during moisture equilibration.

During manufacturing the veneer can be oriented loose side or tight side out in whole piece and slip matched veneer. Several studies and common industry practice suggest orienting panels with the tight side out produces panels with less checking than those with loose side out veneer orientation (Yan & Lang, 1958; Schramm, 2003; Feihl & Godin, 1970; Christiansen & Knaebe, 2004; Cassens & Leng, 2003; Batey, 1955). However, contrary to previous research, a recent study has found evidence that orienting face veneers loose side out will reduce the propensity for checks to develop in panels constructed with sugar maple face veneers (Leavengood, Funck, & Reeb, 2011).

2.4.3 Best practices

In order to minimize checking, the commonly accepted best practices have included recommendations for lathe-check orientation, production cycles, and moisture content. Some of the more pertinent best practices are:

1. Most authors recommend that the face veneer is oriented tight side out (that is, with the lathe-checks facing the substrate) (Holcombe, 1952; Yan & Lang, 1958; Cassens & Leng, 2003; Schramm, 2003; Christiansen & Knaebe, 2004). However, Leavengood et al. (2011) found that maple face veneer oriented loose side out resulted in fewer checks.
2. Time between pressing cycles in a two-step process should be adjusted to account for the requirements of different adhesives, veneer and substrate properties (Yan & Lang, 1958; Schramm, 2003; Christiansen & Knaebe, 2004).
3. Maintain precise, low moisture content levels during veneer production and panel production (Holcombe, 1952; Gilmore & Hanover, 1990; Forbes, 1997; Schramm, 2003; Christiansen & Knaebe, 2004).
4. Using resins with high solids content may reduce the likelihood of check development due to minimizing the addition of water into the panel (Gilmore & Hanover, 1990; Forbes, 1997; Yan & Lang, 1958).

In spite of the established best practices and decades of technological improvements in plywood manufacturing the problems with checking in maple veneered decorative hardwood panels persist. The components available to the industry have changed, too, since early research was completed.

Current knowledge about checking and the practices to minimize the phenomenon are insufficient to substantially ameliorate the issue. Though following current best practices may reduce the incidence and severity of checking in maple veneer decorative plywood panels, more research is required to fully address the issue. This is especially pertinent as some manufacturing methods contradict best practice suggestions; using book-matched veneer for example, exposes both the tight and loose sides of the veneer.

A better understanding of how manufacturing factors contribute to checking and interact with one another to increase or decrease checking is needed to reduce incidences of checking.

2.5 Measurement of checks

Though studies are lacking which generalize the size and shape of veneer checks, they are considered to be narrow (likely less than 0.5 mm wide) and can range greatly in length. Length is measured along the grain, and width perpendicular to the grain. Figure 16 is an illustration of a hypothetical check and includes some potential dimensional measurements.

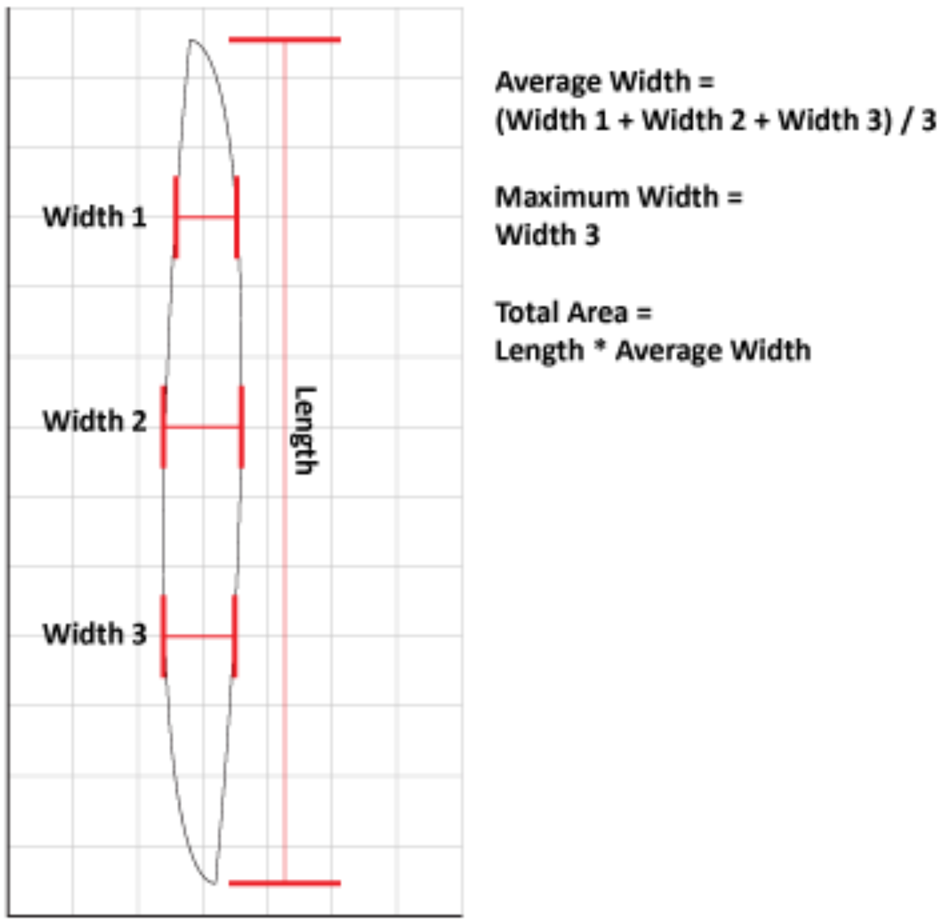

Figure 16 Hypothetical check measurement including width, length and area

2.5.1 Existing manual measurement techniques

Batey (1955) described an effective, yet time-consuming method, in which lines spaced 1-inch apart from each other are drawn surface of the veneer perpendicular to the grain. A check is counted once for each line it crosses. For example a check that crosses one line is counted once, while a check long enough to cross three lines is counted three times (Figure 17). This method relies on the sparse count of check on the surface but does not provide any direct measurements of the check dimensions. Cassens and Leng (2003) expanded this method by counting checks visible in plain light under 16x magnification. While this method provides a standardized method for counting checks, repeatable and consistent measures are difficult to achieve. Furthermore, it is possible for two panels with “equal” amounts (measured by total length, for example) of checking to come up with very different check counts. Consider a check in one panel that is 1.5 inches in length positioned with its midpoint crossing one of the lines in this system. It would be counted only once, while a check of identical (or shorter) length could be counted twice depending on its location with regards to the grid. With regards to subjectivity, the outcome of this method is highly dependent on what is plainly visible to the examiner, and so two different examiners could come up with different check counts on the same panel, making comparisons between panels very difficult.

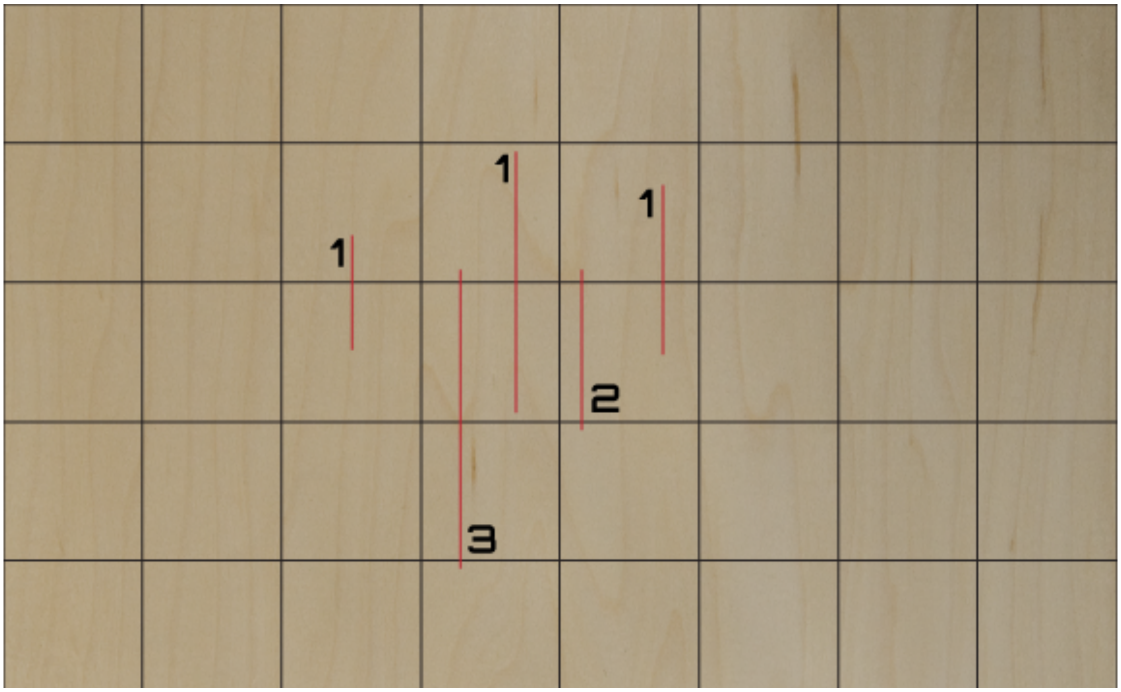

Figure 17 Example of how checks have previously been counted. The red lines represent checks, and the numerical value nearest to each is how many checks the individual check would be counted as.

2.5.2 Existing mechanical and optical methods

The presence of checks contributes to surface roughness may also be used as a measure of checking in veneer. The roughness average R_a (formerly the center line average or, CLA), for example, can be measured before and after certain periods to ascertain changes in roughness, which may be attributed to the development of checks. While there are multiple methods to determine surface roughness, Funck et al. (1992) evaluated two widely used in research environments - laser-scatter and stylus tracing. Funck et al. (1992) found that both methods provide roughness information useful to wood manufacturers. However, these methods could not reliably detect the difference between loose side and tight side (Neese, Reeb, & Funck, 2004), and therefore may be unreliable in detecting smaller checks in face veneers.

Other methods to determine the severity of checks by measuring check depth require microscopic evaluation of the cross section of the check, which requires samples to be sawn, and therefore destroyed. For example, a veneer with a check may be cut through the check, and then examined under a microscope to determine the width and depth of the check (Figure 10). Even then, the point in the check where the cut was made could lead to wildly different results in analysis. This information is interesting and provides insight into the nature of the check, although it is impractical to use as an experimental method for determining multiple check characteristics on a statistically significant number of samples.

Another concern with many of these post hoc methods is the timing of the measurements. Typically, as in Holcombe (1952), Cassens (2003) and Leavengood et al. (2011), measurements were taken periods of exposure to humid and dry conditions, in some cases for periods as long as three weeks. After extended exposure to varying moisture conditions it is possible that a newly opened check in the surface veneer can close as the substrate dries (Figure 11). The face veneer dries out and shrinks before and more quickly than the core; therefore checks may develop quickly in the face veneer. As the core material begins to shrink, the face checks may decrease in severity. Some checks could, therefore, close during the measurement procedure and may be overlooked.

2.5.3 Optical methods utilizing digital image correlation

Advances in optical methods have provided valuable contributions to measuring deformations, including checks and cracks in materials. Using full-field strain measuring techniques, such as digital image correlation (DIC) provide the foundation for these types of measurements. Such methods are valuable because they rely on repeatable and consistent measurements of strains as they develop across the specimen surface visible to the camera (Zink, Davidson, & Hanna, 1995). Recent studies have provided a framework for isolating multiple cracks as they develop[2] (Helm, 2008) and for monitoring deformations in wood as it dries (Kang, Muszynski, & Milota, 2011). These studies utilize DIC principles, which provide for an automatable, nondestructive, and quantitatively objective method for measuring these types of deformations.

DIC has been proven as a reliable method of observing strain in wood products by comparing images taken over a period of time to the original state (i.e., an image taken at time 0) (Zink, Davidson, & Hanna, 1995). Multiple software packages and optical systems exist to perform this type of analysis. While there is no specific software designed to measure checks in wood veneers, the process lends itself to this use. The basics of the process include measuring

[2] Helm sought to isolate cracks and exclude them from analysis, though.

displacements between selected “targets” on the surface of a material (Figure 19) over time. There are no known studies of utilizing DIC to make detailed measurements of veneer checks as they develop, however the concept was proposed by Kang, et al. (2011) after they noticed peaks and valleys in strain measurements from digital image correlation output of oak veneer adhered to a rigid body as it dried.

2.5.4 Using DIC to measure checking

The principal information provided by DIC software is related to the movements of regularly spaced randomly speckled “targets” over time. Data provided by the software provides granular displacement information of points in an x-y coordinate system. That is, the software determines how far each segment of the image has moved in both the x and y directions of the image. From these displacements strain can be calculated, and regions with strain spikes isolated. These regions with strain spikes correlate to the location of checks, and if the strain patterns meet certain criteria can be identified as a check (Kang H. , Muszynski, Milota, Kang, & Matsumura, 2011). The associated displacement data can then be used to provide estimates of the size of the check as it develops.

2.5.5 Summary of check detection methods

More information about check formation is required to provide insights to process and product improvement. More informative measurements that include length, width and area of individual checks, and total values for test specimens will help to better understand the checking problem (See hypothetical check measurement in Figure 16). Additionally, observing and measuring checks as they develop will provide insights into how and when checks form, grow and contract.

Multiple methods have been used to measure checks in veneer. However, these methods have been hindered by excessive time demands, and can be imprecise and lack reproducibility. Advances in optical systems allow objective, precise and reproducible measurements to be automated and utilized in characterizing check severity and development.

Existing methods serve to provide measurements of check severity, but provide little insight into the development of checks over time, or in relationship to the principle cause: stress build up during drying.

Any new system for measuring checks should seek to provide not only a wider range of measurements that detail the severity of checks, but also should provide a means to understand check development.

2.6 Summary

Limited and fragmentary research has produced conflicting, and outdated conclusions regarding key variables that are thought to influence check severity and development in decorative hardwood panels.

Additionally, the labor intensive methodology used in previous research has limited the scope of those studies. Consequently, only a limited numbers factors could be studied at the same time. A new method to automate and improve the process of measure check severity is needed.

2.6.1. Checking is a costly problem

The complications with addressing defects such as checking when they occur in situ lead to high costs (Leavengood, Funck, & Reeb, 2011). Checking in decorative hardwood panels, though it has existed as long as the industry has produced veneer (Holcombe, 1952), has received relatively little attention. Due to the lack of academic attention from the late 1950's until fairly recently, there is much to learn in order to address and resolve this problem.

Anecdotal accounts from current hardwood plywood industry members suggest this problem is on the rise, and the costs of addressing it are also increasing. Indeed, recent industrial concern over this problem is evident to anyone attending regional or national meetings of industry groups as discussions about it are inevitably on the agenda and garner much discussion during the meeting and in the hallways after (Western Hardwood Plywood Producers, 2010; Western Hardwood Plywood Producers, 2012).

2.6.2 Limited and conflicting research

Though the problem has existed for a long time, research has been limited. Very few recent studies exist, and some studies offer conflicting results with regards to findings. In particular and in contrast with previous research, including a recent study by Cassens and Leng (2003), Leavengood, et al. (2011) found that the accepted process of orienting lathe-checks tight side out in maple might actually produce panels that tend to have greater check development issues.

Additionally, early studies suggest thicker veneers are more inclined to check (Yan & Lang, 1958), while recent studies suggest veneers of differing thickness are likely to check differently – thinner veneers are prone to more frequent checks while thicker veneers seem to have wider checks, when they are present (Cassens & Leng, 2003). These disagreements may be attributable to the different thicknesses available at the time studies were conducted.

2.6.2.1 Factors that may impact checking

Manufacturing decorative hardwood plywood includes many steps, and many factors. Many of these factors may contribute to face check development. Those particular interest are:

1. Face veneer orientation. Most authors suggest orienting lathe checks towards the substrate (Holcombe, 1952; Yan & Lang, 1958; Cassens & Leng, 2003; Schramm, 2003; Christiansen & Knaebe, 2004). However,

Leavengood et al. (2011) found that maple face veneer oriented loose side out resulted in fewer checks.

2. Veneer properties such as thickness, preparation method, tightness of cut (Yan & Lang, 1958; Christiansen & Knaebe, 2004)
3. Core material type, because industry members use a variety of products (see section 3.1 Factor)
4. Adhesive type (Yan & Lang, 1958; Cassens & Leng, 2003; Schramm, 2003; Christiansen & Knaebe, 2004)
5. Panel assembly (Cassens & Leng, 2003; Schramm, 2003; Christiansen & Knaebe, 2004)
6. Finishing (Forbes, 1997; Schramm, 2003; Christiansen & Knaebe, 2004)

2.6.2.2 Challenges with measuring checks

The large number of factors that may contribute to check development combined with the difficulty in accurately measuring checks lead to a gap in knowledge regarding the best practices for producing panels that produce the fewest checks. The time required to construct an experiment with enough factors using previously identified methods for counting and measuring checks put a practical limit on the number of factors that could be examined.

Previous research has been hindered by time consuming methods that use difficult to reproduce measurements of checking. These methods limit the number of factors and replicates that can be examined in any one study.

Advances in optical methods provide opportunities for new, automatable and efficient methods to be developed using digital images and digital image correlation. The findings of Kang et al. (2011) provide a basis from which to create this new method.

2.7 Research objectives

The primary objective of this study is to determine which manufacturing factors contribute to check development by conducting a factor screening study. First, the manufacturing factors to be studied must be identified and a method to quantifying checking must be created.

Specific objectives are:

1) Develop a comprehensive matrix of test factor that may affect checking in maple plywood.
2) Develop an efficient method for measurement of checks as they develop gather data to be processed using digital image correlation
3) Measure intensity of checking for combinations of identified factors
4) Identify critical variables and interactions.

3. Materials and Methods

Characterizing check development and severity in decorative hardwood plywood required following several steps: (1) identify the factors to be studied, (2) develop a method to acquire measurements characterizing both check development and severity, (3) acquire materials and produce test panels, (4) conduct the measurements to examine how all identified factors and their interactions contribute to check development and severity, (5) analyze the data and perform statistical analyses.

Factors were identified by careful examination of the literature of the subject and by surveying Oregon's decorative hardwood plywood manufacturers, and their veneer suppliers across North America. The respondents were asked to provide insights into which products they used seemed to have greater check severity. (Section 3.1 Factor).

Data for check measurement analysis were collected using an automated optical method that produced image series that were subsequently analyzed using digital image correlation (DIC) software. The method allowed batches of 32 samples to be tested at a time for check development and severity every four hours, efficiently providing a means to test a large number of samples in a reasonable period of time. (See section 3.6 Apparatus, data collection and processing).

A custom algorithm was designed to examine output data from the DIC analysis and return detailed information about check severity (including check counts and check area) in each sample. Check measurements calculated from images taken at scheduled intervals, which allowed for examination of check development as test panels throughout the test period. This method proved to be consistent and reproducible (see section 3.2 Check measurement method).

A randomized block split-plot design was chosen to provide the foundation for this factor screening study. This design allowed for the study of all 96 treatments that resulted from combining all factors and levels determined in the factor determination stage of this study. Eight replicates of each treatment were created in blocks for a total of 768 samples. (See Section 3.3 Experimental design).

3.1 Factor identification

The factors and levels of the factor included in were informed by a comprehensive literature review and a short questionnaire that was sent to Oregon hardwood plywood panel producers and their major veneer suppliers across North America. The questionnaire was designed to identify common veneer thicknesses and preparation methods, adhesive and cores in current use in the industry. Each questionnaire also asked respondents to provide commentary on how panel checking has affected their business. Additional questions regarding which season of the year, and where in the country, complaints about checks were most likely to arise were asked as well. Full questionnaire forms are available in Appendix 9.

The comprehensive literature review revealed adhesive type, core type, lathe check orientation, veneer thickness, tightness of veneer cut, finishing, panel assembly methods, and other factors are all likely to contribute to checking in decorative hardwood plywood panels.

However, due to the time and budgetary constraints of this project, it was decided to limit the investigation to four factors that were directly related to the most basic decorative hardwood plywood construction. These factors were: core type, adhesive type, veneer characteristics, and lathe check orientation.

Levels of each factor were selected for the study based on the results of the survey.

3.1.1 Oregon's decorative hardwood plywood survey

Oregon's decorative hardwood plywood manufacturers were all members of the Western Hardwood Plywood Producers Association (WHPP), a trade organization for hardwood plywood producers in the western United States. The questionnaire asked manufacturers which types of veneer, substrate and adhesive were commonplace in their production lines. Qualitative information was also sought to illustrate industry concern regarding checking in maple veneer panels. Decorative hardwood plywood producers were asked the following questions:

1) What thicknesses and cut of maple veneer do you purchase?
2) Please list adhesives that you use for maple plywood.
3) Which core types do you use with maple plywood?
4) Which combination of core type, adhesive and prep method (sliced or peeled) leads to the greatest number of customer complaints related to checking?
5) Which season and region are checks in maple veneer typically reported by customers?

The questionnaire was sent to all five decorative hardwood plywood producers in Oregon, and four returned completed questionnaires. Although this is a low number in absolute terms, it does represent 80 % of Oregon's decorative hardwood plywood producers and approximately 40% of all decorative hardwood plywood production with maple face veneers in the U.S. (Hardwood Plywood & Veneer Association, 2010).

Table 7 Decorative hardwood plywood manufacturers questionnaire responses for questions answered by all respondents. Regions refer to those identified in Figure 18

		Respondent			
Question category		**A**	**B**	**C**	**D**
Rotary peeled veneer, by thickness as percent of purchases for this	1/36"	95%	85%	0	80%

		Respondent			
Question category		**A**	**B**	**C**	**D**
category	1/38”	5%	0	63%	20%
	1/42”	0	15%	37%	0
Sliced veneer, by thickness as percent of purchases for this category	1/45”	50%	0	28%	0
	1/48”	0	100%	32%	100%
	1/50”	50%	0	40%	0
Adhesive used as percent of production	UF	93%	97%	38%	98%
	PVA	0	2%	0	2%
	Soy	7%	0	62%	0
Checking claim reports from region 1 (characterized by stable temperature and humidity throughout the year and limited use of heating or A/C*), by season	Spring	0	100%	0	0
	Summer	5%	0	0	0
	Fall	0	0	0	0
	Winter	0	0	0	0
Checking claim reports from region 2 (high desert climate characterized by very dry summers and harsh winters, necessitating heavy use of heating), by season	Spring	0	0	0	0
	Summer	10%	0	48%	0
	Fall	0	0	0	0
	Winter	0	0	22%	0
Checking claim reports from region 3 (characterized by very humid summers and mild winters), by season	Spring	0	0	0	0
	Summer	0	0	0	0
	Fall	0	0	0	0
	Winter	0	0	0	0
Checking claim reports from region 4 (continental climate with diverse local variations, heavy seasonal use of A/C and heating),	Spring	35%	0	0	30%
	Summer	0	0	0	25%
	Fall	5%	0	0	25%

		Respondent			
Question category		**A**	**B**	**C**	**D**
by season	Winter	45%	0	30%	20%

* In winter conditions heating substantially reduces relative humidity indoors exposing decorative panel surfaces to extreme drying conditions. The effect of A/C on indoor humidity is more difficult to assess but its impact on decorative surfaces is likely negligible.

Other questions received incomplete answers, or were answered incorrectly and could not be tallied completely. The tally of incomplete answers for the question about core type usage, suggest veneer core is the predominate core type used in the industry, while combination core, particleboard and MDF cores are used in approximately equal percentages of the respondents production.

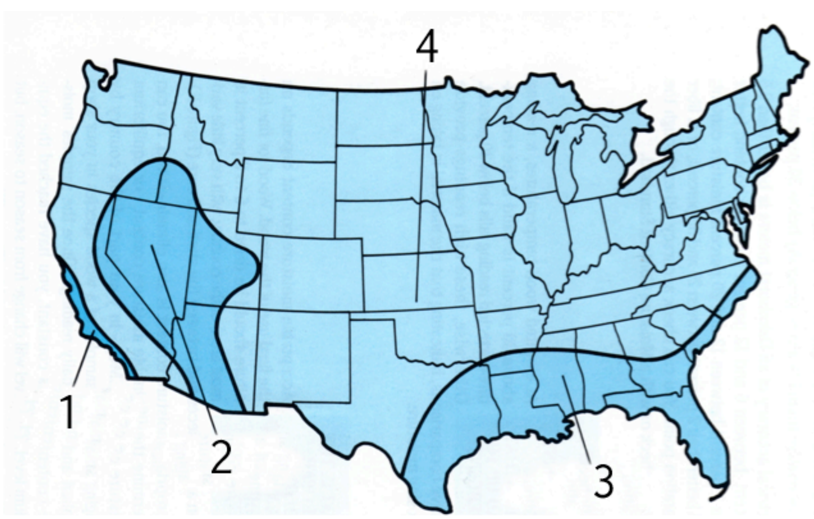

Figure 18 Map of United States with regions segregated by relative EMC values as presented in industry survey

Checking claim reports suggest that region four is where most claims come from. However, this is unsurprising as it represents the majority of the area of the

United States, where continental climate forces heavy seasonal use of air conditioning and heating (Figure 18). Indoor heating during the winter substantially reduces relative humidity indoors, exposing decorative panels to extreme drying conditions.

Asking what percentage of each respondent's production was sold into each region would have enhanced the insightfulness of the results to this question; however, we did not consider this until the results were tallied.

3.1.2 Veneer supplier questionnaire

A questionnaire was developed and sent to veneer producers as well. The veneer producer questionnaire asked about veneer production, regions where logs were purchased, and times of year logs were harvested. The following questions were asked of veneer producers:

1) Please list the primary regions from which you source hard maple logs/flitches.
2) What thicknesses of maple veneer do you produce?
3) Please list the ratio of sliced to rotary peeled maple you produce.
4) How do you condition maple logs/flitches?
5) How do you dry maple veneer (method, time, temperature, etc.)?
6) Which seasons are checks in maple plywood typically reported by customers?

This questionnaire was forwarded to veneer producers by the respondents to the decorative hardwood plywood manufacturers questionnaire. Three responses were received. It is unknown how many veneer producers received the questionnaire. The limited response rate provided equally limited information. All respondents produced rotary peeled veneer, and only one also produced sliced veneer, providing very little insight into sliced veneer production.

Table 8 Tabulated results of questionnaire received from veneer producers

		Respondent		
Question/Category		**A**	**B**	**C**
Log harvest region	CAN	20%	10%	13%
	MI	0	80%	45%
	NY	0	0	11%
	WI	80%	10%	31%
Thickness, Sliced	1/42"	5%	0	0
Thickness, Rotary	1/36"	95%	50%	100%
	1/42"	0%	50%	0
Log/flitch conditioning	Steam	N/A	100%	100%
	Soak	0	0	0
Drying	Press	N/A	100%	0
	Steam	N/A	0	100%
Checking claims by season	Spring	35%	0	0
	Summer	10%	0	43%
	Fall	15%	0	0
	Winter	40%	0	57%

Respondents reported producing veneer at varying thicknesses, and each type of production (slicing, peeling) result in different thicknesses. Thus, veneer thickness and veneer manufacturing mode could not effectively be separated in for the study.

3.1.3 Factor selection summary

Veneer thicknesses reported as used by panel manufacturers were not entirely reflected in the thicknesses reported as produced by veneer suppliers. Thicknesses commonly used in the industry range between 1/36th inch (.706 mm) and 1/50th inch (.508 mm). Rotary peeled veneer is produced on the thicker end of the spectrum, while sliced veneer is produced on the thinner end of the spectrum. Respondents reported that it is uncommon to find peeled and sliced veneer of the same thickness. The final thicknesses chosen were based on what was reported as used by manufacturers, and by choosing divergent thicknesses within each category (e.g., a "thick" peeled veneer and a "thin" peeled veneer).

In addition to veneer thicknesses and preparation methods, the survey also generated information about adhesive and core types. Urea formaldehyde (UF), soy and polyvinyl acetate (PVA) adhesives were the most common; however, a very small percent of producers' overall adhesive usage was reported to be phenol formaldehyde. Veneer core was the most used core type, though all producers reported using MDF, particleboard and combination core as well.

Lathe-check orientation was chosen as a factor because it is commonly cited in best practices (see section 2.4.3 Best practices) and multiple studies (Cassens & Leng, 2003; Leavengood, Funck, & Reeb, 2011). However, the results of these studies differ regarding which lathe check orientation produces panels with fewer checks.

The factors and levels used in this study are listed in Table 9.

Table 9 Factors and levels. *MDF = Medium Density Fiberboard, **Combi-core = veneer core with thin MDF crossbands, ***ULEF = Ultra-low-emitting urea-formaldehyde

Factors	**No. of levels**	**Levels**
Veneer cutting method & thickness	4	Peeled-1/36”
		Peeled-1/42”
		Sliced-1/45”
		Sliced-1/50”
Lathe-check orientation	2	Tight-side out,
		Loose-side out
Core type	4	MDF*
		particleboard
		plywood
		combi-core**
Adhesive	3	ULEF***
		Soy
		Polyvinyl Acetate

As mentioned above, veneer cutting method and thickness could not be separated from one another

3.2 Check measurement method

The overall goals for creating a new check measurement method were:

1) Efficiently accommodate a large number of samples
2) Provide consistent and repeatable measurements of check characteristics such as length, width (0.2mm and wider) and count
3) Provide measurements of check severity and check development

To accomplish these goals a method to obtain check measurements based on surface strain observations gathered from digital image correlation (DIC) was created. This provided complete checking data in 10 minute intervals over a four hour testing period. This method was based on the findings from preliminary tests by Kang et al. (2011) suggesting that using surface strain maps from digital image correlation was an effective way to detect drying checks. Digital image correlation does not measure or detect checks. It provides information on individual points, and regional summary statistics from an analyzed target. Check information can be visually inferred from the graphical output (Figure 25) or calculated based on the individual point data. To investigate this possibility several tests were performed to ensure checks could be both detected and measured.

The smallest check width the method would be required to detect was 0.2 mm as determined by examining existing checks in samples provided by industry members with a scaled loupe and by examining the same samples using image manipulation software. Acquiring an estimate of check width was the primary objective of this exercise, as checks are longer than they are wide, typically. While developing a method to detect checks, our goal was to be able to detect checks as narrow as 0.2 mm.

3.2.1 Check detection proof-of-concept, apparatus

To determine if DIC would provide the required information, the ability to detect checks on panels was first tested. DIC requires two basic items: (1) prepared target item (2) and a series of images taken of the target.

The targets utilized for these proof-of-concept tests were maple veneered decorative hardwood plywood panels from a previous study. Target preparation included applying a speckle pattern on the surface of the panel, and placement of the targets for image capture. The speckle pattern is used by the DIC software to identify discrete areas of the surface, thus allowing the software to monitor and record the movements of those areas (Figure 19).

Figure 19 Speckle pattern applied to panel used for preliminary and proof-of-concept tests

To gather the image series, a monochrome digital camera (an Allied Vision Technologies Dolphin) with two megapixel resolution and a 23 mm lens was used.. Images were captured every ten minutes for a test period of 240 minutes.

The camera was mounted 1.75 m above the targets in this test apparatus (Figure 20).

In order to determine if the system could detect checks, we first had to ensure the test panels would check during examination. To induce checks panels were exposed o drying conditions somewhat more severe than those expected in indoor environments where most claims came from. Prior to these preliminary tests panels were exposed in a conditioning chamber with 30°C and 90% RH set points for at least 72 hours before testing to raise the test panel moisture content. During preliminary tests a small space heater with a fan was placed above the panels and turned to its highest setting. Temperatures reached a peak of 36.5°C and a minimum 22.1% relative humidity at the surface of the test panels.

Over the 240 minute test period 25 images were captured; one image every ten minutes, starting at minute zero. Once images were captured they were transferred to another computer for analysis with DIC software. Each image in these series is referred to as a "stage."

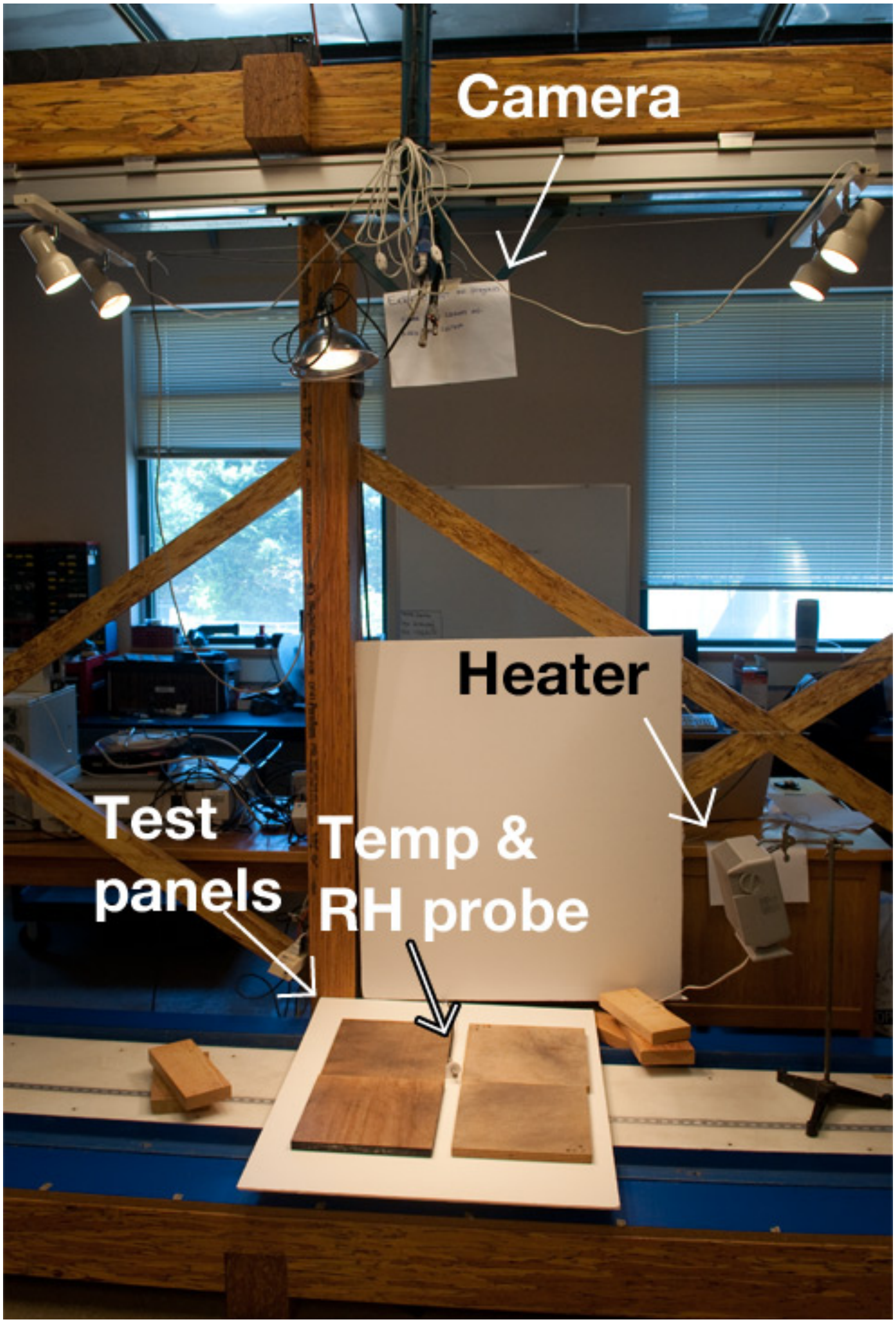

Figure 20 Apparatus for DIC proof-of-concept tests

In addition to these images, a series of five images was acquired prior to the test. These images were taken as quickly as the image capture software would allow, and are used as the basis for determining accuracy and precision of the system. This image series is referred to as the resolution series.

3.2.2 Optical measurement, proof-of-concept

The primary goal of this stage of the proof-of-concept was to determine if the camera was able to capture enough detail to allow the DIC system to detect regions of high and low strain around checks. For this project the DIC software used was ARAMIS version 5.4.3 made by GOM, mbH (GOM, mbH, 2004). This software takes a series of images – each image in the series is called a "stage" – and compares each stage in the series to the first to create a strain map.

The ARAMIS software uses a project-based paradigm, and for each project several inputs are required. Most importantly, an accurate image scale expressed in millimeter per pixel ratio is required to ensure the software returns accurate displacements. To determine this value, an image of a ruled measurement device is imaged at the same distance from the camera the test specimens will be observed from. This image is then examined in a software application that can produce a pixel measurement between two points on an image. The points are selected along the ruled measurement device at a known distance, in millimeters. The software is then used to determine the distance in pixels. From these quantities millimeter per pixel ratio is calculated. Additionally, choosing a facet and step size have a large impact on the accuracy of these measurements. These values are given in pixels, and are:

1) **Facet** is the target area, in square pixels, used to identify points between stages.
2) **Step** is the distance between centers of adjacent facets.

In order to determine the optimum values for facet size and step size, facet sizes were varied between 15 and 5, while step sizes were varied between 13 and 3. The difference between the facet size and the step size is the amount of overlap, in pixels between facets. Through trial and error the values were tested with the following criteria in mind:

1) Effectiveness. Could the combination of facet size and step accurately detect checks?
2) Precision. Were the values returned precise enough to make meaningful calculations of check characteristics such as width and length?
3) Speed. Smaller values for facet and step size lead to more computations, and therefore more time. Larger values reduce the precision of the measurements necessary for check detection.

A facet size of nine by nine pixels, and a step size of seven pixels were determined to best meet the above criteria effectively, and were the best compromise between speed and effectiveness (Figure 21).

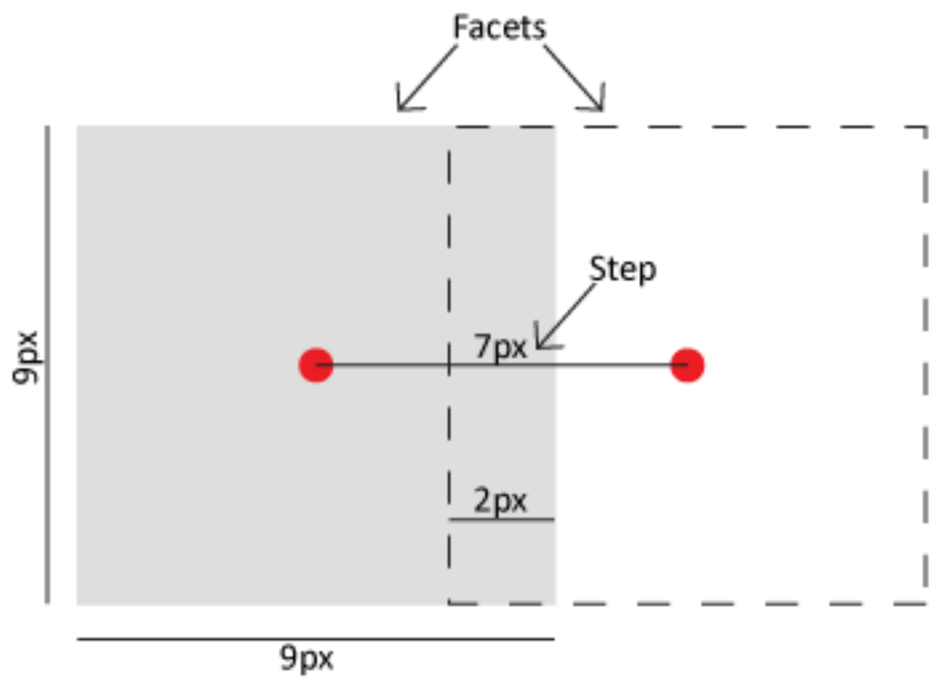

Figure 21 Facet and step size diagram for the sizes (9 and 7) used in this study. The grey box is the first facet, the dashed box is the second, and the centers are 7px, the step size, apart.

Images captured contained more than a single panel and therefore, on each panel surface an area of interest was selected within the DIC software. To do this, the operator selects the largest square area possible within a single panel. Areas less than the entire surface area of a test panel were the norm. Slight rotations in the panels were the most common cause for missing areas during selection of the area of interest (Figure 22). Exporting the information about each point provided the basis of the check measurement software.

Displacements are determined, and strains calculated for each three pixel by three pixel square in the image of the target using the strains calculated in the identified facets above. The calculated quantities describe the state of the centermost pixel of the three pixel square.

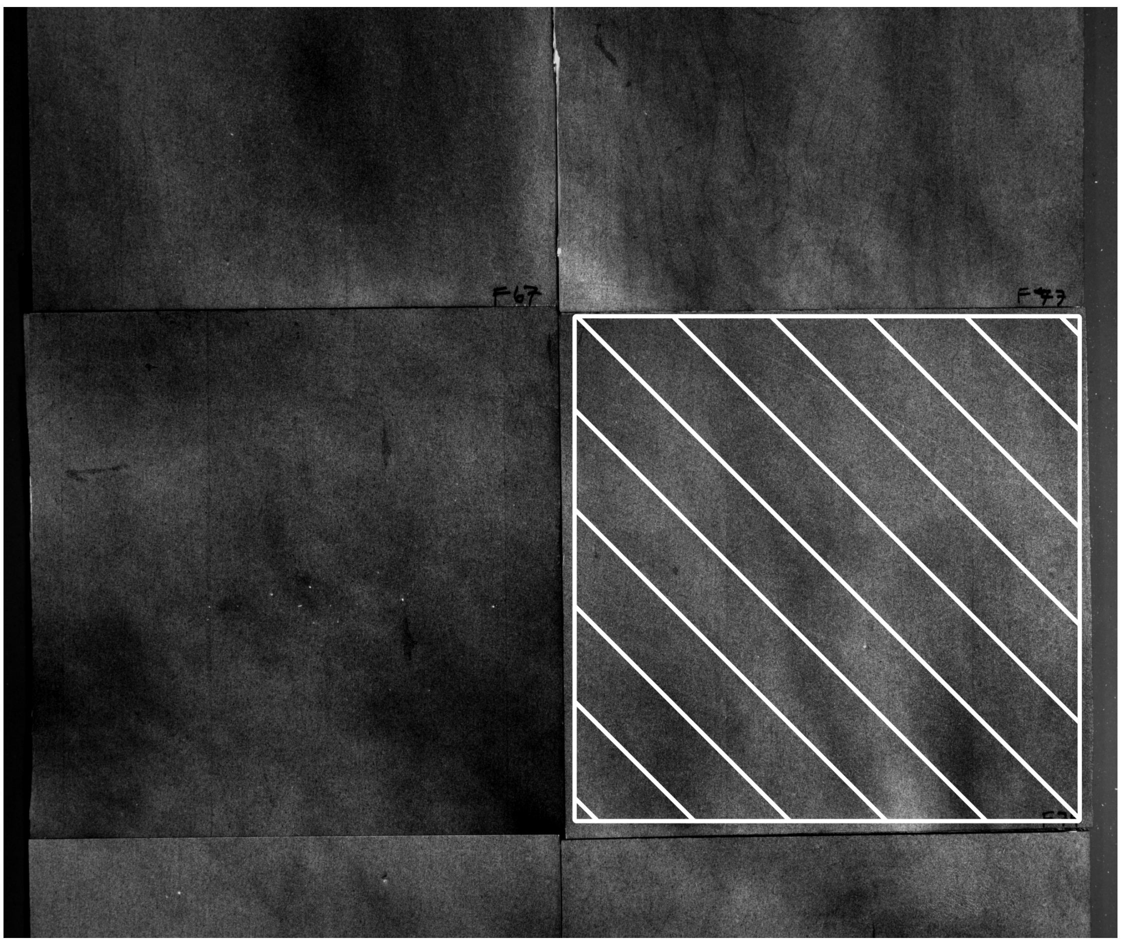

Figure 22 Example area of interest example for one sample

In order to determine the resolution of the optical measurements, a correlation is first performed on a short series of 5 to 6 images captured over a period of two seconds – a period during which no measureable deformation is expected. Figure 23 is a plot of average strain development perpendicular to the grain of the test panel measured over the region of interest (ROI). In the Cartesian coordinate system it is measured in the x direction, and is referred to as ε_{xx}. The expected value of the average ε_{xx} value calculated by the DIC software for the entire stage is zero for all stages. Therefore, the values actually measured in the area may be reasonably assumed to be noise or error. Error bars in the plot in (Figure 23) are the standard deviations of ε_{xx} for the ROI.

The calculated value of ε_{xx} is interpreted as the accuracy of the measurement, while the standard deviation is interpreted as the precision of the measurement.

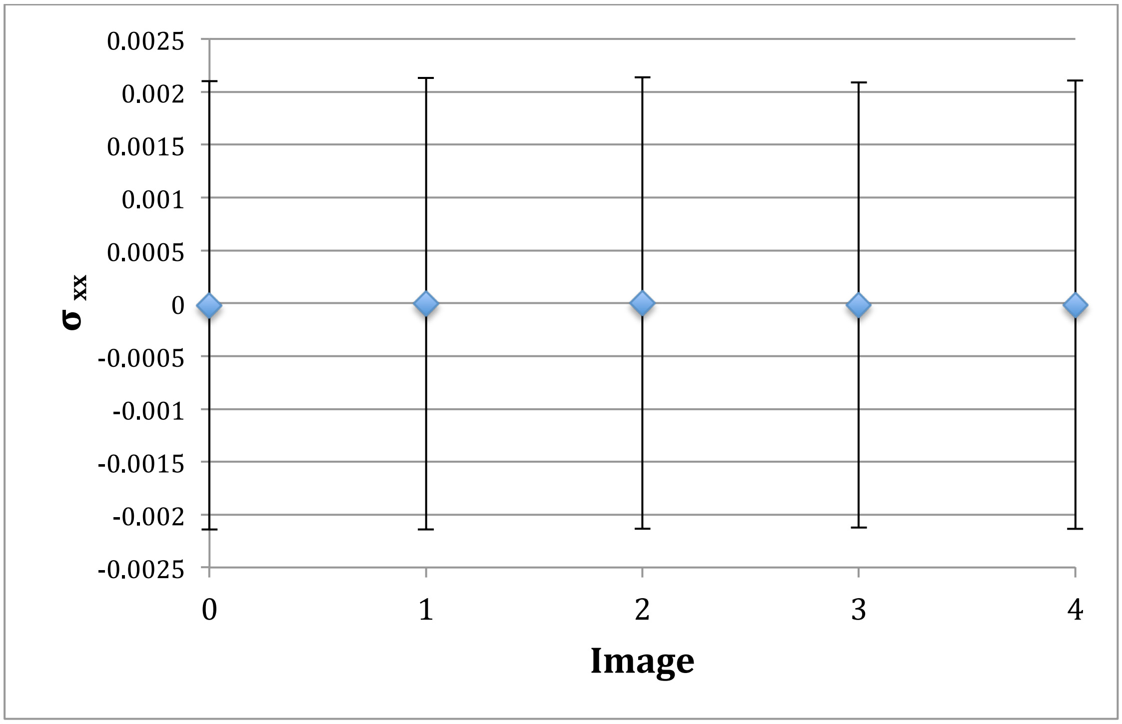

Figure 23 Plot of strain perpendicular to the grain direction (σ_{xx}) by image for resolution test. Error bars are standard deviation of strain.

In addition to strain measurements, plotting displacement calculations provides a scale of accuracy and precision expressed in mm of displacement. Figure 24 shows average displacement measurements from the DIC software, and the standard deviations of those measurements. The precision of the measurement was within +/- 0.03 mm.

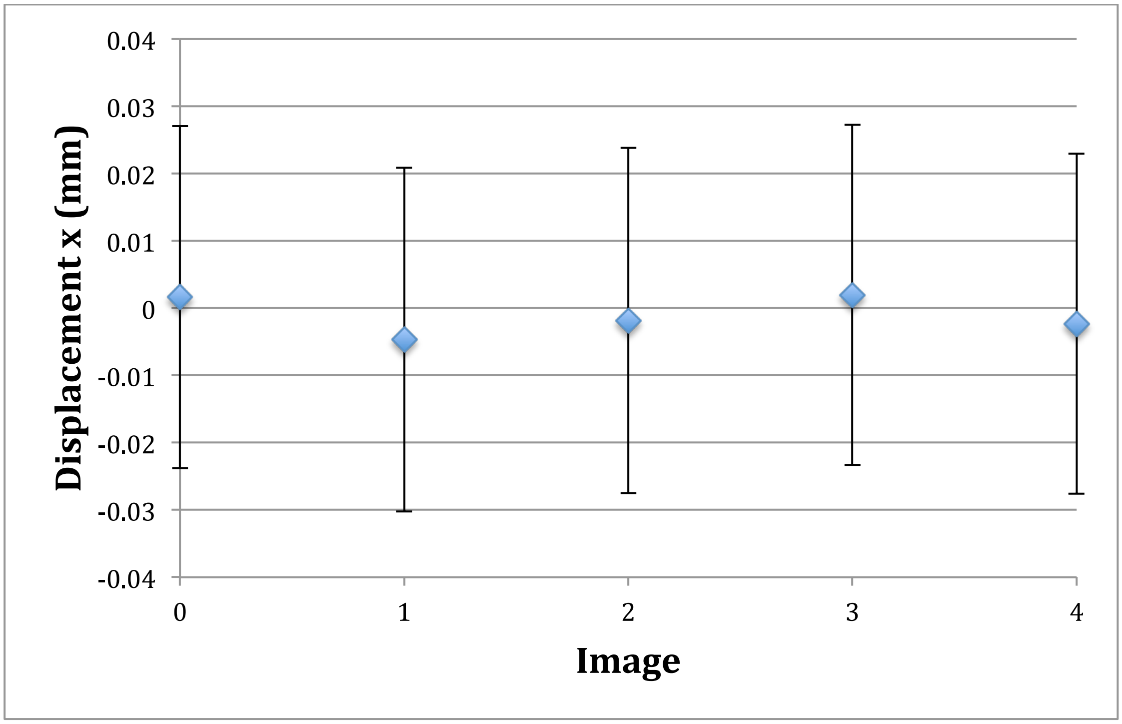

Figure 24 Plot of displacement perpendicular to the grain (mm) by image for resolution test. Error bars are standard deviation of displacement.

This value represents 15% relative to the width of the smallest checks measured manually (0.2mm), and thus was determined to be small enough to provide accurate enough measurements to adequately characterize checks.

3.2.3 Check detection

The strain map generated by the Aramis software includes generalized strain information for each stage image recorded during the course of the 240 minute test period. This strain map shows color coded strain values on a gridded coordinate system (Figure 25). This visual tool is helpful for rapidly assessing the efficacy of the image correlation, and quick determination of the state of the target in question. The narrow regions red visible in the strain map in (Figure

25) are regions of high strain – these are areas that are likely to be checks. The wide blue areas around the edges are also informative. In this case, they are areas of unrestrained shrinkage in the face veneer, where it was not well adhered to the core.

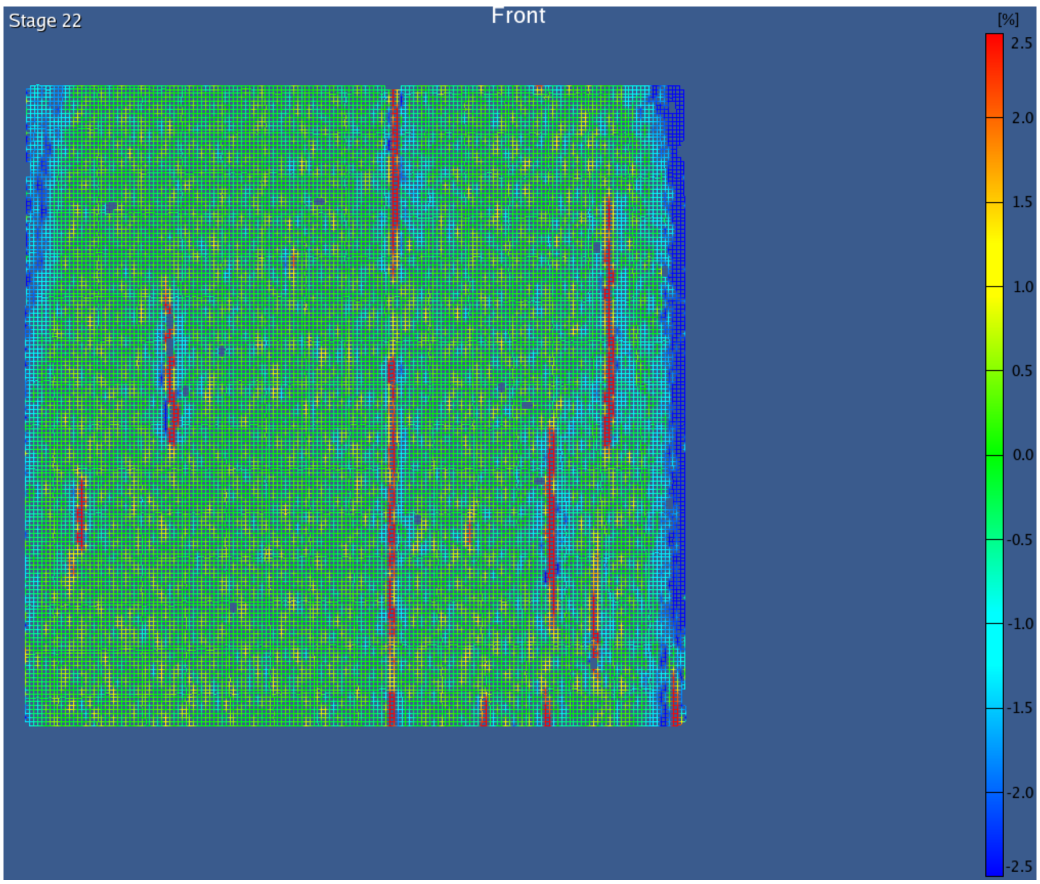

Figure 25 Strain map created by digital image correlation software of sample D-074. Red areas indicate areas of greater positive strain, while blue areas indicate areas of greater negative strain.

3.2.4 Digital image correlation processing

Once images were captured they were transferred the computer with the ARAMIS digital image correlation software. The following steps were taken to process each image:

1) Begin a new project
    a. Name project using panel identification
2) Enter relevant settings
    a. Facet size: 9
    b. Step size: 7
    c. Image scale: 0.26 mm/pixel
3) Select images
4) Select area of interest (Figure 22)
5) Select start point using software's "Auto start point" feature
6) Compute the project
7) Examine the resulting strain map
8) Export point data to a comma separated values file

This stage of the analysis was by far the most time consuming. Processing an image series for a single sample took approximately 15 minutes from step 1 through step 9.

Once an entire set of images (covering all panels tested in a single period) had been processed, the exported point data were transferred to a computer with the check characterization software.

3.2.5 From digital image correlation results to check measurements

To calculate check information, criteria for anomalous regions of high strain, the signature check characteristics in DIC output were determined. Once those regions were identified, the point data was extracted and measurements estimated. The physical specimen was then examined for comparison.

To determine the criteria used to assess if a point was part of a check, detailed information about each point was first exported from the DIC software. A text file containing stage number, x and y coordinates, x and y displacements, and x and y strain values was created for each stage of the image series analyzed. Each file contained one row of information for each point data. An average file contained about 25,000 lines of data. These text files were parsed then inserted into a MySQL database (version 5.1.45) so the data could be stored and rapidly analyzed.

The check characterization software automatically performed its analysis by checking each night at midnight for a new set of files to process. If new files were present the software would first parse the files and insert them into the database, then it would perform check analysis. The results of the check analysis were stored in the database, where they could later be accessed for statistical analysis.

The first goal of this analysis was to determine how to isolate the data points containing useful information about checks. Querying the database of points for those with various strain values (e.g. all points with greater than 2.5% strain) provided a list of points that could be further examined to determine if there was a check and how to form a measurement of the check. Once these data were acquired a quick analysis was needed to ensure the right data were being examined. To do this, a visual tool was created which allowed for quick assessment of the selected points. This tool allowed for comparisons to the strain map (Figure 25) returned by the DIC software and provided a quick means of assessing if checks were present, and where they were located on the actual panel (Figure 26).

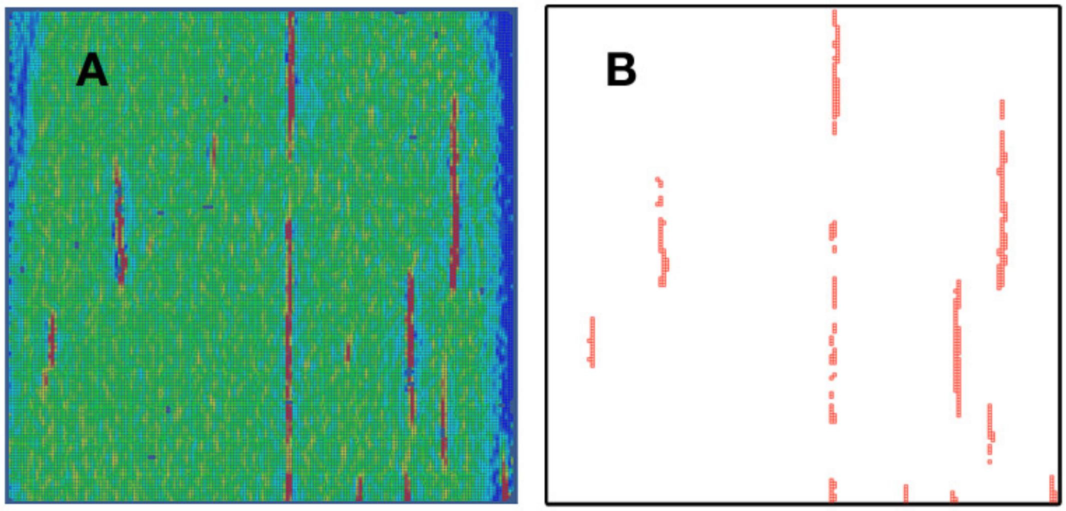

Figure 26 DIC strain map (A) and visual assessment tool (B) created for the project to rapidly assess point selection of check detection algorithm.

In addition to comparing the DIC strain map to the image of the selected points, the actual specimen was examined to ensure checks weren't missed or falsely identified.

Once the point selection criteria was assessed and narrowed using these tools, a custom algorithm was written in the hypertext pre-processor language (PHP). The algorithm examined all stages of each image series for each sample, calculated and stored check development, and characterization information for each sample. The algorithm followed these steps:

1) Identify a single point of high strain (i.e. greater than 2.5%)
2) Examine neighboring points along the x-axis (perpendicular to the grain), these were not always immediate neighbors
3) Recognize nearby points that:

i. Have negative strain values (as in pattern A in Figure 27)
ii. Have strain very close to zero (as in pattern B in Figure 27)
iii. Have very small positive strain values (as in pattern C in Figure 27)

4) Use recognized points to extract displacement values for width measurements (Figure 28)
5) Ensure integrity of data by checking nearby data for blank spots – areas for which data could not be calculated in the DIC analysis
6) Use displacement data of the identified point to determine width of the check
7) Use contiguous points along the y-axis to determine length of the check
   i. Use "smoothing" algorithm to extend check length between non-contiguous points with points of strain under the threshold for check characterization, but high enough to connect to nearby points (less than a millimeter apart, along the y-axis and meeting reduced strain requirements).
8) Use breaks in continuity along both the x and the y-axis to count individual checks
9) Use all of this information to calculate aggregate check information (Table 10) for each stage
10) Store this information in the MySQL database

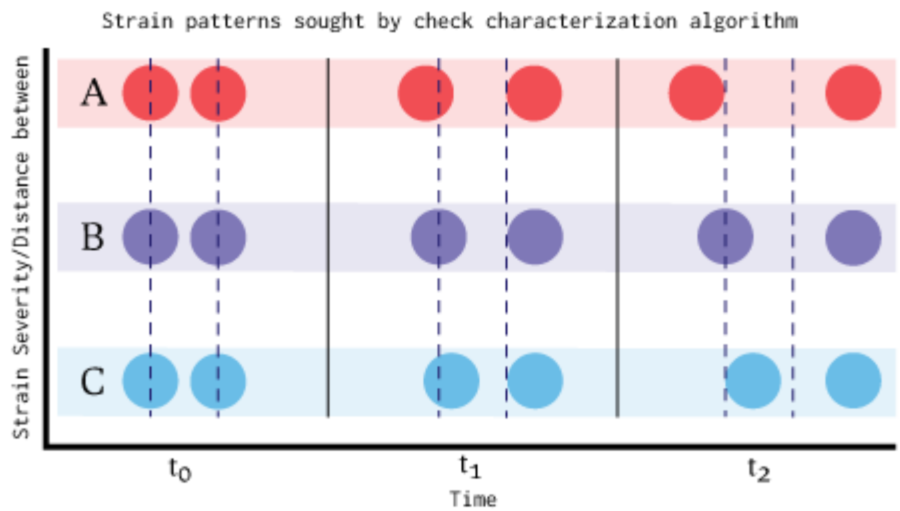

Figure 27 Strain pattern development sought by the check analysis software developed for this study.

Table 10 Values calculated and recorded by check detection and characterization algorithm and their descriptions

Recorded Value	**Description**
Total Check Area	The calculated area of all checks detected
Biggest check	The check with the greatest area
Longest check	The check with the greatest length
Widest check	The check with the greatest width
Total Area	Area examined for checks
Total Check Length	Sum of lengths for all checks detected
Average Check Area	The average area for all checks detected
Average Check Width	The average width of all checks detected
Average Check Length	The average length of all checks detected
Check Density	Total check area divided by area of the region of interest
Check Count	The number of checks detected

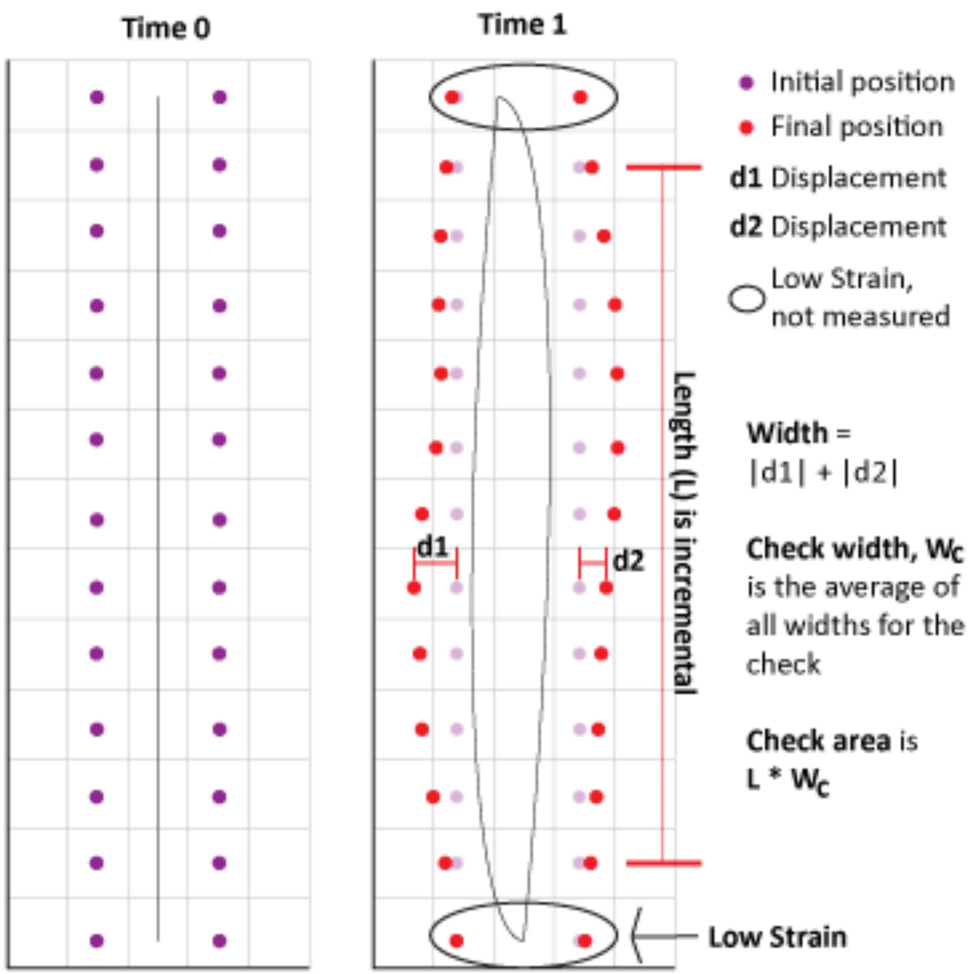

Figure 28 Diagram of individual check measurement performed by software developed for this project

3.2.6 Developing a comparison value

A value to compare between experimental units was required. Previous research utilized check counts. While simple to achieve, counting doesn't necessarily indicate the intensity of checks a panel develops. Additionally, check counts may vary even within small fluctuations in sample size, making comparisons between samples troublesome. To best describe checking intensity, and overcome the issues with area variations between samples this study examines check density (CD): the total area of detected check on a panel (A_{ck}) divided by the area of the region of interest (A_{ROI}) on a sample (Eq. 4).

$$CD = \frac{A_{ck}}{A_{ROI}} \left[\frac{mm^2}{mm^2}\right] \qquad \text{Eq. 4}$$

3.3 Experimental design

The complexity in handling, producing, testing and evaluating a study of this scope requires a well-designed experiment, which limits the interference of nuisance factors. Designed experiments help ensure the observed responses of tests are attributable to the factors being studied. The following constraints provide the foundation for a valid and objective designed experiment:

1) All factors levels must be independent from one another
2) Treatments must be assigned randomly to experimental units
3) True and sufficient replication must occur. A true replication is the independent application of the treatment or protocol to an experimental unit.

Factors levels are independent in an experiment when they are not confounded with levels of another factor. For example, in this experiment, the application of lathe check orientation does not influence the application of which core type was used. In this experiment, veneer thickness is confounded with preparation method (peeling or slicing). This means that veneer thickness could not be considered separately from preparation method, therefore these factors are combined and considered as one factor: veneer type.

Random assignment means that each experiment unit has some known (or knowable) probability of receiving a particular treatment. In this experiment the assignment of each level of each factor to each sample was done randomly. For example, the random assignment of factor levels to sample F-049 was 1/36″ face veneer placed loose side out on particleboard core using soy adhesive. The particular veneer, and core were chosen randomly from the available stock.

Replication is the repetition of the basic experiment (Montgomery, 1997). In this case, producing and testing each complete set of treatments eight times.

The experiment in this study was a randomized block split-plot factor screening design. The split-plot design is used when one factor must be assigned to larger experimental units than others (Montgomery, 1997). The factors that must be assigned to larger experimental units are referred to as whole plots, while the remaining factors are split plots. In this experiment, the whole plot factor was adhesive because each type of adhesive (level of the adhesive factor) was produced and applied to a set of samples. The split plots where combinations of the remaining factors (core type, veneer type, and lathe check orientation) and were applied to individual sample panels.

The specimens were also prepared and observed in blocks. Blocking allows the effects of nuisance factors – those factors that may have an effect on the response, but that are not being studied – to be systematically eliminated from statistical comparisons (Montgomery, 1997). When nuisance factors are known and controllable, such as environmental differences between panel preparation cycles, blocking is an effective method for removing their effect from analysis.

Factor screening experiments allow researchers to detect differences in response changes between levels of individual factors, or when factors and their levels are changed together (Montgomery, 1997). For example, this factor screening experiment was able to detect statistically significant differences in changes in core types, and differences occurring when core type and adhesive type are changed together. In this experiment, statistically significant differences between treatments for main effects, two-way, three-way and four-way interactions are possible to detect.

3.3.1 Treatments and replicates

Ninety-six combinations of four factors (a 4x4.3.2 factorial arrangement) were examined in this study. Eight replicates of each adhesive combination were made. Each set of replicates was produced in a block, allowing environmental factors affecting the observed responses to be eliminated from the results. Table 11 lists each factor and factor combination, number of treatments including those factor combinations and the observations per treatment in each block. There were 8 blocks, and therefore 8 replicates for complete treatment combination (e.g. combination of level of each factor).

Table 11 Factor combinations, treatments per combination and observations per treatment in each block. * The average of checking values for all 32 panels made with a single adhesive type constituted an "observation"

Factors, and factor combinations	**No. of treatments**	**Observations per treatment per block**
Veneer type	4	24
Core type	4	24
Adhesive	3	3*
Lathe check orientation	2	48
Veneer type x core type	16	6
Veneer type x adhesive	12	8
Veneer type x lathe checks	8	12
Core type x adhesive	12	8
Core type x lathe checks	8	12
Adhesive x lathe checks	6	16
Veneer type x core type x adhesive	48	2
Veneer type x core type x lathe checks	32	3
Core type x adhesive x lathe checks	24	4
Veneer type x core type x adhesive x lathe checks	96	1

3.3.2 Whole plot and split plot factors

The UF and soy-based adhesives were limited to small batch preparation because of their short pot lives (see section 2.2.3.3 Adhesive properties). This complication required the use of the split-plot design. Therefore adhesive was the whole plot factor, while core, lathe-check orientation and face veneer were split plot factors. Figure 29 illustrates the production of a single block. The colored sections marked "Soy," "UF," and "PVA" represents all 32 combinations for each adhesive, and together comprise the experimental unit (EU) for that adhesive. Each rectangle in the grid within the colored sections represents a single combination of factors using a particular adhesive. The individual rectangles within the colored regions represent a single EU for the remaining factors (core, lathe-check orientation and veneer).

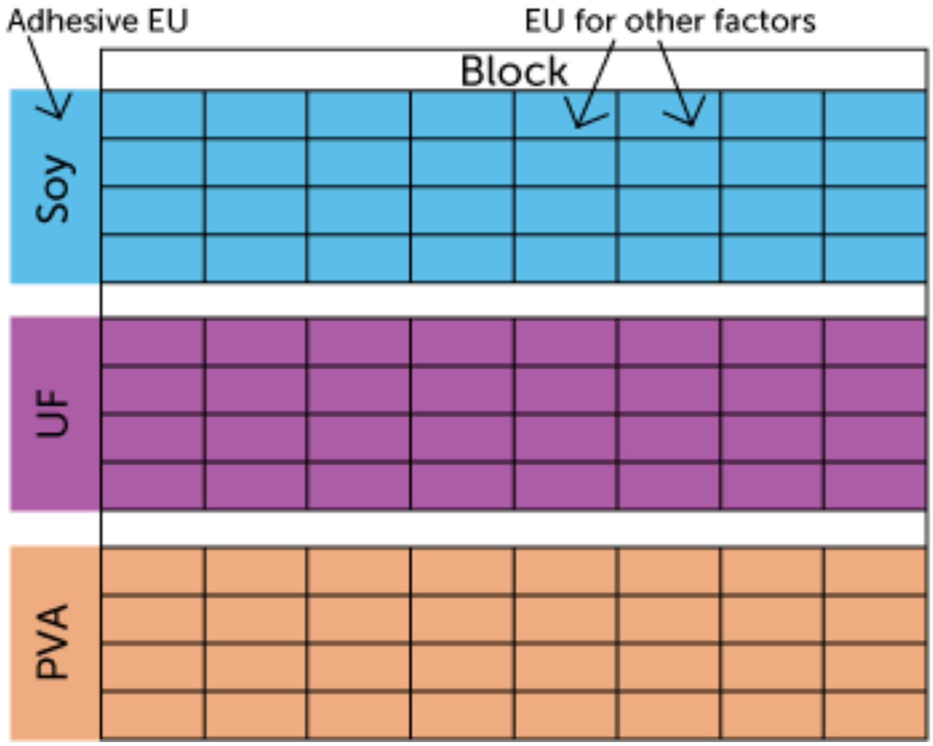

Figure 29 Split plot design. Adhesives are the whole plot factor, and the color stripes associated with Soy, UF and PVA are the experimental units (EU's) for each adhesive, while the smaller rectangles represent the EUs for all other factors.

All 32 combinations of factors for a single adhesive type were created in a single batch followed by all 32 combinations of another adhesive type and so on. In a single day of production all 96 combinations of factors were produced, constituting a block.

3.3.3 Randomization

A computer program was used to randomly determine the assignment of each adhesive to the set of samples used within each block. Similarly, a computer program randomized the remaining factor combinations within each adhesive group (see Appendix 7 Randomization script).

For example, the computer program chose urea-formaldehyde as the first adhesive for block “A”. The researchers, therefore, mixed the adhesive then all 32 combinations of the factors using that adhesive. The order of panel production was according to pre-determined randomized order as laid out by the randomization script. The researchers would then move on to the next adhesive for block “A” and produce all of the panels with that adhesive. Table 12 contains the adhesive order for each block. A sample of the production sheet specifying randomized factor order can be found in

5. Sample production sheet.

Table 12 Adhesive order for each block of samples

Block	**Adhesive 1**	**Adhesive 2**	**Adhesive 3**
A	UF	Soy	PVA
B	UF	Soy	PVA
C	PVA	Soy	UF
D	Soy	PVA	UF
E	PVA	UF	Soy
F	PVA	Soy	UF
G	Soy	UF	PVA
H	Soy	PVA	UF

3.3.4 Experimental Units

An experimental unit is the smallest amount of experimental material to which a treatment could have been assigned. Usually one observation (data point) is collected from each experimental unit for comparison in statistical analysis. Due to the split-plot design of this experiment adhesives have a different experimental unit than do other factors being studied. The observation used for the experimental unit of "adhesive" is the average check density of all 32 test panels created within each adhesive group of each block. That is, the value used for statistical analysis of the Soy adhesive is the mean check density of all 32 panels in the group adhesive 1 in blocks “D”, “G”, and “H”, adhesive 2 in blocks, “A”, “B”, “C”, and “F” and adhesive 3 in block “E” (Table 12).

The experimental units for all other factors are derived from the check density observed in the individual panels.

Experimental units vary based on the interaction with other factors for complex and mixed effects (Table 11). A two-way interaction, for example between lathe-check orientation and core type has for its experimental unit all combinations of each lathe-check orientation with each core types. That is, all tight side out veneers on particleboard represent the experiment unit for that combination. There are four veneer types and 3 adhesives in this study, which means 12 observations, will be used for each lathe-check orientation within each block as experimental units for the two-way interaction between core and lathe-check orientation.

3.3.5 Statistical analysis

3.3.5.1 Structure of observed data

The structure of the data collected falls into two categories. First, the number of checks present on a given test specimen were recorded. These data are discrete counts. Second, the check density was recorded, which is a continuous number. Many panels did not check, causing a significant number of zero values to be present in both the check count data and the check density data. Additionally, the observed, non-zero check density data were heavily skewed near the origin with a long right tail (Figure 30). The presence of zeroes and skewed distribution of observed positive values cannot be approximated by the normal distribution. Therefore, traditional analytical methods such as analysis of variance, which assume a normal distribution, are not appropriate.

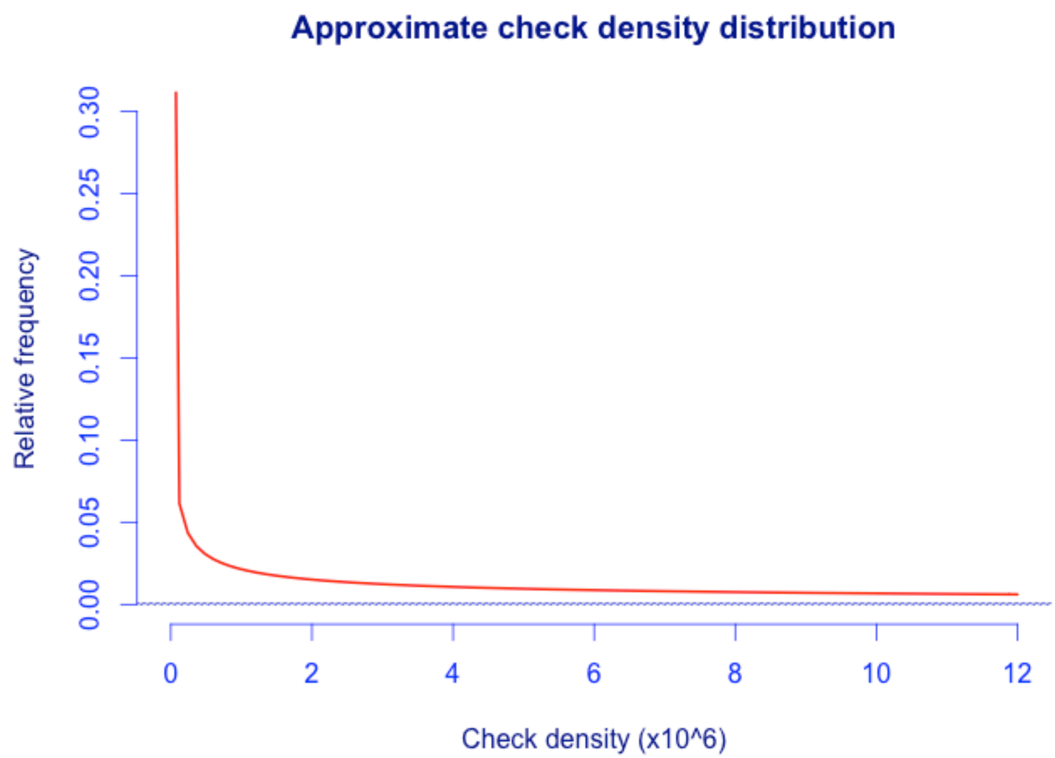

Figure 30 Check density fit to a gamma distribution.

3.3.5.2 Random effects and mixed models

The inclusion of blocking and implementation of the split-plot design used in the experiment required including both the blocking effect and the whole plot effect in the statistical models used to predict means for each treatment. When both fixed effects (e.g. veneer type, core type) and random effects are included in a statistical model, the model is referred to as a "mixed model."

3.3.5.3 Tweedie compound Poisson distribution

Suppose X, the number of checks on a sample, is Poisson distributed random variable with mean λ (Eq. 5):

$$X \sim Pois(\lambda); \qquad X = 0,1,2,3,4, \dots \qquad \text{Eq. 5}$$

and that the area of one check, Y_i, is a Gamma random variable with mean α and variance $\alpha\beta^2$ (Eq. 6):

$$Y_i \sim \; Ga(\alpha\beta), \qquad for\; Y > 0; \qquad \text{Eq. 6}$$

Then the check density (CD) (proportional to the total check area) has a Tweedie compound Poisson distribution if X is independent from Y_i (Eq. 7)(Zhang, 2012).

$$CD \sim \; \sum_{i=1}^{X} Y_i\,, \qquad (X \perp Y_i) \qquad \text{Eq. 7}$$

Actuarial science, rainfall modeling, and ecological studies have been cited as examples where the compound Poisson distribution is a useful predictive model (Dunn & Smyth, 2005; Zhang, 2012). The Tweedie compound Poisson distribution is an exponential dispersion model where the variance is proportional to the mean raised to a power (Jorgensen, 1987; Dunn & Smyth, 2005; Zhang, 2012).

For example, in a rainfall study, X is the number of rain events in a period, where Y_i is the intensity of rain for a given rain event then the total rainfall has a Tweedie compound Poisson distribution (Zhang, 2012).

3.3.5.4 Statistical software

The statistical software program R (version 2.15.2) was used for model fitting, chart generation and analysis (R Core Team, 2012). Additionally, the cplm package (version 0.6-4) was used for fitting the compound Poisson generalized linear mixed model (Zhang, 2012). The gamlss package (version 4.2-0) was used for fitting and plotting the Gamma distribution of check density (Stasinopoulos, Rigby, & Akantziliotou, 2012). Some plotting was accomplished using the helpful tools in the R package, ggplot2 (version 0.9.2.1) (Wickham, 2009).

3.3.5.5 Model fitting

The check count data were fit to a Poisson distribution with check counts truncated at 10 or more. The count was truncated to 10 or more, because of the presence of 0 incidences for 11 and 12 checks with one incidence of 13 checks. Therefore, the one occurrence of 13 checks was combined with the occurrences of 10 checks and designated 10 or more checks. The positive check density values were scaled (effectively converting the value from mm^2/mm^2 to mm^2/m^2), and then transformed by applying the natural logarithm to the observed positive check densities to demonstrate the fit of the gamma distribution. The resulting fit is shown in Figure 31 and Figure Figure 32.

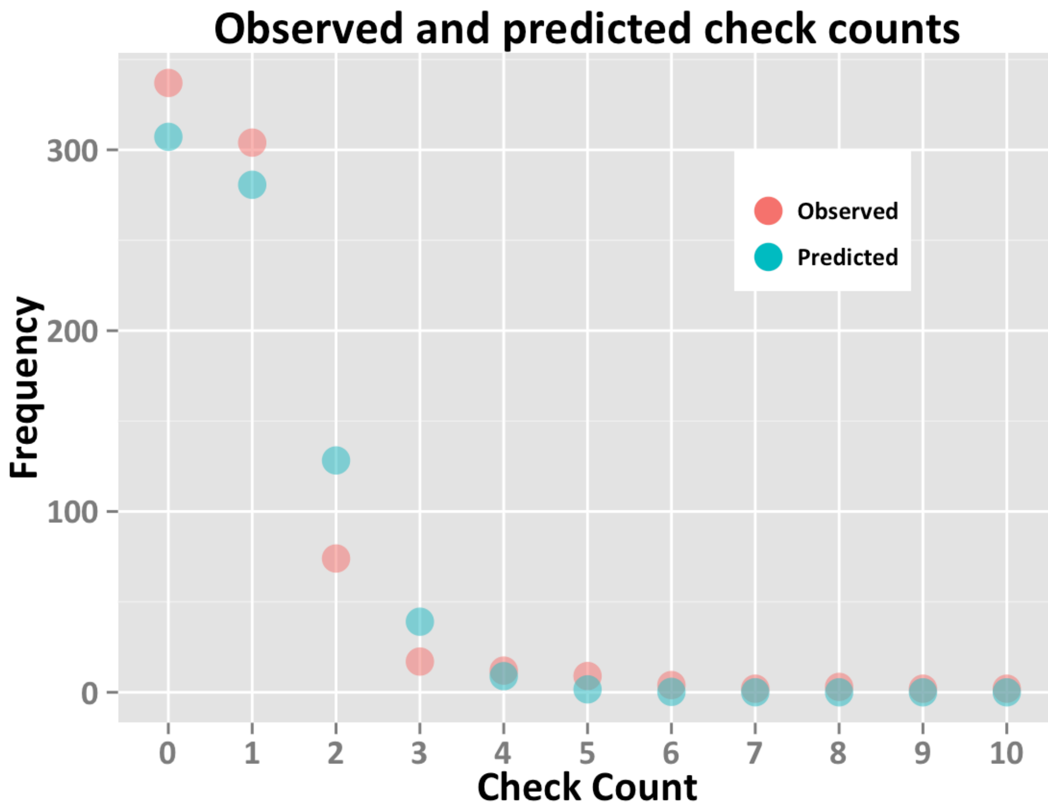

Figure 31 Check count fit to a Poisson distribution

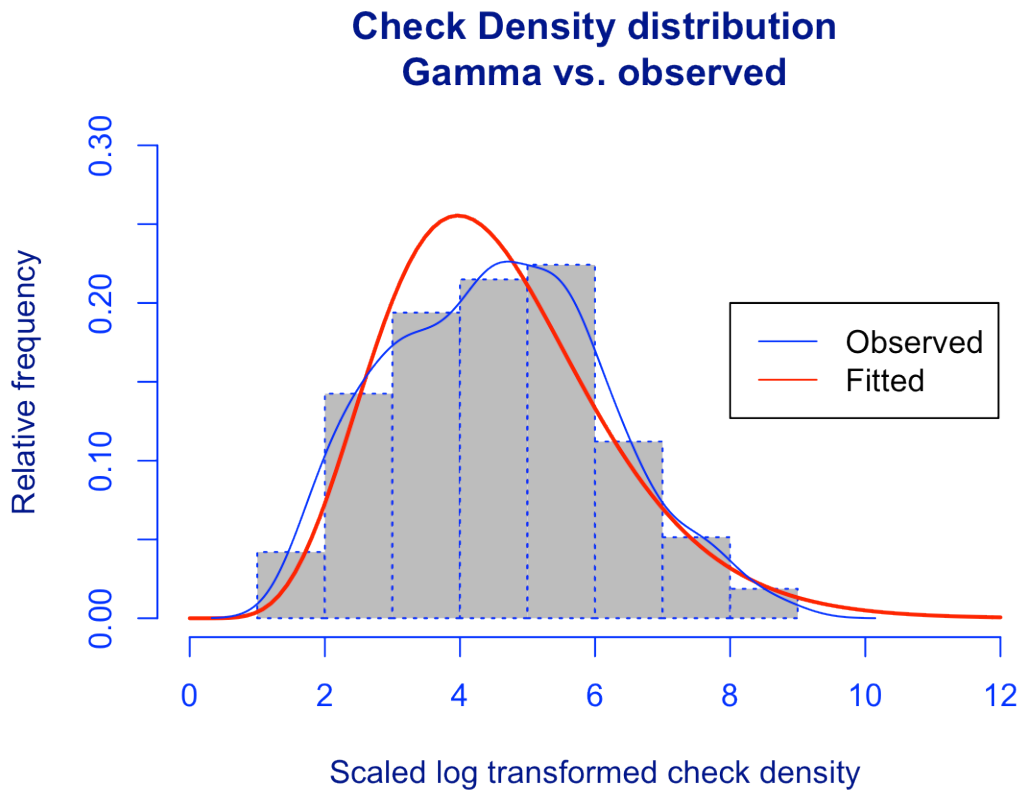

Figure 32 Histogram of positive log transformed check density with fit gamma distribution

Additionally, because the data were transformed before fitting the statistical model, back-transformed predicted treatment means and their confidence intervals are presented in the results. Standard errors cannot be back transformed; they are only meaningful when applied to their respective mean value. However, standard errors are presented in Appendix 8 along with the predicted means and associated confidence intervals on the log scale.

3.4 Material acquisition

An industry member working for a cooperating company and member of the WHPP volunteered to organize material acquisition. Industry members who donated the materials cut cores and veneers to size (12 inch by 12 inch, 30.5 cm by 30.5 cm) prior to shipping the products to Oregon State University. Veneer suppliers labeled the tight side and the loose sides of each veneer specimen on two out of four veneer types. The researchers examined and labeled the remaining veneers as described in section 3.4.1.

A regional adhesive supplier donated the PVA and UF adhesives. A cooperating industry company supplied the soy-based adhesive. The soy and PVA adhesives were supplied premixed, while the UF was mixed before each use. The soy-based adhesive and PVA adhesive used in this study are thermoplastic, while the ultra-low-emitting urea-formaldehyde adhesive is a thermoset.

For this study, "blanks," or pre-made cores, were used to reduce variability during production and to mimic a common practice within the industry.

3.4.1 Determining tight- and loose-side of the veneer

Though all veneers were supposed to have labels identifying the tight or loose side, half of those received were unlabeled. The researchers, therefore, were required to label the unlabeled veneers.

To determine the tight and loose side of the veneers, multiple methods were examined. The "tape test" (Cassens & Leng, 2003) was inconclusive and on multiple occasions damaged the veneer. A tactile approach was determined to provide the most reliable results. In order to be sure the proper side was labeled, 16 unlabeled samples were selected at random and numbered. Four researchers examined the veneers and wrote down which side of the veneer was numbered. The smoother of the two sides was marked "T" for tight; the rougher side was marked "L" for loose. Researchers had 85% agreement on first inspection and 100% agreement after a second inspection.

Following this exercise, the unlabeled veneers were examined and labeled appropriately.

3.5 Panel production

Panels comprised of all 96 combinations of factors described in Table 11 were produced in one day, for each of the eight blocks. The 96 treatments were split into three groups, one for each adhesive used, and all 32 treatments for using that adhesive were produced before switching to the next adhesive. A sample production sheet for one adhesive set within a block is included in Appendix 5 Sample production sheet.

Lab panel production used the following process:

1) Prepare each adhesive and load the spreader

   a. The soy adhesive experienced shear thickening and required mixing using the lab mixer (DITO EM 10) prior to loading the spreader
   b. The UF adhesive was prepared and mixed according to manufacturer instructions (section 3.5.1 Urea-formaldehyde adhesive preparation)
   c. The PVA adhesive was premixed, and only required loading into the spreader

2) Select cores for four samples
3) Label each core with the sample identification scheme (e.g. A-064, "block – sample number")
4) Weigh each core and record its weight
5) Apply glue using a glue spreader, targeting a spread rate of 15.9 g per panel (+/- 0.4 g) (35 lbs. / 1000 sq. ft. sgl)
6) Weigh core with adhesive to determine amount of glue applied
   a. Confirm adhesive is within acceptable range of the target spread rate. If not, apply more or remove adhesive using a spackle knife.
   b. Confirm even adhesive cover of core – correct if needed using spackle knife
   c. Record final weight.
7) Select veneer and apply with appropriate lathe check orientation.

8) Place in pre-press (or, cold press, a CP SPX 55T ECN Press 1851) for approximately 5-7 minutes
9) Place in hot press (Clifton Hydraulic Press 1500) under 0.93 GPa pressure with top platen heated to 113° C.
10) Remove from press and allow to cool in the laboratory until all panels were pressed and labeled
11) Label face veneer side with sample identification from core
12) Move samples to conditioning chamber with 21 ° C temperature set point, and 65% relative humidity set point (wood EMC of approximately 12.0%)
13) Apply speckle pattern to samples (e.g. a light spray paint layer)
14) At 24 hours before samples are to be tested and after at least 72 hours in the 12.0% conditioning chamber, move samples to the hot/wet conditioning chamber with 30° C temperature set point and 90% relative humidity set point (wood EMC of approximately 18.8%).

All adhesives were spread at a target rate of 15.9 g (+/- .4g) per glue line. This rate was recommended by a cooperating industry member, and was based on that company's production spread rates (Anonymous, 2012).

Panels were produced unbalanced – without a back veneer – because it was believed this might increase check severity based on the literature review (Forbes, 1997; Schramm, 2003; Christiansen & Knaebe, 2004).

Test panels made in addition to those being observed for checking data were produced and tested for moisture content by ASTM Standard D4442 method A to confirm the MC of the panels prior to and after testing. This method is for solid wood, and composite materials such as decorative hardwood plywood panels may have different moisture contents than calculated by these methods. Using this method yielded an average moisture content of 10.8% for panels that had been through the conditioning cycle listed in steps 12 and 13 above.

A random speckle pattern (a combination of white and black colored acrylic matte spray paint) was applied to all panels before being moved to the hot/wet climate chamber.

3.5.1 Urea-formaldehyde adhesive preparation

The urea-formaldehyde was supplied in its component parts because of its short pot-life once mixed. The components were, not including water:

1. Urea-formaldehyde suspension
2. Wheat flour (a filler)
3. Citric acid (for pH balance)
4. Ammonium chloride (a catalyst)

The mixing ratios by percent and weight, along with the mixing procedure are found in Appendix 6.

3.5.2 Destroyed Samples

During panel conditioning, 15 samples from the PVA adhesive group in block "B" were destroyed due to a leaky pipe in the conditioning chamber, which leaked water on to the samples (see list and images of damages in Appendix 3 Destroyed samples).

For blocking and replication integrity it would have been ideal to reproduce all 96 panels for block "B." However, due to the quantity of materials and time required to reproduce the entire block, only the 32 samples from the PVA adhesive group within block "B" were reproduced during the following PVA production cycle; this was during production of block "F." These reproduced samples were considered to be part of the original block for statistical analysis.

3.5.3 Material Shortages

On two occasions material shortages caused interruptions to the production process. Both combination core and 1/36" peeled veneer supplies were depleted prior to starting production for block "F." In the case of the combination core, the actual amount donated by the vendor was not the quantity described when the materials were received. The veneer shortage was not noticed because they were miscounted when they arrived. New materials were immediately ordered and were picked up nine days later. Production began again after the materials were allowed to acclimate in the lab for three days.

Additionally, due to defective 1/50" sliced veneers, two specimens were not made. These were samples, H-94 and H-96 which were:

> H-94: 1/50th sliced veneer, loose side out, particleboard core, urea formaldehyde adhesive.
>
> H-95: 1/50th sliced veneer, tight side out, MDF core, urea formaldehyde adhesive.

These were the final two combinations using 1/50th sliced veneer as their face material.

3.5.4 Adhesive spread rate analysis

To ensure consistency and provide an opportunity to check if adhesive spread rate influenced check severity and development, adhesive spread rate was recorded for each panel produced. The mean, standard deviation, minimum and maximum values for spread rates in grams are grouped by block are listed in Table 13. The spread rates for individual panels are available in Appendix 12 CD-ROM Attachments. Final weights were not recorded for seven panels in addition to the two panels not made because of material shortages. Consequently, the statistics below do not reflect their values.

Table 13 Adhesive spread rates in grams by block with total summary statistics.

Block	**No. of specimens**	**Mean**	**Std. Dev.**	**Min**	**Max**
A	94	16.00	1.26	14.52	27.03
B	93	15.72	1.73	11.50	20.20
C	96	15.77	1.87	5.66	23.25
D	96	15.71	1.14	11.04	18.28
E	96	15.91	0.84	13.47	17.75
F	95	15.94	0.91	14.48	21.20
G	95	16.01	0.84	14.07	17.73
H	94	16.18	1.11	13.34	22.90
Total	**759**	**15.91**	**1.28**	**5.66**	**27.03**

Figure 33 illustrates the variability of adhesive spread rate distributions by block in a box-and-whiskers diagram (or, boxplot). Such a diagram indicates the median value with the thick black line in the middle of the box, the top end of the box is the upper quartile (75^{th} percentile), and the top whisker is the maximum, excluding outliers. The bottom end of the box is the lower quartile (25^{th} percentile), and the lower whisker is the minimum, excluding outliers. Outliers are the circles outside of the box-and-whisker portion of the diagram.

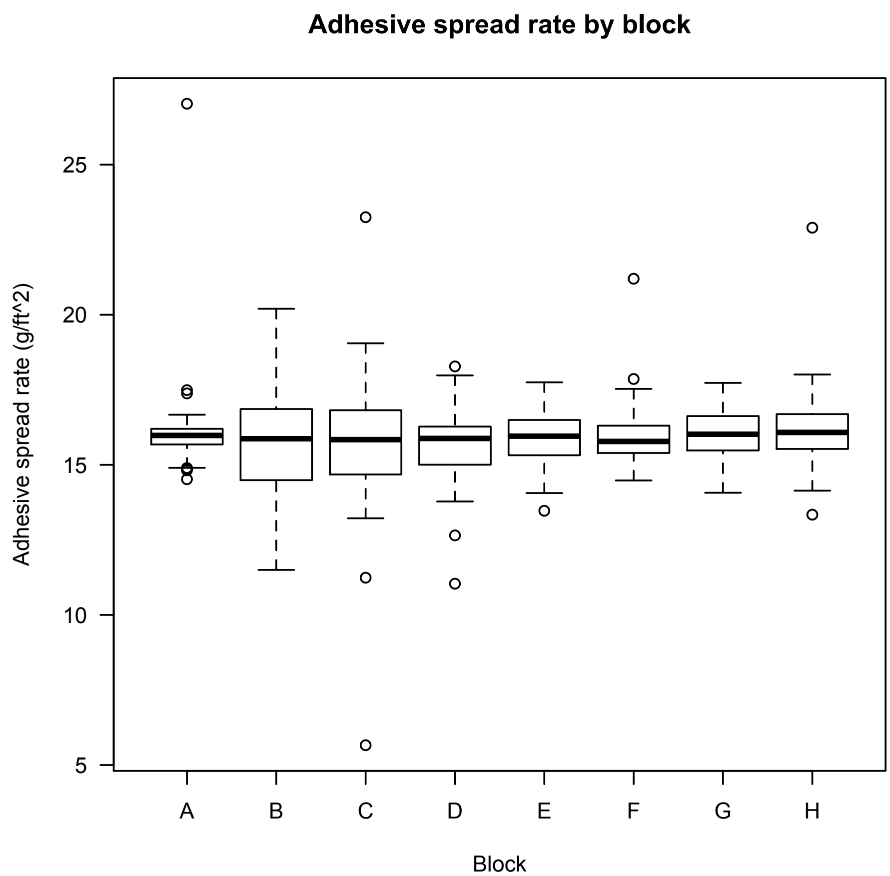

Figure 33 Adhesive spread rate by boxplot revealing differences between block. Extreme outliers (27.03 on the upper end and 5.66 on the lower end) are likely mistakes in recording the values, probably from recording the 10's digit incorrectly during production.

Boxplots of adhesive spread rate by factor levels are included below (Figure 34) illustrating mean spread rate was within the targeted range of 15.9 g/ (+/- 0.4 g), for all blocks and factors except for core type, which had two levels outside of the target rate. The mean adhesive spread rate for particleboard was 15.41 g, nearly

0.1 g below the targeted range. The mean adhesive spread rate for veneer, however, was 16.47 g, nearly 0.2 g above the targeted range (Figure 34). These are not considered to be significantly out of line. The spread rate for each panel is recorded and therefore, those panels with values outside the target range were examined for abnormal checking behavior that may be attributed to these spread rates (see Appendix 12 CD-ROM Attachments). No correlation between check density and spread rate was determined to exist.

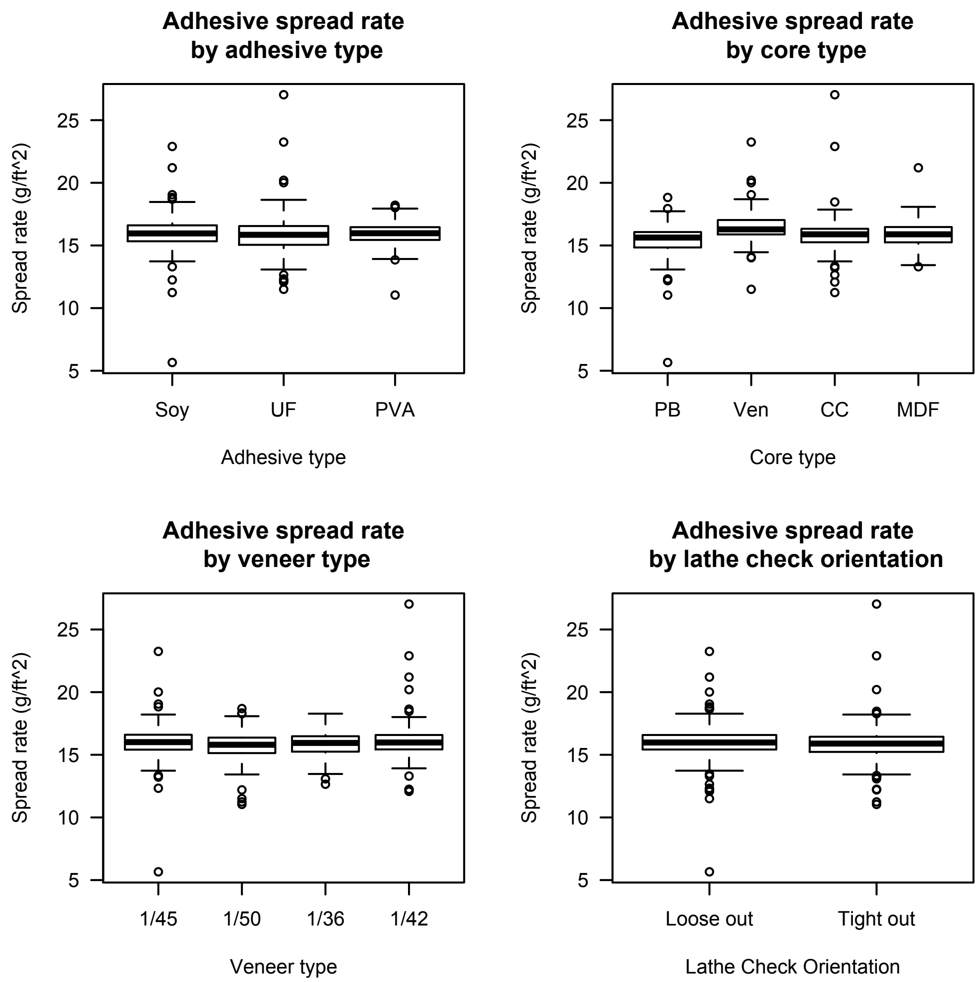

Figure 34 Boxplots showing variation in adhesive spread rate by adhesive type, core type, veneer type and lathe check orientation

3.5.5 Face veneer orientation

Face veneer orientation is an important aspect of decorative hardwood plywood panel manufacturing as noted in section 2.2.4. Pressing panels. Face veneers applied to veneer core were parallel laminated, counter to common industry practice. The likely implication of this error is increased checking for the panels with veneer core.

3.6 Apparatus, data collection and processing

With the method for characterizing check development and severity established, a means to apply that method to many specimens was required. Additionally, a test environment designed to help isolate the samples from the changing environmental conditions in the laboratory was built. Not only did this test environment regulate environmental conditions between tests, it allowed us to create a harsh environment for the samples increasing the likelihood they would check.

3.6.1 Automation of image capture using track system

In order to rapidly test as many samples as quickly as possible, a track-mounted camera was employed. The track system allowed the camera to be moved above a collection of samples so each pair of side-by-side samples could be imaged simultaneously (Figure 22). Track position and panel identification were recorded to aid with digital image correlation processing (Figure 35).

The camera used during testing was a Point Grey Research Grasshopper2 FireWire camera with a 5-megapixel monochrome image sensor. The camera was mounted 1.75 m above the test panels.

The motor powering the track movement was a Parker Daedel 204000 Series motor, and it was controlled by a Parker Compumotor SX-6 Drive, which received its commands by a RS-232 interface. Position was controlled to within 0.006 mm.

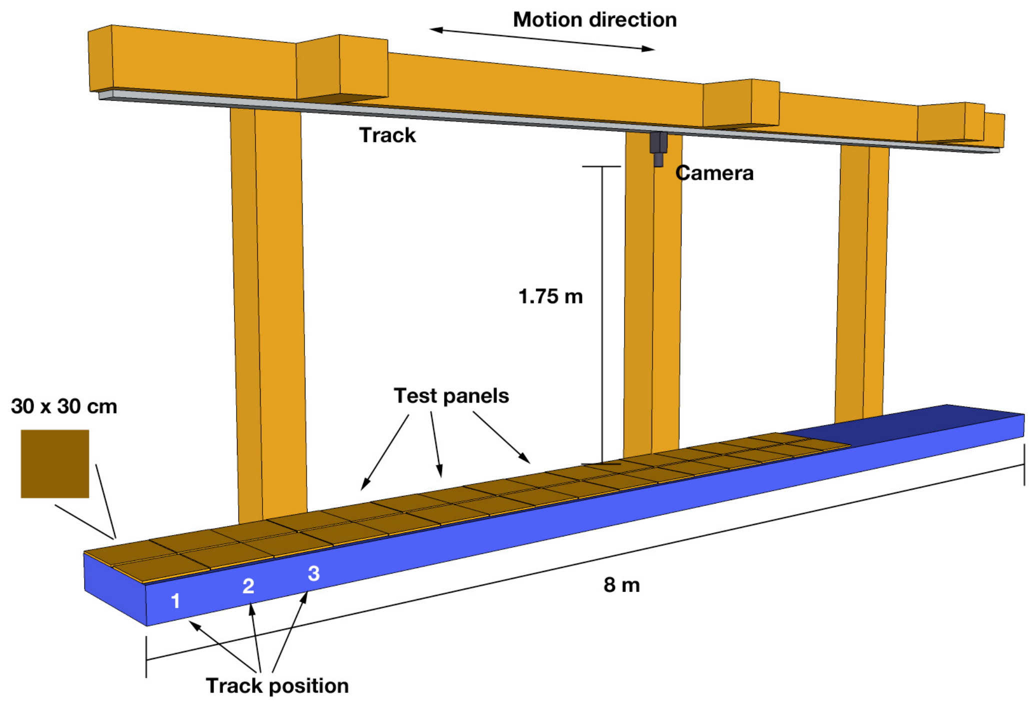

Figure 35 Track system diagram

The track system was programmed to take an image of each sample pair at 10-minute intervals over a four-hour period.

3.6.2 Enclosure and climate conditions

Climate controls within buildings change temperature and relative humidity conditions, which in turn change the moisture content of wood products in the building. These conditions are dependent on outdoor conditions, and vary between night and day, week and weekend and by season. Testing the specimens under these variable conditions may have interfered with testing, and a means to keep the conditions steady was needed. Enclosing the track system in a tent-like chamber isolated the environment and allowed for control of the conditions inside the enclosure. The enclosure was built on a steel pipe frame and covered in construction plastic (Figure 36).

Figure 36 Track system enclosure, external view

The environment was to some degree isolated from the building climate control systems, and allowed us to lower relative humidity and increase the temperature, by using two electric space heaters, four lamps, and a dehumidifier. A fan was added to keep the air in motion (Figure 37).

The enclosure and climate control measures proved effective for creating a warm and dry environment. Temperatures at the specimen surface were typically increased by approximately 10° C and relative humidity decreased by approximately 20% compared to laboratory conditions outside the enclosure. Prior to testing periods, the heaters, lights, fan and dehumidifier were turned on and allowed to warm up for at least 45 minutes. This resulted in effective temperature stabilization, but relative humidity continued to drop throughout the testing period. This resulted in decreasing wood equilibrium moisture contents during the test period as well. Before each image capture interval, temperature and relative humidity were read and recorded from a Vaisala Humidity and Temperature Transmitter HMT 330. Wood equilibrium moisture content was calculated using Simpson's formula (Simpson, 1998) and these data were recorded.

Figure 37 Track enclosure, internal view. Heaters, lights, a fan, and dehumidifier (not pictured) helped create a warm and dry environment for data collection.

During testing periods temperatures were between 28.4 °C and 33.0 °C, relative humidity was lowered to a maximum of 34.3% and a minimum of 23.0%. Table

14 includes relevant climate indicators for each block. It is important to note that there were three test periods per block, and these numbers include all three tests within the group.

Table 14 Climate conditions inside testing enclosure. Summary statistics fare or 25 readings over a period of four hours, taken in 10-minute intervals. *EMC was calculated using Simpson's formula and is for solid wood (Simpson, 1998)

	Temperature (°C)		**Relative Humidity (%)**		**EMC* (%)**	
Block	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
A	31.7	0.85	28.9	1.26	5.8	0.21
B	31.1	0.42	27.2	1.38	5.5	0.27
C	30.4	0.38	25.6	1.16	5.3	0.19
D	30.2	0.23	24.4	0.86	5.1	0.15
E	30.6	0.23	25.6	0.69	5.3	0.11
F	30.4	0.44	27.0	0.80	5.5	0.13
G	30.1	0.51	25.9	1.30	5.3	0.22
H	30.6	0.61	25.5	1.57	5.3	0.26

Figure 38 is a plot of a typical progression of temperature, relative humidity and wood equilibrium moisture content for an individual test period.

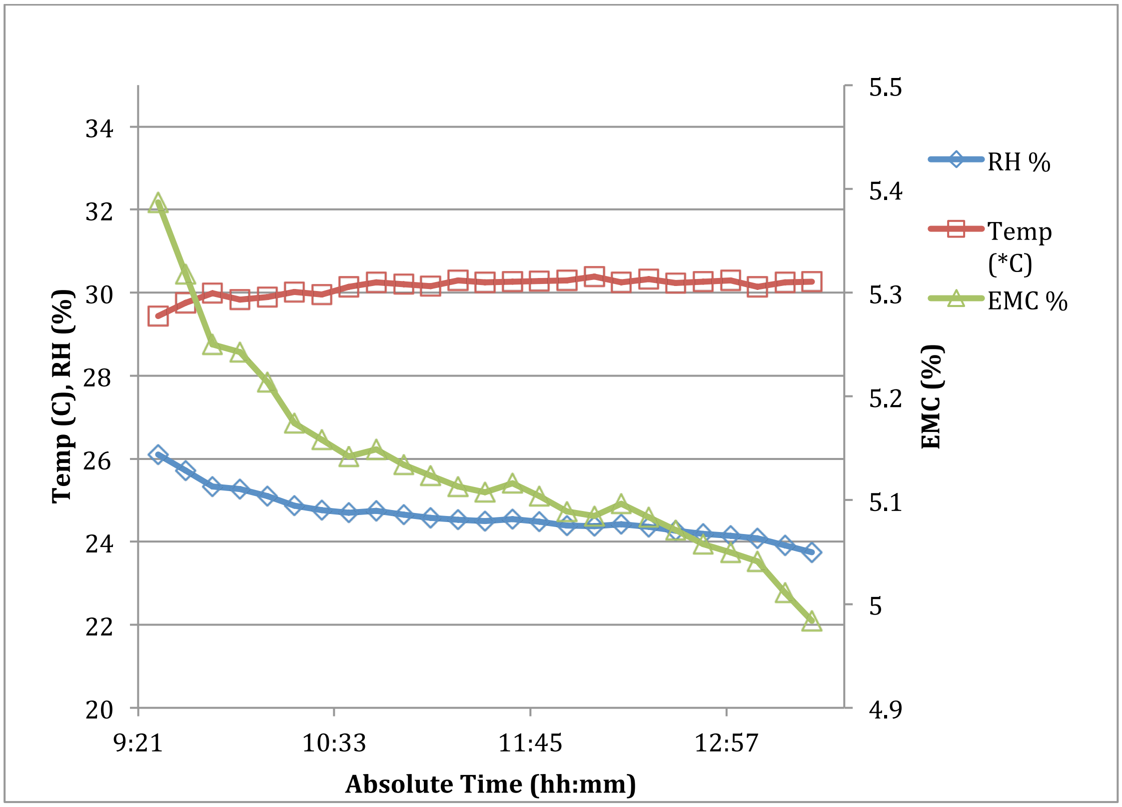

Figure 38 Typical environmental changes during testing a testing period. EMC calculated using Simpson's formula (Simpson, 1998).

3.6.5 Issues with collected images and apparatus

3.6.5.1 Computer system malfunction during data collection

While collecting data for the UF adhesive group of block E, the temperature and humidity probe interface malfunctioned, causing a failure in the image collection system. To correct this error, a reboot of the system was required. This happened after the fourth image was captured (after the samples had been in the testing chamber for at least 40 minutes). Restarting the image capture system at precisely 50 minutes after the first image was captured ensured a full series of images were taken.

3.6.5.2 Image adjustments

Some image series did not produce enough contrast between shades of grey for the DIC software to effectively analyze strain and displacement values (see list in 11. List of samples that received contrast adjustment). These images were adjusted using the image editing software package ImageJ (Rasband, 1997-2012). Contrast was adjusted using the software's built in contrast adjustment tool, which automatically alters the image to produce greater contrast. Figure 39 shows a "before and after" comparison of an altered image. In all cases this greatly improved the ability of software to effectively analyze the image series.

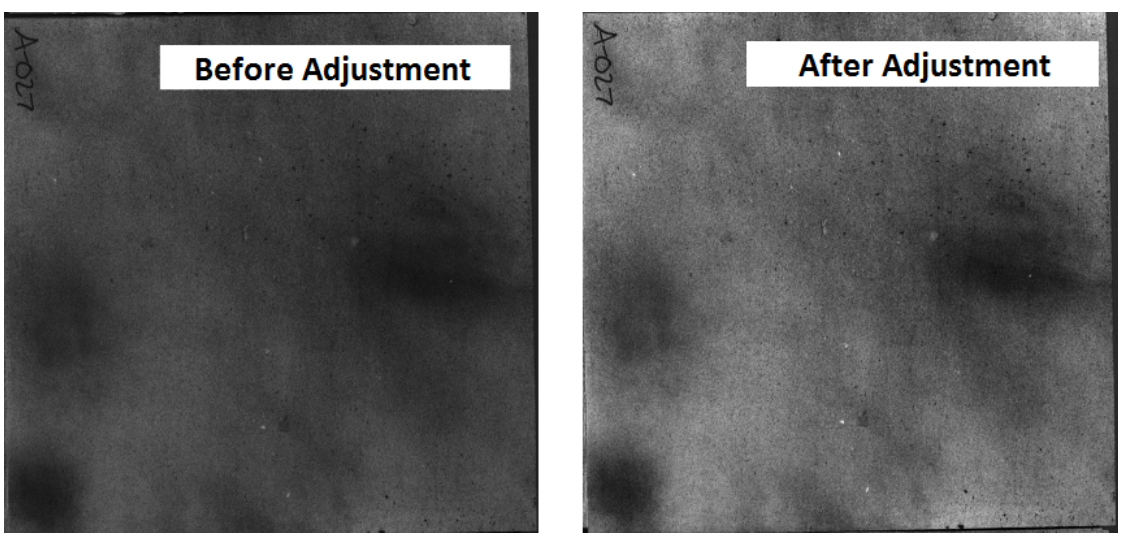

Figure 39 Example of contrast adjustment

4. Results

4.1 Survey analysis

In addition to yielding information about material attributes used to produce maple veneer and decorative maple veneered plywood panels as discussed in section 3.1 Factoridentification, analysis of the plywood producer survey also provided qualitative information regarding what plywood producers considered to be the leading factors contributing to maple veneer checking. Several points stand out:

1) For those producers that manufacture with plain-sliced veneer it was part of the combination of factors that produced the most claims.
2) Each combination of factors cited as resulting in the most claims list MDF as a core type, either as the main core, or as the crossband member of combi-core
3) PVA adhesive was listed as the adhesive in two of the four top claim-producing combinations of factors.

Additionally, panel producers from Oregon were asked to identify locations in the United States from which claims resulting from veneer checking originated and what time of year they most commonly occurred. Using a map with numbered regions (Figure 18) respondents were asked to list the percentage of claims from a particular region for each season (Summer, Fall, Winter, Spring). These regions correlate to wood MC values recommended for interior use. In regions 1 and 3 wood MC should be approximately 11%, 6% in region 2 and 8% in region 4. Region 4 and region 2 were the regions with the most reported claims, and most of these occurred in winter and summer. These are the seasons when many homes will employ heating or air conditioning, which significantly affect the climate conditions within the home. Correspondingly, wood EMC is affected and dimensional changes will occur which may lead to checking.

4.2 Assessing check severity

Out of a total of 766 panels tested, 429 (56%) had detectable checks. One panel was rejected from the data set because the regions determined by the check detection and characterization system were erroneous. Therefore, of the remaining 765 panels, 428 (56%) had detectable checks while 337 had no detectable checks (44%).

Out of all 96 treatments, only one had no detectable checks in the 8 samples prepared and examined. This combination was peeled, 1/36” veneer on particleboard core using polyvinyl acetate adhesive with the lathe checks oriented out (loose side out). No statistical predictions could be made for this treatment combination because it had no variance, but clearly, it performed well. It is not included in the charts with predicted treatment means. Only four treatment combinations had detectable checks on all test specimens (Table 15).

Table 15 Treatment combinations for which all 8 specimens had detectable checks

Veneer type	Core type	Adhesive	Lathe check orientation
Peeled, 1/36”	Veneer	UF	Tight side out
Peeled, 1/42”	Veneer	UF	Loose side out
Sliced, 1/50”	Veneer	Soy	Loose side out
Sliced, 1/50”	Veneer	UF	Tight side out

4.2.1 Impact of treatments

Treatment impact is reported based on the back transformed predicted check densities values from the Tweedie compound Poisson distribution fit to the observed data. These values infer what the range of results may be in future experiments.

Values for check density are very small and by any metric, check severity may be hard to visualize. From the observed data, very small check densities, those, for example less than 1×10^{-5} mm^2/mm^2, generally represented 1 or 2 small checks, which may have been as small as 1mm long, and approximately as narrow as 0.2mm. Larger check densities may have had larger individual checks or a greater number of small checks. The longest observed checks were over 100mm long, while the widest were more than 1mm wide. Check density values greater than 2.5×10^{-5} represent panels where checking was clearly more prevalent and could be considered comparatively “extreme.”

There is no standard for the acceptable amount of checking on decorative hardwood plywood panels, therefore examining the range of predicted values provides the most insightful analysis of which treatments are likely to perform well and which treatments are not.

The data suggests the presence of a four-way interaction between the factors. Which means the level of a factor **in combination** with other levels of other factors is responsible for check development. Certain levels of certain factors may seem to have consistently lower or higher predicted means, however, on average (that is, when differences among levels are averaged over all the levels of the other factors in the treatment) the effect of the level is not large.

Amongst the 95 treatments there were some were predicted to be clearly better than the others. Plotting the ordered predicted back-transformed means by treatment, with 95% confidence intervals, as in (Figure 40) (tabularized data in Table 20, Appendix 8. Tables) allows one to plainly see that differences amongst the lower range of predicted means is rather small, while differences amongst the upper range of predicted means can be rather large. Where confidence levels do not overlap, one can be more certain that a particular treatment is better or worse than another.

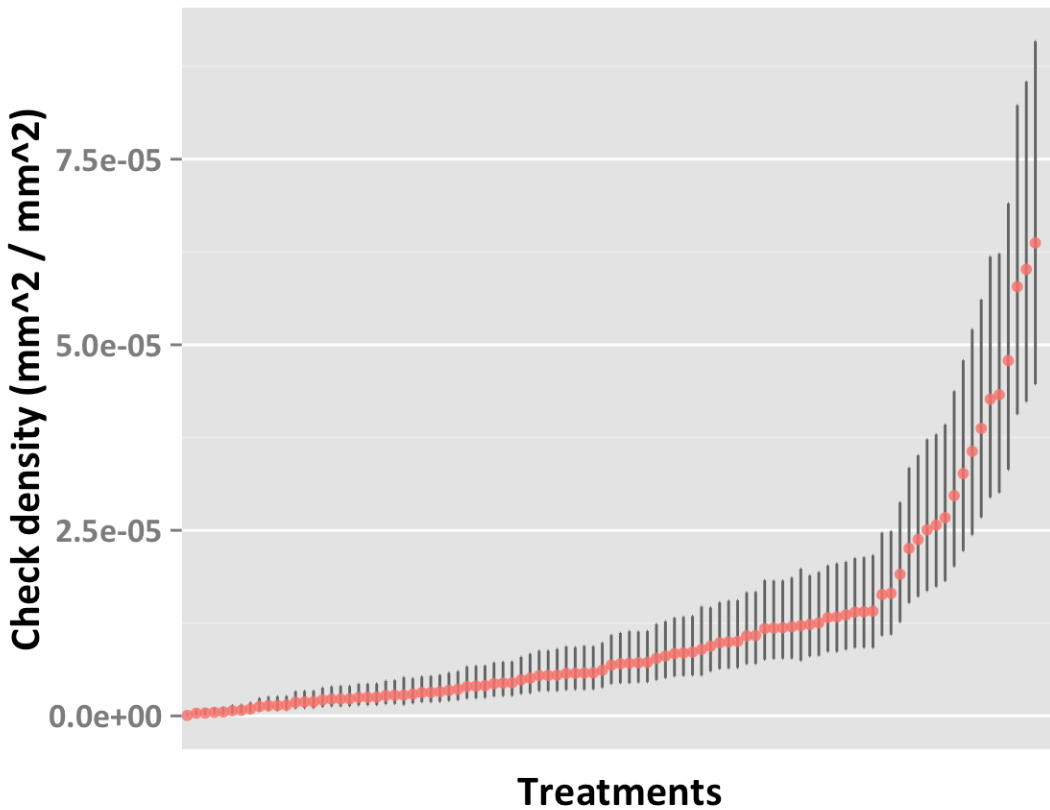

Figure 40 Predicted treatment means with 95% confidence intervals

The ten treatments predicted to have the greatest check density include all but sliced 1/45" veneer types, all adhesive types, both lathe check orientations and both veneer core and combination core (Table 16).

Table 16 Ten treatments predicted to have the greatest check density

Factors[3]				Predicted Check Density (mm²/mm²)		
Veneer	Core	Adhesive	Lathe Checks	Mean	95% CI Lower Bound	95% CI Upper Bound
S. 1/50"	Ven	UF	TO	6.37E-05	4.47E-05	9.09E-05
S. 1/50"	Ven	Soy	TO	6.02E-05	4.24E-05	8.54E-05
P. 1/42"	CC	Soy	LO	5.78E-05	4.07E-05	8.23E-05
S. 1/50"	Ven	UF	LO	4.79E-05	3.32E-05	6.90E-05
P. 1/36"	CC	Soy	TO	4.33E-05	3.01E-05	6.23E-05
P. 1/42"	Ven	UF	TO	4.27E-05	2.94E-05	6.19E-05
P. 1/42"	Ven	PVA	TO	3.87E-05	2.67E-05	5.61E-05
P. 1/36"	CC	UF	LO	3.56E-05	2.44E-05	5.21E-05
P. 1/36"	Ven	UF	LO	3.26E-05	2.22E-05	4.79E-05
P. 1/42"	Ven	UF	LO	2.97E-05	2.01E-05	4.37E-05

The ten treatments with the lowest predicted check density include all factors except soy adhesive (Table 17). While it may be tempting, therefore, to postulate that using soy adhesive will necessarily produce panels that will check more, this is inaccurate. None of the factors are clearly responsible, on their own, for check development. Likewise, all factors are shown to contribute to checking when combined with at least one other factor.

[3] Veneer designations preceded by "S." referred to sliced veneer. Those preceded by "P." refer to peeled veneer. CC stands for combination core; Ven for veneer. UF is urea formaldehyde and PVA is polyvinyl acetate. TO and LO refer to tight side out and loose side out lathe check orientation, respectively.

Table 17 Ten treatments predicted to have the lowest check density

Factors[4]				Predicted Check Density (mm^2/mm^2)		
Veneer	Core	Adhesive	Lathe Checks	Mean	95% CI Lower Bound	95% CI Upper Bound
P. 1/42”	MDF	PVA	TO	7.20E-08	2.49E-08	2.08E-07
P. 1/36”	MDF	PVA	LO	3.65E-07	1.68E-07	7.92E-07
S. 1/45”	CC	PVA	LO	3.92E-07	1.83E-07	8.42E-07
S. 1/50”	PB	UF	TO	4.85E-07	2.29E-07	1.03E-06
P. 1/42”	MDF	UF	TO	5.30E-07	2.53E-07	1.11E-06
P. 1/42”	PB	UF	LO	6.93E-07	3.43E-07	1.40E-06
P. 1/42”	Ven	PVA	LO	7.66E-07	3.90E-07	1.50E-06
P. 1/36”	PB	PVA	LO	9.38E-07	4.90E-07	1.80E-06
P. 1/36”	PB	UFA	TO	1.26E-06	6.73E-07	2.38E-06
S. 1/45”	PB	UF	LO	1.39E-06	7.47E-07	2.58E-06

4.2.2 Factor effects

While predicted check density cannot be attributed to any individual factor, it is useful to see where in the distribution of all treatment means each level of a given factor lies. Each factor, therefore, is examined individually below. All plots in this section are based on the back transformed predicted means for each treatment.

4.2.2.1 Core type

Of the 10 treatments with the greatest predicted check density, veneer core is the core type in seven treatments, while combination core is used in three. The high

---

[4] Veneer designations preceded by “S.” referred to sliced veneer. Those preceded by “P.” refer to peeled veneer. CC stands for combination core, Ven for veneer and MDF for medium density fiberboard. UF is urea formaldehyde and PVA is polyvinyl acetate. TO and LO refer to tight side out and loose side out lathe check orientation, respectively.

frequency of veneer core amongst the treatments with the greatest check density is likely attributed to the fact that these panels were laid up with the face veneer grain orientation parallel to the grain orientation of the core material. For combination core, grain orientation was uncontrolled.

Figure 41 is a plot of the range of check densities separated by core type. Each of the 95 predicted treatment means are displayed, but each core type is given its own subsection of the plot to more clearly show the range of check densities occupied by each core type. Of note in Figure 41 is that veneer core seems to be distributed through the entire range of predicted check densities and though combination core is present throughout as well, it is more heavily present in the lower and middle regions of the range.

Indeed, outside of four treatments combination core is found predominantly in the lower and middle ranges of check density. The treatments, which may be considered to perform abnormally poor for combination core are:

1) Peeled, 1/45” veneer, soy adhesive, loose side out lathe check orientation
2) Peeled, 1/36” veneer, soy adhesive, loose side out lathe check orientation
3) Peeled, 1/36” veneer, UF adhesive, tight side out lathe check orientation
4) Sliced, 1/50” veneer, PVA adhesive, loose side out lathe check orientation

Similarly, particleboard has one treatment that may perform particularly poorly when compared to other treatments with particleboard core: sliced 1/45" veneer, soy adhesive and tight side out lathe check orientation.

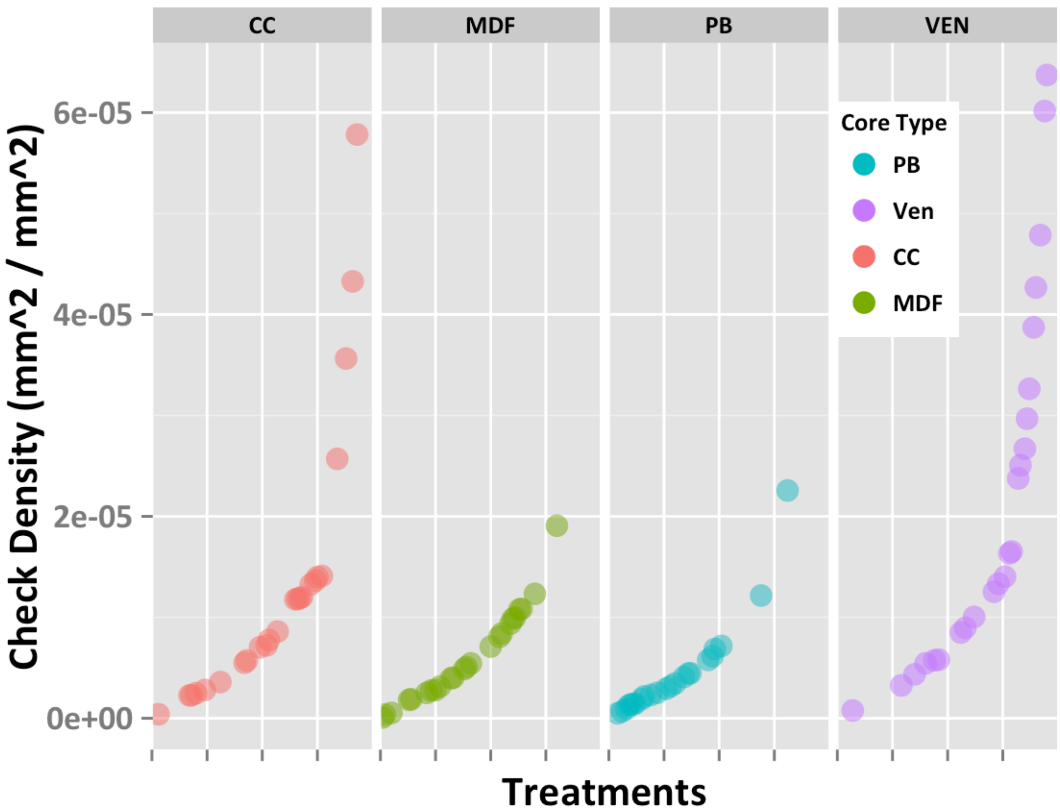

Figure 41 Predicted check density treatment means separated by core type

4.2.2.2 Veneer type

Within the four levels of veneer type, the sliced 1/45" type had the most consistently low predicted check density (Figure 42). Groupings of higher predicted means are evident in treatments using all other types of veneer.

The three worst-case scenario treatments for each other veneer type are:

For peeled 1/36” veneer:

1) Combination core, soy adhesive, tight side out lathe check orientation
2) Combination core, UF adhesive, loose side out lathe check orientation
3) Veneer core, UF adhesive, loose side out lathe check orientation

For peeled 1/42” veneer:

1) Combination core, soy adhesive loose side out lathe check orientation
2) Veneer core, UF adhesive, tight side out lathe check orientation
3) Veneer core, PVA adhesive, tight side out lathe check orientation

For sliced 1/50” veneer:

1) Veneer core, UF adhesive, tight side out lathe check orientation
2) Veneer core, soy adhesive, tight side out lathe check orientation
3) Veneer core, UF adhesive, loose side out lathe check orientation

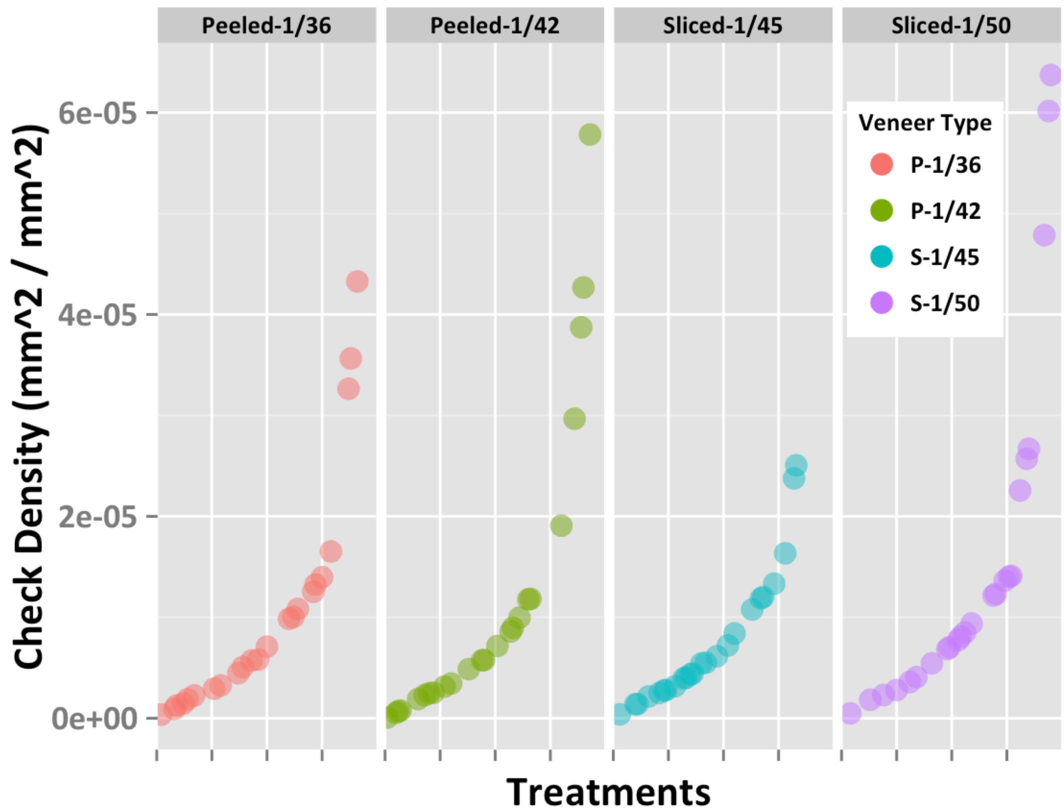

Figure 42 Predicted check density treatment means separated by veneer type

4.2.2.3 Adhesive type

Both soy and UF adhesive types are represented in treatments relatively evenly throughout the range of predicted check densities (Figure 43). With the exception of two treatments, PVA adhesive occupies the lower range of predicted check densities.

For PVA the two treatments with highest predicted check densities are:

1) Peeled, 1/45” veneer, veneer core, tight side out lathe check orientation

2) Sliced, 1/50" veneer, combination core, loose side out lathe check orientation

Soy adhesive, interestingly, is the only level of any factor not found in the lowest range of predicted means[5]. In fact, the first treatment with soy as the adhesive is the 21st in an ordered list of predicted means. It is, however, distributed rather densely in the middle range of check densities. Only three treatment means with soy adhesive are distant from the bulk of the other treatment means. These three predicted means are amongst the five highest predictions. The treatments were:

1) Sliced, 1/50" veneer, veneer core, tight side out lathe check orientation.
2) Peeled, 1/42" veneer, combination core, loose side out lathe check orientation
3) Peeled, 1/36" veneer, combination core, tight side out lathe check orientation

UF adhesive covers the full range of predicted means, and is well distributed amongst them. Of the 10 combinations with the highest predicted check density, six utilize UF adhesive. The three predicted to have the highest check density:

1) Sliced, 1/50" veneer, veneer core, tight side out lathe check orientation
2) Sliced, 1/50" veneer, veneer core, loose side out lathe check orientation
3) Peeled, 1/42" veneer, veneer core, tight side out lathe check orientation

[5] Though, both veneer core and combination core could also be considered to be under represented in the lowest range of the predicted check densities.

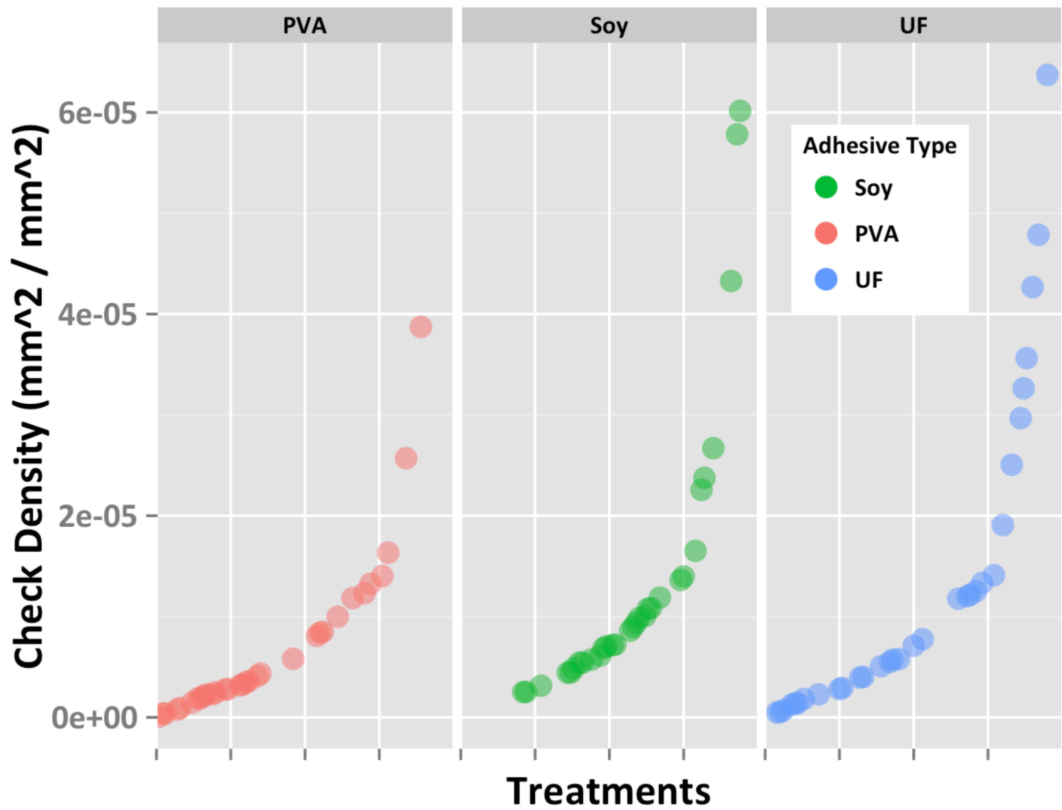

Figure 43 Predicted check density treatment means separated by adhesive type

4.2.2.4 Lathe check orientation

Attempting to determine any difference between lathe check orientations is more challenging, because means for treatments with each level of the factor occupy the entire range of predicted means (Figure 44). This may support for the hypothesis that lathe check orientation itself may not have a strong influence on check development. Indeed, there are no cases where alternating lathe check orientations while keep other factors the same leads to a substantial increase or decrease in predicted check density.

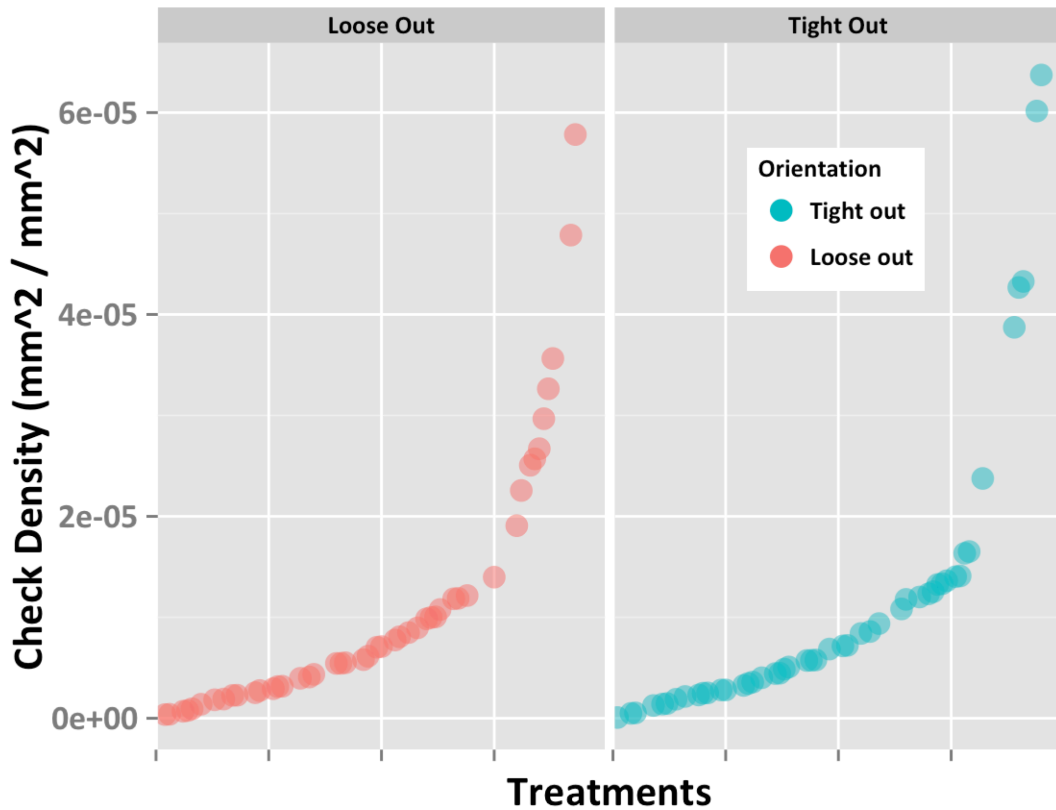

Figure 44 Predicted check density treatment means separated by lathe check orientation

4.3 Check development

In addition to examining the effect of the factors on check density, the method used to detect checks also allowed us to monitor and study check development over time. This section examines the relationship between surface strain development and check density development, as well as surface strain indicators and checking, in a more general sense.

Check density was calculated for each stage (time interval) of data collection. Each stage represents the state of the panel at incremental 10-minute intervals for the 240-minute test period. Very few checks were detected within the first 120 minutes in the test chamber and this analysis therefore focuses on what happened after the first 120 minutes of the test.

4.3.1 Check density development over time

Of the 438 panels with detectable checks 243 (55%) reached their peak check density before the end of the test period, while 195 (45%) reach their peak check density at the end of the test period, indicating check density may still have been increasing for those panels. This indicates that more time may have been needed for some samples to reach their peak check density. It is possible, too, that new checks could have opened during a prolonged test period on panels that reached their peak check density before the end of the test period increasing check density again.

In most cases check densities reached their peak before the end of the examination period then decreased towards the end of the test period as in Figure 45. Panel F-62 shows a more typical progression, peak check density relatively close to the final check density. Panel C-83, however, shows a more extreme case: the peak check density is much higher than the final check density. This is attributed to checks narrowing or closing as the cores begin to shrink, pulling open checks back together.

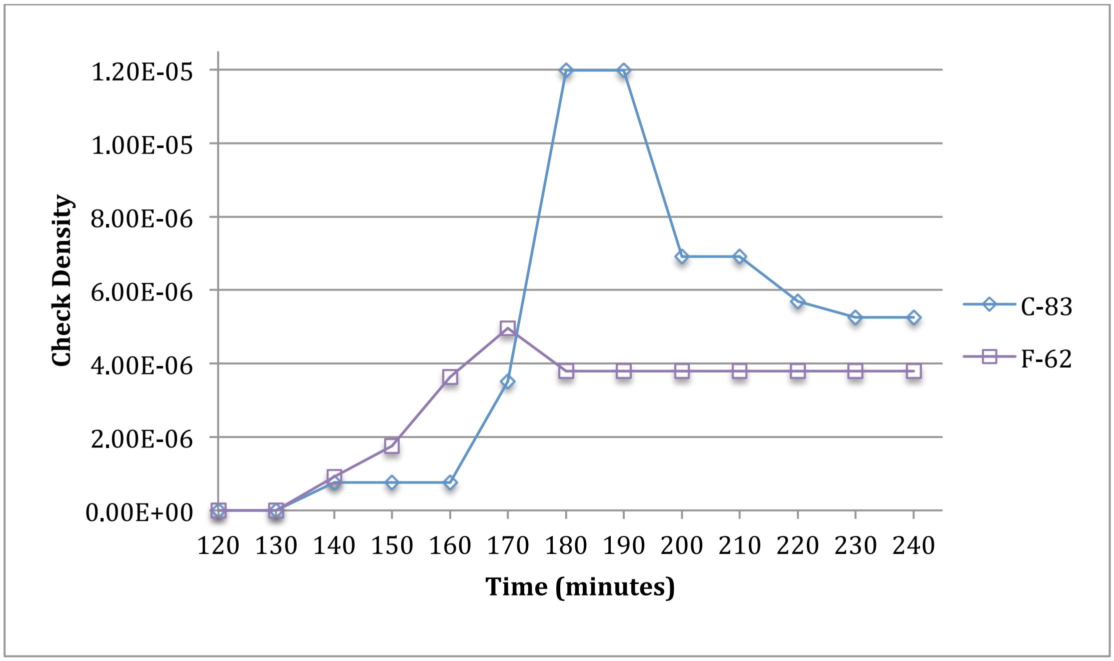

Figure 45 Check development demonstrating check densities that decreased after reaching their peak (C-83 and F-62 are examples of this)

Check density increased throughout the entire test period for many samples as in Figure 46. This plot shows check density changes over time for three test panels representing check development for panels with check densities considered to be "high" (panel C-67), "medium" (panel D-35) and "low" (panel B-73).

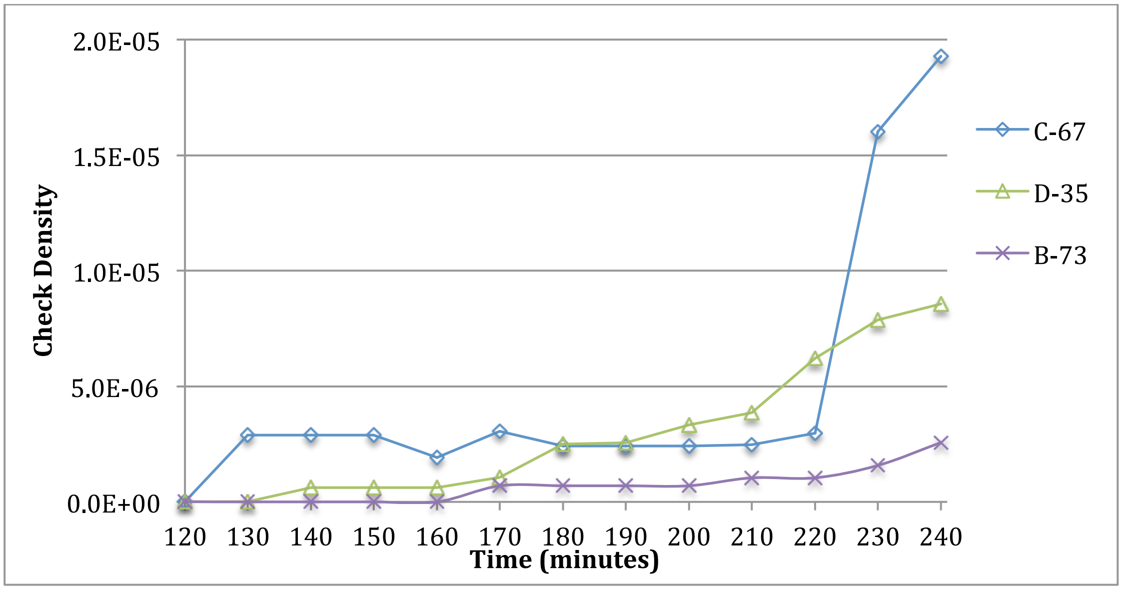

Figure 46 Check Development for test panels B-73, C-67, D-35

4.2.2 Check development in relation to strain development

Strain values are used to determine locations and measurements of checks in the check characterization method we created, so there is an expected correlation between strain development and check development. However, because the regions with strain spikes used to determine the location and size of a check are necessarily anomalous segments of surface strain on any given panel, visualizing the trend using surface strain indicators is challenging. Localized peaks in strain don't affect the overall average strain across the surface of the panel to a great degree, and therefore different subsets and products of strain were explored to examine the relationship between overall surface strain and check development.

Four indicators of surface strain were examined:

1) Average strain: the average of all strain measurements taken from a sample
2) Average positive strain: the average of all strain measurements greater than zero taken from a sample
3) Average negative strain: the average of all strain measurements less than zero

Of these indicators the average negative strain development seemed to most closely indicate how check density would develop; panels with greater average negative strain tended to have greater check density. Figure 47 is a plot of check development and three strain indicators on the same chart. When examining negative, average, and positive strain on the same chart, their individual changes are harder to notice. However, this figure does indicate changes in average strain values were relatively small throughout the test period.

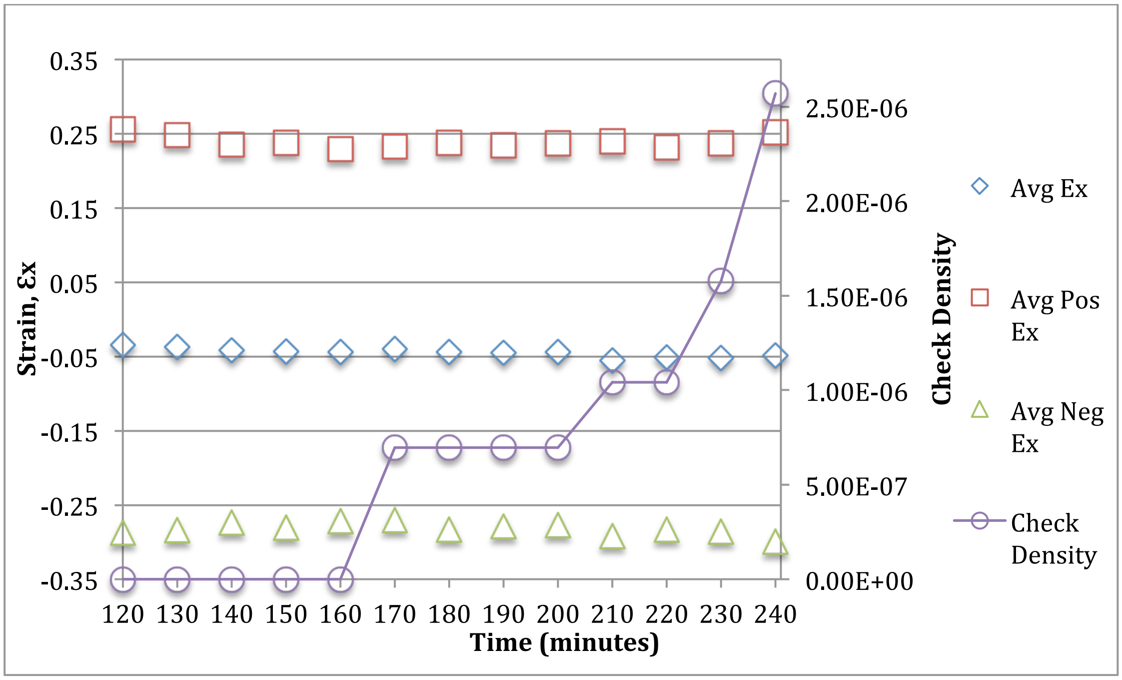

Figure 47 Strain indicators and check density for test panel H-27

Examining the absolute value of negative strain as it develops overlaid on check density development aids in seeing a potential correlation (Figure 48). Sample B-27 provides the clearest indication that there may be a correlation between negative strain development and check density development.

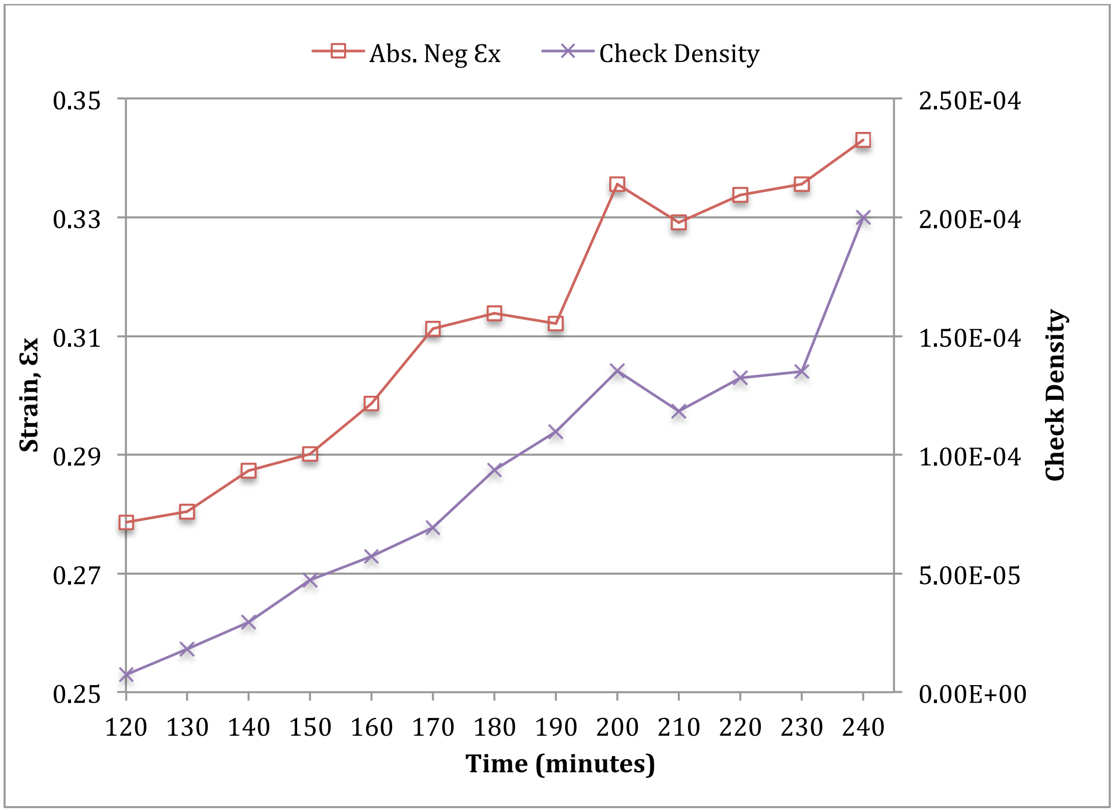

Figure 48 Absolute negative strain development and check development for panel B-27

There were many samples tested that had no detectable checks. Comparing surface strain indicators between groups of samples with checks, and groups of samples without checks provides some insight into what surface strain conditions exist when panels check.

The magnitudes of the mean values for both surface strain indicators were greater in the group of panels with checks, than without (Table 18). However, these are heavily influenced by extreme values and may not be reliable indicators.

Table 18 Surface strain indicators by checking groups

	Positive Ɛx		Negative Ɛx		
Group	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**n**
Checks	0.317	0.083	-0.342	0.087	427
No Checks	0.261	0.034	-0.277	0.043	336

Interestingly, panels that checked had approximately double the standard deviation of those that did not (0.083 versus 0.034 for positive strain, 0.083 versus 0.043 for negative strain, Table 18).

5. Conclusion & Recommendations

5.1 Meeting objectives

The primary objectives of this study were completed successfully. A new, optical method for detecting and characterizing checks was developed using methods based on digital image correlation. A system was built to implement the method at scale, and it was used to study the 96 treatments identified as important to the industry in this study.

The specific objects were met as follows:

- Develop a comprehensive matrix of test factor that may affect checking in maple plywood.
  - Four manufacturing factors were identified as likely to influence check development, each with multiple factors.
    - **Core type:** peeled 1/36”, peeled, 1/42”, sliced 1/45”, sliced 1/50”
    - **Veneer type:** combination core, medium density fiberboard, particle board, veneer
    - **Adhesive type:** soy based, polyvinyl acetate, urea formaldehyde
    - **Lathe check orientation:** tight side out, loose side out

- Develop an efficient method for measurement of checks as they develop gather data to be processed using digital image correlation
    - A novel use of digital image correlation principles was developed and implemented in an automated system which allowed many samples to be efficiently tested
- Measure intensity of checking for combinations of identified factors
    - 766 specimens were tested an analyzed over the course 24 four-hour sessions over a period of 16 days.
- Identify critical variables and interactions.
    - Using statistical modeling based on the Tweedie compound Poisson distribution, means for each of the 96 treatments were predicted and analyzed

5.2 Summary of experimental findings

Checks were detected on 428 out of a total of 765 inspected specimens (56%). Only one treatment had no detectable checks on any replication. This combination was peeled 1/36" veneer on particleboard core using polyvinyl acetate adhesive with the lathe checks oriented out (loose side out). In only four treatments checks were detected in all investigated samples (see Table 15 in section 4.2 Assessing check severity).

The industry survey performed in this study outlined several manufacturers opinions about the manufacturing factors responsible for checking. Here, those opinions are compared with the results from the analysis:

- Manufacture using plain-sliced veneer reported part of the combination of factors that produced the most claims.
    - Veneer type was part of a four way interaction between factor levels prevent it from being isolated as leading to more checking
- All manufacturers reporting claims listed MDF as the core, or the crossband material in combination core
    - As with veneer type, a particular core type could not be linked greater check severity.
- PVA adhesive was listed as the adhesive in two of the four top claim-producing combinations of factors.
    - Though PVA has the same caveat as the previous factors, it did seem to perform well more often than the other adhesives.

5.2.1 Significant treatments

The predicted mean check densities revealed that some factor combinations were clearly worse than others, while the bulk of the treatments were similar in severity. When a manufacturer is constrained by customer demand or product availability, the predicted means offer a guide to choose the best-case scenario based on the model created from the data collected in this experiment. For example if a customer specifically orders panels made on veneer core (perhaps because they are concerned about fastener withdrawal) with a soy based adhesive, the results suggest the best options for lathe check orientation and veneer are sliced 1/45" veneer with the loose side out, or peeled 1/42" with the tight side out. Similarly, if a customer requested whole piece 1/36" veneer and soy adhesive, but was not concerned with core type or lathe check orientation, the manufacturer should choose particleboard core and orienting the veneer tight side out or MDF core with the veneer oriented loose side out.

Based on the data, all factors had some degree of interaction with one another. That is, the mean check density expected for a given level of a factor will vary based on the levels of another factor it is combined with. This four-way interaction prevents statements about the relative impact any single factor may have had on check development from being made.

Those combinations predicted to have the greatest check density were (greatest to least):

1) Sliced 1/50" veneer, veneer core, UF adhesive, tight side out lathe check orientation
2) Sliced 1/50" veneer, veneer core, soy adhesive, tight side out lathe check orientation
3) Peeled 1/42" veneer, combination core, soy adhesive, loose side out lathe check orientation

4) Sliced 1/50" veneer, veneer core, UF adhesive, loose side out lathe check orientation
5) Peeled 1/36" veneer, combination core, soy adhesive, tight side out lathe check orientation

The combinations predicted to perform the best (have the lowest check density) are (least to greatest):

1) Peeled 1/42" veneer, MDF core, PVA adhesive, tight side out lathe check orientation
2) Peeled 1/36" veneer, MDF core, PVA adhesive, loose side out lathe check orientation
3) Sliced 1/45" veneer, combination core, PVA adhesive, loose side out lathe check orientation
4) Sliced 1/50" veneer, particleboard core, UF adhesive, tight side out lathe check orientation
5) Peeled 1/42" veneer, MDF core, UF adhesive, tight side out lathe check orientation

5.3 Check development

The method developed for this study provided a new means to gain insight into checking in decorative hardwood plywood panels. Check density was measured at every 10 minute increment over a 240 minute test period. Therefore, monitoring check development was possible. It was determined that for those panels that had detectable checks 243 (55%) reached their peak check density before the end of the test period, and therefore indicated a reduction in check density near the end of the test period. The remaining 195 (45%) panels with detectable checks reach their peak check density at the end of the test period, indicating that the more checking may have occurred in a harsher environment, or over a longer test period.

Examining the groups that checked in comparison with those that did not, it was evident that the group with detectable checks had significantly higher standard deviations in the observed positive and negative strain than those panels with no detectable checks.

5.4 Limitations

Though every attempt was made to make this study as robust as possible, there are limitations to the study. The primary factors limiting this study were the manufacturing decision to not use a back veneer on the panels, and the manufacturing error of applying face veneers with their grain oriented parallel to the veneer core grain direction.

Additionally, although many other factors were suggested by manufacturers for inclusion in this study, time and product availability limited the number of factors considered. See section 6.3 Other factors that could provide insight for a list of other factors that can be studied to better understand their contribution to check development in decorative hardwood panels.

5.4.1 Manufacturing decisions

To increase the propensity of panels to check, researchers decided to use an unbalanced construction procedure and not apply back veneers, which are considered essential for reducing panel defects including warp and checking. Indeed, there was considerable warping observed in many panels. It is possible the warping alleviated enough of the drying stress to reduce checking observed in the warped panels.

5.4.2 Manufacturing errors

The common industry practice is to manufacture decorative hardwood panels with the face veneer grain oriented perpendicular to the core and surface of the veneer core. In this experiment face veneers were inadvertently applied with their grain direction oriented parallel to the core and surface of veneer core. Industry wisdom suggests this leads to heavy check development. This likely caused higher than normal check densities for veneer core panels.

5.4.3 Random effects in the compound Poisson model

The estimation theory of generalized linear mixed models (such as the Tweedie compound Poisson linear mixed model used in this study), for distributions other than the normal distribution, is not completely mathematically tractable. In particular it is not known how the estimation of the random effects should be incorporated into the standard errors of the predicted means. This is an ongoing area of statistical research and these effects are not incorporated into our analysis. The degree to which this may change the outcome of the results is unknown, but expected to be limited.

6. Future work

The method, experiment and analysis of the data all provide opportunities for future work.

6.1 Expanding the method

This method, while greatly expanded information about check development is fully capable of further expansion. Other measures of interest, which may be readily calculated from existing data, are:

1) Individual check size
2) Check location

Both measures could provide helpful insight for industry members and further the scientific understand of why checks occur. For example, if a particular veneer type was found to have many checks but they were found to be under a certain size threshold, that veneer could be deemed acceptable for certain uses (e.g. such as the interior of a cabinet). Check location may present diagnostics information for glue spreading, or variations in pressing (temperature, or pressure inconsistencies across the surface of the press). For example, if a particular manufacturer found that checks more frequently occurred in a certain region of their panels, they may be able to assess glue spread in that region or examine their press for inconsistencies in that region.

Additionally, adding a second camera to the apparatus would allow for out-of-plane deformations (i.e., panel warp) to be measured and considered.

6.2 Veneer core with perpendicularly oriented face veneer

Examining panels made with veneer core and face veneer oriented perpendicular to the grain of the core veneers outer most layer to determine if they check differently than the veneer core panels in this study will help overcome of the main limitations of this study.

6.3 Other factors that could provide insight

Many factors surfaced during the literature review and in discussions with industry members regarding checking in decorative hardwood panels.

1.) Panel thickness
2.) Veneer drying method
3.) Log preparation method (steam versus soak)
4.) Veneer preparation method (slicing versus peeling)
5.) Slicing methods (half-round versus plain-sliced)
6.) Log harvest season,
7.) Other face veneer species
8.) Sanding and finishing

This experiment examined the factors manufacturers have the most control over, and represent the basic and unavoidable decisions during manufacturing. A manufacturer cannot make a panel without choosing to use some type of face veneer, some sort of core, or some sort of adhesive. Every attempt was made to utilize levels of those factors that manufacturers commonly use when manufacturing decorative hardwood panels.

There were, however, many factors that we would have liked to explore, but could not due to product availability and limited time. Veneer preparation method (slicing versus peeled), in particular, may have an effect on check development. However, because slicing and thickness are confounded they could not be separately analyzed.

6.4 Analyzing strain data

A wide array of strain data was collected in this study, which provides many avenues for further research. Finding a relationship between strain development and check development that could provide more insight into how specific factors may contribute to check development. Identifying such correlations could substantially simplify and speed up the analysis of data collected by the optical system. For example, if a tight correlation existed between some strain related indicator and levels of check severity, the actual amount and characterization of the checks may not need to be calculated, significantly reducing computational and analytical time. This would allow for more factors to be efficiently studied in future research.

6.5 Statistical analysis

The next step in the analysis of the data using the Tweedie compound Poisson distribution is to determine how the random effects from the split plot design and blocking affect the predicted means reported in the results.

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Appendices

1. Recommended decorative hardwood plywood ordering checklist

This checklist is provided as a recommendation to the purchases from the American National Standards Institute and the Hardwood Plywood and Veneer Association. The goal of the organization is to ensure that no assumptions are left to the producers and to encourage purchasers to have a clear specification in mind when they place an order. The checklist is reproduced below (ANSI, 2004).

1) Number of panels
2) Type of plywood
3) Number of plies
4) Thickness of face veneer and thickness of panels
5) Width (across the grain)
6) Length (with the grain)
7) Species of face ply and, if applicable, whether light, medium or dark color
8) Grade of face ply, pattern or type of cut, and matching requirements
9) Grade of back ply and, if applicable, pattern or type of cut and matching requirements
10) Species and grade of lumber core and type of banding (if required)
11) Type and grade of particle board core (if required)

12) Type of MDF and hardboard core (if required)

13) Type of special core (if required)

14) Sanding requirements

15) Solid core (if required) (Grade J inner plies)

16) Specific gravity category of inner plies from Table 1*

Table 1 separates species in to groups by range of specific gravity and is not replicated here.

2. Three-cycle soak test

This test describes methods and failure criteria for testing Type II (interior) plywood bond lines. Section 4.6 is repeated from the 2004 ANSI/HPVA standard for hardwood decorative plywood.

> "The 127 mm by 50.8 mm (5 inches by 2 inches) specimens from each test panel shall be submerged in water at 24 ± 3°C (75 ± 5°F) for 4 hours and then dried at a temperature between 49 and 52°C (120 and 125°F) for 19 hours with sufficient air circulation to lower the moisture content of specimens to within the range of 4 to 12 percent of the ovendry weight. This cycle shall be repeated until all specimens fail or until three cycles have been completed, whichever occurs first. A specimen shall be considered as failing when any single delamination between two plies is greater than 50.8 mm (2 inches) in continuous length, over 6.4 mm (1/4 inch) in depth at any point, and 0.08 mm (0.003 inch) in width, as determined by a feeler gage 0.08 mm (0.003 inch) thick and 12.7 mm (1/2 inch) wide. Delamination due to tape at joints of inner plies or defects allowed by the grade shall be disregarded. Five of the 6 specimens shall pass the first cycle and 4 of the 6 shall pass the third cycle in 90% of the panels tested. Within any given selection of test panels, 95% of individual specimens shall pass the first cycle and 85% of the specimens shall pass the third cycle."

3. Destroyed samples

Those samples destroyed were:

B-36, B-38, B-40, B-42, B-46, B-48, B-49, B-50, B-51, B-52, B-53, B-56, B-59, B-61, B-63.

Figure 49 Top view of four water damaged samples

Figure 50 Edge view of four damaged samples

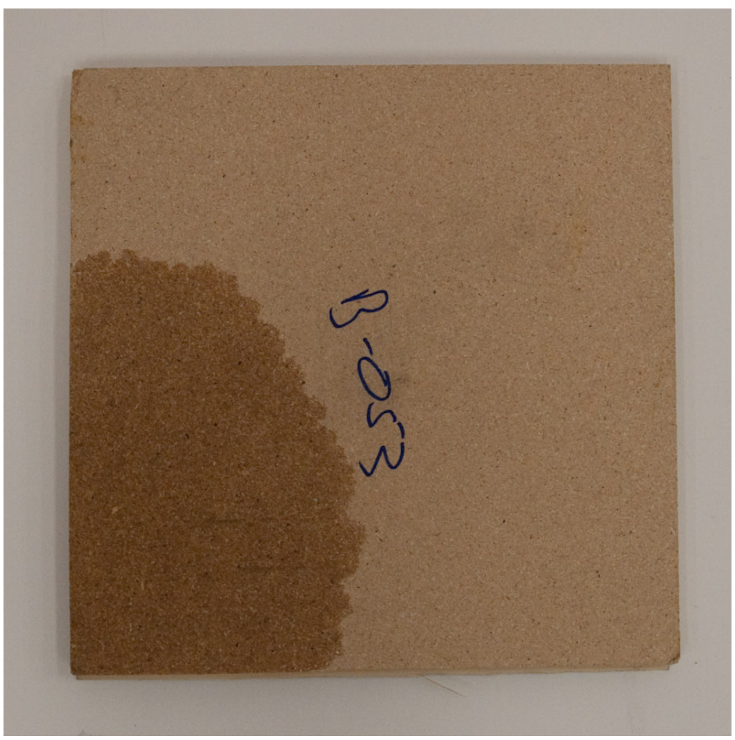


Figure 51 View of the back side of a damaged panel

4. Production procedure

Below is a reproduction of the panel production procedure using during panel construction.

```
/*********************************************************************
*	Naming: A-036 = Block A, 36th Sample
*	Construct method: P3-T-V-U = (Veneer)-(Side)-(Core)-(Glue)
*	ABBREVIATION KEY:
*	Veneer: P3 = Peeled 1/36", P4 = Peeled 1/42", S4 = Sliced 1/45th
*			S5 = Sliced 1/50"
*	Side:	L = Loose-side OUT, T = Tight-side OUT
*	Core:	V = Veneer, P = Particleboard, C = combicore, M = MDF
*	Glue:	U = Urea formaldehyde, P = Polyvinyl Acetate, S = Soy
*********************************************************************/
```

Panel prep procedure

1) Prepare the press
  a) Make sure the surface is clean
  b) Warm up the upper platen
    i) Temperature: 113 C (235 F)
  c) Set to pressure mode: 1.31 (931 kPa, 135 PSI)

2) Prepare of type necessary (located in the upper right corner of the production sheet) *instructions for each on separate page
  a) Fill the glue spreaders upper reservoir with the adhesive
  b) refill as necessary

3) Using production sheets & make samples in the order they are specified
  a) Select the core, label it with the name from the production sheet, weigh it and record this weight
  b) Apply 15.9g (+/- 0.4g) adhesive and spread evenly using glue spreader, and ensure even spread
  c) Re-weigh to confirm the proper amount of adhesive
    i) Apply or remove as needed
    ii) *weigh again and record this weight
  d) Apply veneer paying close attention to "tight" and "loose" side orientation
  e) Once 4 specimens are prepared

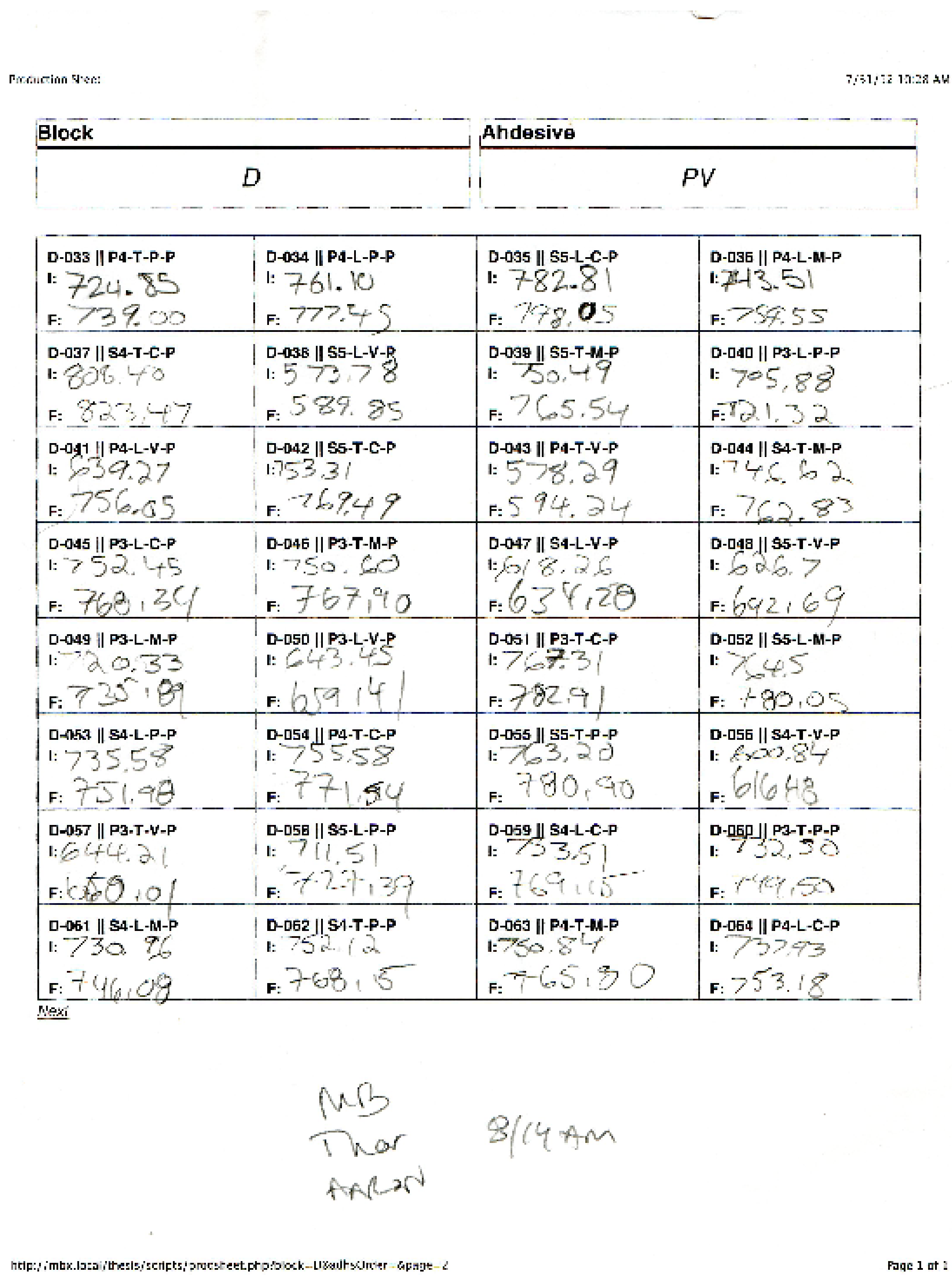
i) Place in cold-press, veneer side DOWN, engage press to about 135 PSI
ii) After 5-7 minutes, move panels to hot-press, veneer side UP
iii) Engage press, and begin timer once the pressure reaches the target

f) Using oven mitts, remove samples from press
g) After specimens have cooled, label the front of the panel with the name from the back (ie, H-025)

4) Cleanup

5. Sample production sheet

The following image is a scanned copy of an actual production sheet used while construction sample panels. It includes the order of panel construction, panel identifiers, block and adhesive, the, initial and final weights recorded and used to confirm adhesive spread rate, production date and a list of researching producing panels during that period.



Production Sheet 7/31/12 10:28 AM

Block	Ahdesive
D	PV

D-033 ‖ P4-T-P-P I: 724.85 F: 739.00	D-034 ‖ P4-L-P-P I: 761.10 F: 777.45	D-035 ‖ S5-L-C-P I: 782.81 F: 798.05	D-036 ‖ P4-L-M-P I: 743.51 F: 759.55
D-037 ‖ S4-T-C-P I: 806.40 F: 823.47	D-038 ‖ S5-L-V-P I: 573.78 F: 589.85	D-039 ‖ S5-T-M-P I: 750.49 F: 765.54	D-040 ‖ P3-L-P-P I: 705.88 F: 721.32
D-041 ‖ P4-L-V-P I: 739.27 F: 756.65	D-042 ‖ S5-T-C-P I: 753.31 F: 769.49	D-043 ‖ P4-T-V-P I: 578.29 F: 594.24	D-044 ‖ S4-T-M-P I: 746.62 F: 762.83
D-045 ‖ P3-L-C-P I: 752.45 F: 768.34	D-046 ‖ P3-T-M-P I: 750.60 F: 767.90	D-047 ‖ S4-L-V-P I: 618.26 F: 634.20	D-048 ‖ S5-T-V-P I: 676.7 F: 692.69
D-049 ‖ P3-L-M-P I: 720.33 F: 735.89	D-050 ‖ P3-L-V-P I: 643.45 F: 659.14	D-051 ‖ P3-T-C-P I: 767.31 F: 782.91	D-052 ‖ S5-L-M-P I: 764.5 F: 780.05
D-053 ‖ S4-L-P-P I: 735.58 F: 751.98	D-054 ‖ P4-T-C-P I: 755.58 F: 771.84	D-055 ‖ S5-T-P-P I: 763.20 F: 780.90	D-056 ‖ S4-T-V-P I: 600.84 F: 616.48
D-057 ‖ P3-T-V-P I: 644.21 F: 660.01	D-058 ‖ S5-L-P-P I: 711.51 F: 727.39	D-059 ‖ S4-L-C-P I: 753.51 F: 769.05	D-060 ‖ P3-T-P-P I: 732.50 F: 748.50
D-061 ‖ S4-L-M-P I: 730.86 F: 746.09	D-062 ‖ S4-T-P-P I: 752.12 F: 768.15	D-063 ‖ P4-T-M-P I: 750.84 F: 765.30	D-064 ‖ P4-L-C-P I: 737.93 F: 753.18

Next

MB
Thor
Aaron
8/14 AM

http://mbx.local/thesis/scripts/procsheet.php?block=D&adhesive=&page=2 Page 1 of 1

Figure 52 Production sheet used for block D group 2

6. Urea formaldehyde mixing information

Table 19 Urea formaldehyde mixing ratios

Material	**% of total weight**	**Weight used (g)**
Urea-formaldehyde	52.07	781.05
Wheat flour	25.87	388.05
Citric acid	0.23	3.60
Ammonium chloride	0.67	10.05
Water	21.50	322.50

The target quantity of adhesive for each batch was 1.5 kg.

The mixing procedure was:

1. Measure each material into separate containers
2. Mix urea formaldehyde and water together for 1.5 – 2 minutes in laboratory mixer
3. Add ½ of wheat flour, mix for 1.5-2 minutes
4. Add ammonium chloride, citric acid and remaining wheat flour, mix for 2-3 minutes

1.5 kilograms was the target weight because it provided enough adhesive to cover all 32 panels and to charge the glue spreader. Additionally, the laboratory mixer readily mixed this quantity.

7. Randomization script

The following script, written in the hypertext pre-processor (PHP) scripting language, randomized the order or treatment application to panels. It was designed to account for the randomized block split plot design. The split plot design requires all split plot treatments be randomized within each whole plot factor. Whole plot factors were randomized within each block. The first function, createWholePlots() randomizes adhesive order and is called once per block. It calls makeCombos() randomizes the split plot factors and creates other data to help with tracking before createWholePlots() writes that data to the database, one whole plot at a time.

```
function createWholePlots($block)
{
	$adhs = array(1=>"1", 2=>"2", 3=>"3"); //Adhesives
	shuffle($adhs);
	foreach($adhs AS $k=>$v)
	{
		if($k == 1) { $sp = 0; }
		elseif($k == 2) { $sp = 33; }
		else { $sp = 65; }
		$combos = makeCombos($block, $sp, $v);
		writeToDB($combos);
	}
}

function makeCombos($block, $sp, $adhs)
{
	$lco = array(1=>"T", 2=>"L"); //Lathe check orientation
	$ven = array(1=>"P3", 2=>"P4", 3=>"S4", 4=>"S5"); //Thickness
	$core = array(1=>"M", 2=>"V", 3=>"C", 4=>"P"); //Core

	$i=1;
	$arr = array();
	foreach($ven as $k=>$v)
	{
		foreach($lco as $k2=>$v2)
		{
			foreach($core as $k3=>$v3)
			{
```

```
                    $arr[$i]['veneer'] = $k;
                    $arr[$i]['lathe_checks'] = $k2;
                    $arr[$i]['core'] = $k3;
                    $arr[$i]['adhesive'] = $adhs;
                    $i++;
                }
            }
        }
        shuffle($arr);
        for($i=0;$i<=31;$i++)
        {
            $x=$i+$sp;
            if($x<10) { $coding = '00'.$x; }
            elseif($x<100) { $coding = '0'.$x; }
            else { $coding = $x; }
            $arr[$i]['block'] = $block;
            $arr[$i]['name'] = $block.'-'.$coding;
            $arr[$i]['combo_string'] = makeComboString($arr[$i]);
        }
        return $arr;
}
```

8. Tables

Table 20 Check density values ordered by observed mean check density per treatment. LCO = lathe check orientation

Factors					Observed Check Density (mm^2/mm^2)		Predicted Check Density (mm^2/mm^2)		
Ven.	**Core**	**Adh.**	**LCO**	**n**	**Mean**	**Std. Dev.**	**Mean**	**95% CI L. Bnd.**	**95% CI U. Bnd.**
P3	PB	SO	LO	8	0	N/A	N/A	N/A	N/A
P4	MD	PV	TO	8	2.90E-07	8.21E-07	7.20E-08	2.49E-08	2.08E-07
S4	CC	PV	LO	8	4.55E-07	7.02E-07	3.92E-07	1.83E-07	8.42E-07
P4	MD	UF	TO	8	7.11E-07	1.48E-06	5.30E-07	2.53E-07	1.11E-06
P4	PB	UF	LO	8	8.70E-07	2.46E-06	6.93E-07	3.43E-07	1.40E-06
S5	PB	UF	TO	8	1.02E-06	2.89E-06	4.85E-07	2.29E-07	1.03E-06
P3	MD	PV	LO	8	1.47E-06	4.17E-06	3.65E-07	1.68E-07	7.92E-07
P3	PB	UF	TO	8	1.58E-06	2.27E-06	1.26E-06	6.73E-07	2.38E-06
S4	PB	UF	TO	8	1.89E-06	3.57E-06	1.40E-06	7.56E-07	2.61E-06
P4	PB	PV	LO	8	2.03E-06	2.31E-06	1.90E-06	1.07E-06	3.38E-06
S4	PB	UF	LO	8	2.23E-06	3.91E-06	1.39E-06	7.47E-07	2.58E-06
S5	PB	PV	TO	8	2.46E-06	2.92E-06	2.30E-06	1.32E-06	4.02E-06
P4	VE	PV	LO	8	2.65E-06	6.64E-06	7.66E-07	3.90E-07	1.50E-06
P3	MD	PV	TO	8	3.27E-06	5.67E-06	1.88E-06	1.06E-06	3.35E-06
P3	PB	PV	TO	8	3.34E-06	6.18E-06	1.46E-06	7.99E-07	2.66E-06
P4	CC	UF	LO	8	3.43E-06	7.52E-06	2.28E-06	1.29E-06	4.03E-06
S5	MD	UF	LO	8	3.45E-06	8.04E-06	1.83E-06	1.01E-06	3.30E-06
P3	PB	PV	LO	8	3.60E-06	9.83E-06	9.38E-07	4.90E-07	1.80E-06
S4	PB	SO	TO	8	3.86E-06	9.32E-06	4.43E-06	2.70E-06	7.27E-06
S5	MD	UF	TO	7	3.90E-06	7.32E-06	2.80E-06	1.51E-06	5.20E-06
P3	VE	PV	TO	8	4.29E-06	6.57E-06	3.25E-06	1.93E-06	5.50E-06
P4	PB	SO	LO	8	4.32E-06	6.64E-06	2.53E-06	1.47E-06	4.35E-06
S4	PB	PV	LO	8	4.73E-06	7.89E-06	3.17E-06	1.87E-06	5.37E-06
S4	MD	UF	LO	8	4.86E-06	7.07E-06	3.96E-06	2.35E-06	6.65E-06
S5	CC	PV	TO	8	4.91E-06	7.26E-06	3.58E-06	2.14E-06	6.01E-06
P4	CC	PV	TO	8	5.30E-06	9.33E-06	2.48E-06	1.43E-06	4.30E-06
P3	CC	PV	LO	8	5.74E-06	1.10E-05	2.26E-06	1.29E-06	3.95E-06
P3	PB	UF	LO	8	5.84E-06	1.39E-05	2.93E-06	1.69E-06	5.05E-06
S4	CC	UF	LO	8	5.87E-06	8.22E-06	5.50E-06	3.36E-06	9.00E-06
S4	CC	PV	TO	8	5.98E-06	1.11E-05	2.80E-06	1.64E-06	4.79E-06
S4	MD	UF	TO	8	6.23E-06	9.16E-06	4.01E-06	2.39E-06	6.74E-06

Factors					Observed Check Density (mm^2/mm^2)		Predicted Check Density (mm^2/mm^2)		
Ven.	Core	Adh.	LCO	n	Mean	Std. Dev.	Mean	95% CI L. Bnd.	95% CI U. Bnd.
P3	PB	SO	TO	8	6.84E-06	9.63E-06	4.46E-06	2.72E-06	7.32E-06
S4	VE	SO	LO	8	6.90E-06	1.17E-05	5.43E-06	3.36E-06	8.78E-06
P4	MD	SO	TO	8	7.08E-06	9.12E-06	4.87E-06	2.98E-06	7.93E-06
P4	PB	UF	TO	8	7.21E-06	8.58E-06	5.78E-06	3.54E-06	9.42E-06
P3	MD	UF	TO	8	7.43E-06	1.33E-05	5.08E-06	3.08E-06	8.36E-06
S4	MD	SO	TO	8	7.50E-06	1.72E-05	2.51E-06	1.46E-06	4.33E-06
P4	MD	SO	LO	8	7.84E-06	1.48E-05	3.14E-06	1.86E-06	5.30E-06
P3	VE	PV	LO	8	7.97E-06	1.21E-05	5.81E-06	3.60E-06	9.37E-06
S4	PB	PV	TO	8	8.37E-06	2.30E-05	2.16E-06	1.23E-06	3.79E-06
P4	CC	SO	TO	8	8.49E-06	8.54E-06	8.59E-06	5.49E-06	1.34E-05
S4	MD	PV	LO	8	8.68E-06	2.05E-05	2.75E-06	1.60E-06	4.72E-06
S5	CC	UF	LO	8	8.70E-06	1.53E-05	7.75E-06	4.86E-06	1.24E-05
S4	VE	PV	LO	8	9.50E-06	1.51E-05	4.35E-06	2.64E-06	7.18E-06
P4	VE	SO	TO	8	9.54E-06	1.35E-05	5.74E-06	3.56E-06	9.24E-06
P4	PB	PV	TO	8	9.59E-06	2.19E-05	3.44E-06	2.05E-06	5.79E-06
P3	CC	UF	TO	8	9.75E-06	1.59E-05	5.72E-06	3.51E-06	9.34E-06
S5	VE	PV	LO	8	9.87E-06	1.15E-05	8.49E-06	5.40E-06	1.33E-05
S5	PB	PV	LO	8	1.04E-05	2.20E-05	4.08E-06	2.46E-06	6.77E-06
P3	MD	UF	LO	8	1.30E-05	2.84E-05	7.10E-06	4.42E-06	1.14E-05
P3	VE	UF	TO	8	1.33E-05	1.33E-05	1.25E-05	8.11E-06	1.94E-05
P3	CC	PV	TO	8	1.34E-05	1.79E-05	1.33E-05	8.67E-06	2.03E-05
S4	CC	UF	TO	8	1.35E-05	1.61E-05	1.20E-05	7.75E-06	1.86E-05
S5	CC	SO	LO	8	1.37E-05	2.51E-05	7.03E-06	4.43E-06	1.12E-05
P4	CC	PV	LO	8	1.46E-05	1.34E-05	1.18E-05	7.69E-06	1.82E-05
S5	MD	PV	LO	8	1.54E-05	2.91E-05	8.07E-06	5.12E-06	1.27E-05
S4	VE	UF	TO	8	1.55E-05	1.82E-05	1.33E-05	8.66E-06	2.05E-05
S5	VE	PV	TO	8	1.55E-05	2.53E-05	1.40E-05	9.21E-06	2.14E-05
S4	MD	SO	LO	8	1.60E-05	2.14E-05	1.08E-05	6.98E-06	1.66E-05
S4	PB	SO	LO	8	1.67E-05	3.30E-05	6.15E-06	3.84E-06	9.85E-06
P3	CC	SO	LO	8	1.79E-05	3.00E-05	1.40E-05	9.20E-06	2.12E-05
P3	MD	SO	TO	8	1.84E-05	3.29E-05	1.08E-05	7.02E-06	1.67E-05
S5	MD	PV	TO	8	1.84E-05	2.77E-05	1.23E-05	8.03E-06	1.89E-05
P4	CC	UF	TO	8	1.87E-05	2.97E-05	1.18E-05	7.59E-06	1.83E-05
S5	MD	SO	LO	8	1.91E-05	5.03E-05	5.44E-06	3.37E-06	8.79E-06
P3	MD	SO	LO	8	1.97E-05	3.56E-05	9.85E-06	6.35E-06	1.53E-05

Factors					Observed Check Density (mm^2/mm^2)		Predicted Check Density (mm^2/mm^2)		
Ven.	Core	Adh.	LCO	n	Mean	Std. Dev.	Mean	95% CI L. Bnd.	95% CI U. Bnd.
S4	CC	SO	TO	8	2.03E-05	4.57E-05	7.22E-06	4.56E-06	1.14E-05
P3	VE	SO	TO	8	2.15E-05	2.25E-05	1.65E-05	1.10E-05	2.49E-05
S5	PB	UF	LO	7	2.18E-05	3.54E-05	1.22E-05	7.45E-06	1.98E-05
P4	MD	UF	LO	8	2.22E-05	3.01E-05	1.91E-05	1.27E-05	2.88E-05
S4	MD	PV	TO	8	2.25E-05	5.51E-05	8.40E-06	5.34E-06	1.32E-05
S5	VE	SO	LO	8	2.30E-05	2.54E-05	2.67E-05	1.82E-05	3.92E-05
P3	VE	SO	LO	8	2.70E-05	5.97E-05	1.00E-05	6.48E-06	1.56E-05
P4	PB	SO	TO	8	2.73E-05	7.32E-05	7.16E-06	4.52E-06	1.14E-05
S5	CC	UF	TO	8	2.77E-05	7.02E-05	1.41E-05	9.19E-06	2.16E-05
P4	VE	UF	LO	8	2.97E-05	3.56E-05	2.97E-05	2.01E-05	4.37E-05
S5	PB	SO	TO	8	3.03E-05	8.49E-05	6.85E-06	4.31E-06	1.09E-05
S5	MD	SO	TO	8	3.12E-05	7.46E-05	9.38E-06	6.02E-06	1.46E-05
P3	VE	UF	LO	8	3.32E-05	6.04E-05	3.26E-05	2.22E-05	4.79E-05
P4	VE	SO	LO	7	3.39E-05	8.16E-05	8.95E-06	5.45E-06	1.47E-05
P4	VE	UF	TO	8	3.55E-05	6.85E-05	4.27E-05	2.94E-05	6.19E-05
P4	MD	PV	LO	8	3.57E-05	9.45E-05	9.98E-06	6.42E-06	1.55E-05
S4	VE	UF	LO	8	3.60E-05	5.76E-05	2.51E-05	1.69E-05	3.72E-05
S5	PB	SO	LO	8	3.68E-05	5.85E-05	2.26E-05	1.52E-05	3.34E-05
S5	VE	UF	LO	8	4.16E-05	4.62E-05	4.79E-05	3.32E-05	6.90E-05
S5	CC	PV	LO	8	4.43E-05	8.05E-05	2.57E-05	1.74E-05	3.79E-05
S4	CC	SO	LO	8	4.60E-05	1.21E-04	1.19E-05	7.74E-06	1.82E-05
P3	CC	UF	LO	8	4.98E-05	7.73E-05	3.56E-05	2.44E-05	5.21E-05
S5	CC	SO	TO	8	5.11E-05	1.30E-04	1.36E-05	8.95E-06	2.07E-05
P4	VE	PV	TO	8	5.49E-05	1.02E-04	3.87E-05	2.67E-05	5.61E-05
S4	VE	PV	TO	8	5.53E-05	1.40E-04	1.63E-05	1.08E-05	2.47E-05
S5	VE	UF	TO	8	7.70E-05	7.01E-05	6.37E-05	4.47E-05	9.09E-05
S5	VE	SO	TO	8	8.16E-05	1.98E-04	6.02E-05	4.24E-05	8.54E-05
S4	VE	SO	TO	8	9.35E-05	2.50E-04	2.38E-05	1.61E-05	3.51E-05
P4	CC	SO	LO	8	9.90E-05	2.40E-04	5.78E-05	4.07E-05	8.23E-05
P3	CC	SO	TO	8	1.00E-04	1.69E-04	4.33E-05	3.01E-05	6.23E-05

Table 21 Log scale treatment means, standard error and log scale 95% confidence interval bounds

Factors					Predicted check values (mean, CI's in mm^2/mm^2)			
Ven	Core	Adh	LCO	N	Mean	Std. Error	95% CI Lower Bound	95% CI Upper Bound
P3	PB	SO	LO	8	N/a	N	N/a	N/a
P4	MD	PV	TO	8	-16.4463	0.5419	-17.5085	-15.3841
P3	MD	PV	LO	8	-14.8224	0.3949	-15.5963	-14.0484
S4	CC	PV	LO	8	-14.7509	0.3896	-15.5145	-13.9873
S5	PB	UF	TO	8	-14.5386	0.3841	-15.2914	-13.7859
P4	MD	UF	TO	8	-14.4495	0.3777	-15.1897	-13.7092
P4	PB	UF	LO	8	-14.1820	0.3593	-14.8863	-13.4777
P4	VE	PV	LO	8	-14.0820	0.3441	-14.7565	-13.4076
P3	PB	PV	LO	8	-13.8796	0.3317	-14.5298	-13.2295
P3	PB	UF	TO	8	-13.5805	0.3221	-14.2118	-12.9492
S4	PB	UF	LO	8	-13.4868	0.3168	-14.1077	-12.8660
S4	PB	UF	TO	8	-13.4760	0.3162	-14.0957	-12.8564
P3	PB	PV	TO	8	-13.4386	0.3067	-14.0398	-12.8374
S5	MD	UF	LO	8	-13.2121	0.3018	-13.8037	-12.6205
P3	MD	PV	TO	8	-13.1822	0.2934	-13.7573	-12.6071
P4	PB	PV	LO	8	-13.1730	0.2929	-13.7471	-12.5988
S4	PB	PV	TO	8	-13.0463	0.2867	-13.6082	-12.4844
P3	CC	PV	LO	8	-12.9997	0.2844	-13.5572	-12.4422
P4	CC	UF	LO	8	-12.9911	0.2905	-13.5606	-12.4217
S5	PB	PV	TO	8	-12.9811	0.2835	-13.5368	-12.4253
P4	CC	PV	TO	8	-12.9059	0.2800	-13.4546	-12.3571
S4	MD	SO	TO	8	-12.8948	0.2775	-13.4386	-12.3510
P4	PB	SO	LO	8	-12.8874	0.2771	-13.4305	-12.3442
S4	MD	PV	LO	8	-12.8043	0.2753	-13.3438	-12.2648
S4	CC	PV	TO	8	-12.7860	0.2744	-13.3238	-12.2481
S5	MD	UF	TO	7	-12.7853	0.3160	-13.4048	-12.1659
P3	PB	UF	LO	8	-12.7420	0.2785	-13.2879	-12.1960
P4	MD	SO	LO	8	-12.6717	0.2674	-13.1958	-12.1476
S4	PB	PV	LO	8	-12.6617	0.2689	-13.1887	-12.1348
P3	VE	PV	TO	8	-12.6358	0.2677	-13.1606	-12.1111
P4	PB	PV	TO	8	-12.5788	0.2652	-13.0987	-12.0589
S5	CC	PV	TO	8	-12.5391	0.2635	-13.0557	-12.0226
S4	MD	UF	LO	8	-12.4402	0.2650	-12.9595	-11.9208

Factors					Predicted check values (mean, CI's in mm^2/mm^2)			
Ven	Core	Adh	LCO	N	Mean	Std. Error	95% CI Lower Bound	95% CI Upper Bound
S4	MD	UF	TO	8	-12.4262	0.2644	-12.9443	-11.9080
S5	PB	PV	LO	8	-12.4091	0.2581	-12.9149	-11.9032
S4	VE	PV	LO	8	-12.3453	0.2555	-12.8461	-11.8446
S4	PB	SO	TO	8	-12.3274	0.2530	-12.8233	-11.8315
P3	PB	SO	TO	8	-12.3205	0.2527	-12.8159	-11.8252
P4	MD	SO	TO	8	-12.2334	0.2493	-12.7220	-11.7447
P3	MD	UF	TO	8	-12.1910	0.2546	-12.6899	-11.6921
S4	VE	SO	LO	8	-12.1228	0.2451	-12.6031	-11.6425
S5	MD	SO	LO	8	-12.1217	0.2450	-12.6019	-11.6415
S4	CC	UF	LO	8	-12.1109	0.2513	-12.6035	-11.6183
P3	CC	UF	TO	8	-12.0708	0.2498	-12.5603	-11.5812
P4	VE	SO	TO	8	-12.0684	0.2430	-12.5447	-11.5921
P4	PB	UF	TO	8	-12.0620	0.2494	-12.5508	-11.5731
P3	VE	PV	LO	8	-12.0561	0.2442	-12.5347	-11.5775
S4	PB	SO	LO	8	-11.9998	0.2405	-12.4711	-11.5285
S5	PB	SO	TO	8	-11.8907	0.2365	-12.3543	-11.4271
S5	CC	SO	LO	8	-11.8648	0.2356	-12.3267	-11.4030
P3	MD	UF	LO	8	-11.8555	0.2416	-12.3290	-11.3820
P4	PB	SO	TO	8	-11.8464	0.2350	-12.3070	-11.3859
S4	CC	SO	TO	8	-11.8391	0.2347	-12.2991	-11.3790
S5	CC	UF	LO	8	-11.7681	0.2384	-12.2353	-11.3009
S5	MD	PV	LO	8	-11.7270	0.2323	-12.1824	-11.2716
S4	MD	PV	TO	8	-11.6873	0.2310	-12.1401	-11.2346
S5	VE	PV	LO	8	-11.6771	0.2306	-12.1292	-11.2251
P4	CC	SO	TO	8	-11.6649	0.2288	-12.1133	-11.2166
P4	VE	SO	LO	7	-11.6233	0.2535	-12.1201	-11.1265
S5	MD	SO	TO	8	-11.5770	0.2259	-12.0197	-11.1343
P3	MD	SO	LO	8	-11.5278	0.2243	-11.9674	-11.0883
P4	MD	PV	LO	8	-11.5152	0.2253	-11.9568	-11.0737
P3	VE	SO	LO	8	-11.5091	0.2237	-11.9475	-11.0707
S4	MD	SO	LO	8	-11.4333	0.2213	-11.8669	-10.9996
P3	MD	SO	TO	8	-11.4381	0.2214	-11.8721	-11.0041
P4	CC	UF	TO	8	-11.3446	0.2199	-11.7756	-10.9137
P4	CC	PV	LO	8	-11.3495	0.2241	-11.7887	-10.9103
S4	CC	SO	LO	8	-11.3411	0.2184	-11.7691	-10.9130

Factors					Predicted check values (mean, CI's in mm^2/mm^2)			
Ven	Core	Adh	LCO	N	Mean	Std. Error	95% CI Lower Bound	95% CI Upper Bound
S4	CC	UF	TO	8	-11.3298	0.2234	-11.7678	-10.8919
S5	PB	UF	LO	7	-11.3178	0.2496	-11.8070	-10.8287
S5	MD	PV	TO	8	-11.3040	0.2186	-11.7325	-10.8755
P3	VE	UF	TO	8	-11.2874	0.2221	-11.7227	-10.8521
P3	CC	PV	TO	8	-11.2314	0.2164	-11.6556	-10.8072
S4	VE	UF	TO	8	-11.2256	0.2201	-11.6571	-10.7941
S5	CC	SO	TO	8	-11.2038	0.2143	-11.6238	-10.7837
P3	CC	SO	LO	8	-11.1781	0.2136	-11.5967	-10.7596
S5	VE	PV	TO	8	-11.1748	0.2147	-11.5957	-10.7539
S5	CC	UF	TO	8	-11.1694	0.2184	-11.5975	-10.7413
S4	VE	PV	TO	8	-11.0219	0.2103	-11.4341	-10.6096
P3	VE	SO	TO	8	-11.0111	0.2088	-11.4203	-10.6018
P4	MD	UF	LO	8	-10.8671	0.2095	-11.2778	-10.4564
S5	PB	SO	LO	8	-10.6991	0.2005	-11.0921	-10.3061
S4	VE	SO	TO	8	-10.6477	0.1992	-11.0381	-10.2572
S4	VE	UF	LO	8	-10.5943	0.2022	-10.9905	-10.1980
S5	CC	PV	LO	8	-10.5691	0.1984	-10.9579	-10.1802
S5	VE	SO	LO	8	-10.5307	0.1964	-10.9156	-10.1458
P4	VE	UF	LO	8	-10.4252	0.1979	-10.8130	-10.0374
P3	VE	UF	LO	8	-10.3299	0.1956	-10.7132	-9.9466
P3	CC	UF	LO	8	-10.2420	0.1935	-10.6212	-9.8628
P4	VE	PV	TO	8	-10.1590	0.1889	-10.5291	-9.7888
P4	VE	UF	TO	8	-10.0619	0.1894	-10.4331	-9.6907
P3	CC	SO	TO	8	-10.0479	0.1855	-10.4115	-9.6843
S5	VE	UF	LO	8	-9.9472	0.1869	-10.3134	-9.5809
P4	CC	SO	LO	8	-9.7580	0.1798	-10.1104	-9.4057
S5	VE	SO	TO	8	-9.7186	0.1790	-10.0694	-9.3677
S5	VE	UF	TO	8	-9.6609	0.1810	-10.0157	-9.3061

9. Wood equilibrium moisture content equation

This empirical formula, often referred to as Simpson's formula, fitted to the experimentally determined sorption isotherms for many species of wood allows us to predict with some level of accuracy how much the moisture content of wood may change when moving from one environment to another, and is important for determining dimensional changes occurring in wood once it is placed in service. This formula was used to calculate EMC values of the test environment during testing.

$$EMC(\%) = \frac{1800}{W}\left(\frac{Kh}{1-Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1+\ K_1Kh +\ K_1K_2K^2h^2}\right)\ eq.3$$

Where h is relative humidity and the following variables are defined in relation to temperature, T:

Table 22 Variable definitions for EMC calculation (Simpson, 1998)

Variable	**Value (Temp in °C)**	**Value (Temp in °F)**
W	$349 + 1.29T + 0.0135T^2$	$330 + 0.452T + 0.00415T^2$
K	$0.805 + 0.000736T – 0.00000273T^2$	$0.791 + 0.000463T – 0.000000844T^2$
K_1	$6.27 - 0.00938T – 0.000303T^2$	$0.805 + 0.000775T – 0.0000935T^2$
K_2	$1.91 + 0.0407T – 0.000293T^2$	$0.805 + 0.0284T – 0.0000904T^2$

10. Questionnaires used in survey

Questionnaire for Veneer Manufacturers

The Oregon Wood Innovation Center at Oregon State University is conducting a research project to better understand the factors leading to checking of maple veneer in hardwood plywood. The primary objective is to identify the optimum combination of variables (veneer thickness, adhesive, core type, etc.) to minimize checking in maple veneer. We are working with WHPP to select the variables to be explored in the study. Your assistance is critical to ensure we select variables that are most relevant to the hardwood plywood industry.

1. Please list the primary regions from which you source hard maple logs/flitches:
   State/Province_________, volume of material as % of total______

   State/Province__________, volume of material as % of total______

   State/Province_________, volume of material as % of total______

   State/Province_______, volume of material as % of total_____

   (please add more lines if needed)

2. What thicknesses of maple veneer do you produce?

	Rotary (% Produced)	Sliced (% Produced)
1/36”		
1/42”		
Other:		
Other:		
Other:		

3. Please list the ratio of sliced to rotary peeled maple you produce:
   Plain sliced, ___% of total
   Peeled, ___% of total

4. How do you condition maple logs/flitches:
   Hot water bath, ___% of total

Steam, _____% of total

Other__________, ___% of total

5. How do you dry maple veneer (method, time, temperature, etc.)?

6. Which season are checks in maple veneer typically reported by customers?

Questionnaire for Plywood Producers

The Oregon Wood Innovation Center at Oregon State University is conducting a research project to better understand the factors leading to checking of maple veneer in hardwood plywood. The primary objective is to identify the optimum combination of variables (veneer thickness, adhesive, core type, etc.) to minimize checking in maple veneer. We are working with WHPP to select the variables to be explored in the study. Your assistance is critical to ensure we select variables that are most relevant to the hardwood plywood industry.

7. What thicknesses and cut of maple veneer do you purchase?

	Sliced (% of Purchases)	Rotary (% of Purchases)
1/36"		
1/42"		
Other:		
Other:		
Other:		

8. Please list the adhesives that you use for maple plywood:
UF, ____% of total

PVA, ___% of total

Soy-based, _____% of total

Other__________, ___% of total

9. Which core types do you use with maple plywood?

	UF / ULEF (% of Production)	NAUF (% of Production)	NAF (% of Production)
Particleboard			
MDF			
Veneer			
Combination			
Other:			

10. Which combination of core type, adhesive, and prep method (sliced or peeled) leads to the greatest number of customer complaints related to checking?

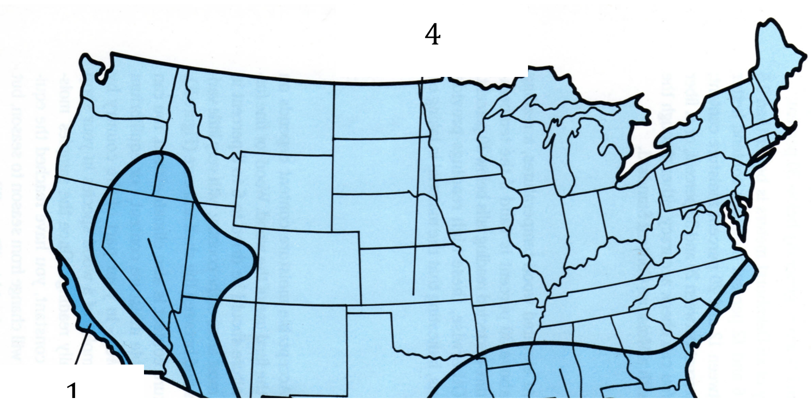
    1st ____

    2nd ____

    3rd ____

11. Which season and region (1-4) are checks in maple veneer typically reported by customers?

	Percent of claims by region			
	1	2	3	4
Summer				
Fall				
Winter				
Spring				



11. List of samples that received contrast adjustment

The following samples had their image series contrast adjusted using ImageJ.

Block	Samples
A	1, 4, 8, 22, 25, 26, 29, 30, 31, 41, 44. 45. 42, 58, 59, 60, 65, 69, 72, 83, 85, 96
B	28
F	91

12. CD-ROM Attachments

Attached on CD-ROM are copies of the check finding and characterization software, data sets, and survey response.