SCANNING ELECTRON MICROSCOPY OF PLYWOOD GLUE LINES[1]

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ABSTRACT

Douglas-fir plywood panels made under specific conditions to represent dried-out, undercured, high-moisture, and rough-veneer glue bonds were tested in shear, and the failure surfaces were evaluated by light and scanning electron microscopy.

Results showed low shear strength and low percentages of wood failure in all above panels. Wood failure occurred both by intrawall failure and transwall failure parallel with the grain direction in wood. Scanning electron microscopy made it possible to distinguish between glue-coated areas versus uncoated wood fracture and clearly showed glue distribution and the physical form of glue on the failure surface.

Dried-out bonds are characterized by the lack of a continuous glue line, little or no transfer of glue onto the face veneer, and mostly by adhesive failure. The most important features of high-moisture joints are the formation of numerous steam bubbles in the glue line and the lack of a continuous glue bond. These are due to the excessive squeeze-out of glue in the press and the overpenetration of glue into the wood. Both rough-veneer and low-pressure joints provide discontinuous glue lines because of the lack of continuous contacts between the adjacent veneers.

All results show that examination of shear specimens by SEM is an effective method for determining the cause of glue-line failure.

INTRODUCTION

The study of glue lines has been of prime interest to the plywood manufacturer at the manufacturing plants. The quality of glue line is evaluated mostly by the standard shear test, and the cause of failure is determined mostly on the bases of visual observations of the exposed fracture surfaces. At the research level, the glue line is routinely studied by light microscopic techniques, including standard stereo and transmitted light, and more recently by fluorescence microscopy in sectional and surface views (Quirk 1968; Côté and Vasishth 1970). The latter is based on the property that the adhesive fluoresces differently from wood, either on its own or through the addition of fluorochromes.

The present study employs scanning electron microscopy for glue line evaluation. This instrument has been selected because it is able to distinguish most accurately between the areas covered with glue and those that are free of adhesives.

MATERIALS AND METHODS

This investigation utilized Douglas-fir plywood panels formed with phenol formaldehyde for the study of the quality of glue bond. Several panels were made experimentally with the following variables: (1) high moisture content (12%), (2) dried-out glue line before hot pressing, (3) rough-veneer surface, (4) short pressing time, and (5) normal conditions.

The quality of glue bond was evaluated by the standard shear test and the percentage of wood failure. In each case the one-square-inch shear failure surface was

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studied by stereo-light microscopy, and the percentage of wood failure was determined by area measurements.

Representative areas (1 cm^2) were also selected for scanning electron microscopic observations. These specimens were mounted onto standard aluminum stubs with double-coated tape and were then coated with a 200-Å-thick layer of gold-palladium alloy in a high vacuum evaporator. The edges of the specimens were painted with silver to provide contact with the aluminum stub and the examination was carried out in the Cambridge Stereoscan II electron microscope. This technique provided excellent three-dimensional views of the overall surface morphology of plywood fracture.

RESULTS AND DISCUSSIONS

Failure can occur in principally three different sites: (1) in wood, (2) within the glue line (cohesive failure), and (3) at the interface of wood and glue (adhesive failure). When failure occurs entirely within wood, thus exposing wood on both surfaces, this is designated as "100% wood failure." This occurs mostly when there is a good glue bond, but sometimes when the veneer surface is weakened by frequent and intensive lathe checking.

Conversely, when failure occurs entirely within the glue line, without exposing any wood, this is designated as "cohesive glue failure." This type of failure is due to inferior glue quality, since under normal conditions a good glue bond is stronger than wood.

When failure occurs at the interface of the glue line and wood, thus exposing 100% glue on one surface and 100% wood on the opposite surface, this is designated as "adhesive failure." This occurs when the adhesive strength between glue and wood is weaker than either the cohesive strength of glue or the strength of wood. In most instances failure in the glue line region involves the combination of the three types of failure: wood, glue, and interface. These will be described in the various types of glue joints.

Good bond

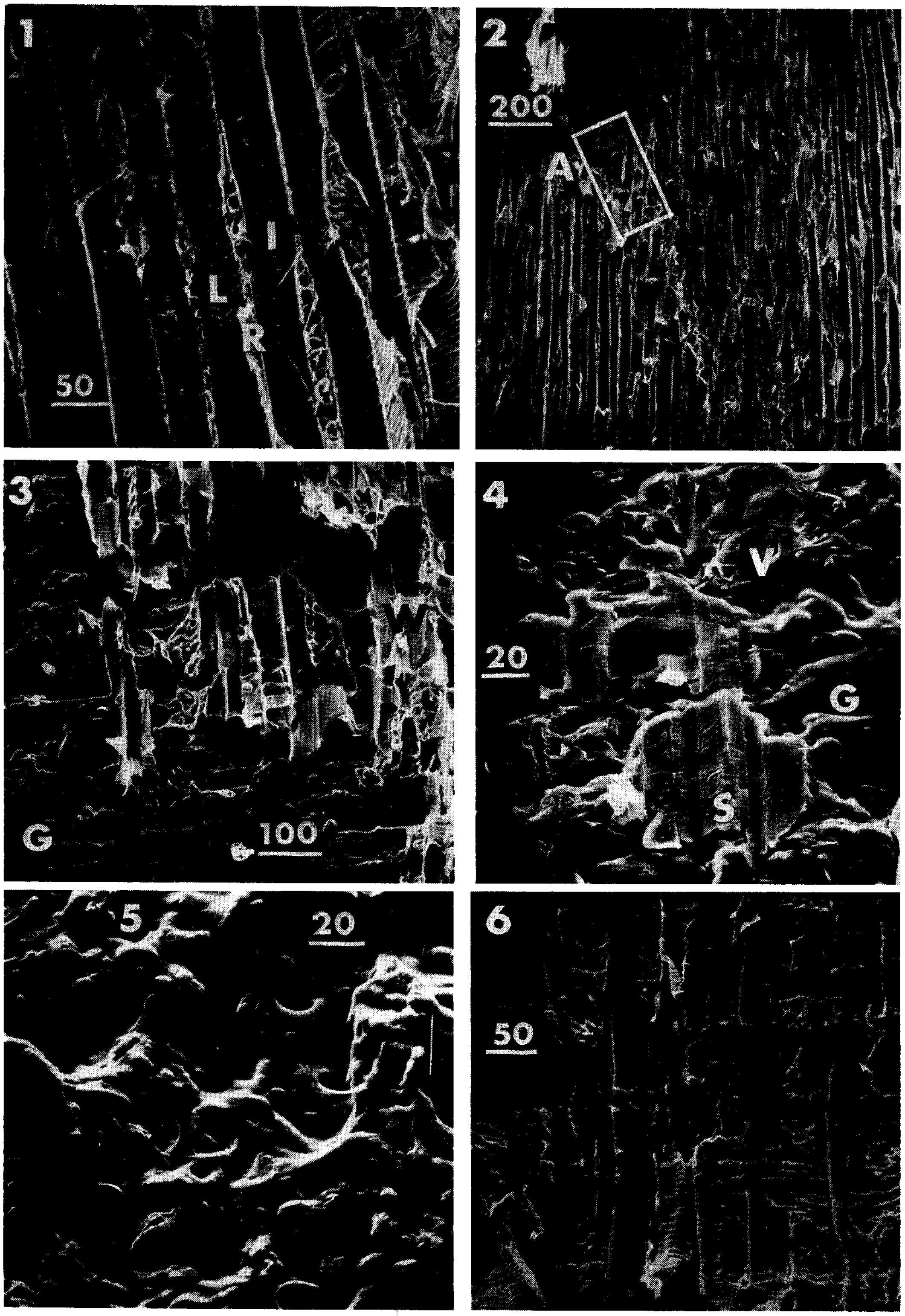
This bond is formed as a result of optimum conditions in wood, glue, and in the manufacturing variables. Good bond is characterized by high breaking stress and by a high percentage of wood failure (93%) obtained in the shear test. Microscopic examination shows continuous glue lines between the various veneer layers, without the presence of air bubbles, and optimum glue penetration into the tracheid lumens immediately adjacent to the glue line. Here the glue remains in close contact with the lumen lining without any separation between the cell wall and the glue.

As expected from the geometry of the test specimen, the plane of failure coincides with the tangential plane in wood. More specifically, the zone of failure falls either in the springwood zone, or alternatively at the growth ring boundary. At the cellular level the fracture path may go across the tracheids, or it may remain within the tracheid wall.

Figure 1 shows an example in which the tracheids on the veneer surface are split into two halves parallel to their long axes, thus exposing the fractured radial walls (*R*) and the inner surfaces of tracheids from the lumen side, that is the S_3 layer of the secondary wall with the spiral thickening (*L*). In the fractured radial walls (*R*), all layers of the fiber wall are exposed. This type of wood failure is defined as "transwall failure parallel with the tracheid axis."

Figure 2 shows a representative example where failure occurs across several tracheids, as a result exposing their end walls and lumens. This type of failure is defined as "transwall failure perpendicular to the tracheid axis" (Koran 1968).

Figure 1 shows several examples in which the site of failure falls within the double tracheid wall (*I*), thus exposing its internal structure. This type of failure has been defined as "intrawall failure" (Koran 1968). In general, the areas exposed by transwall failure parallel with the tracheid axis and by intrawall failure are about equal. Transwall failure perpendic-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ular to the tracheid axis is the least common type of failure.

Dried-out glue line

This type of glue line is formed when much of the water has evaporated from the glue film before the glue film contacts the unspread surface. As a result, the glue film does not flow under heat and pressure and adequately "wet" the unspread surface. Thus, a substandard glue bond is formed.

Studies made on four independent "dried-out" specimens revealed (1) low shear stress values, (2) low percentage of wood failure (15%), (3) little or no glue transfer, (4) little or no glue penetration into the face veneer. Bond failure consisted mainly of (a) wood failure, (b) adhesive failure, and (c) unbonded areas.

A representative example of wood failure is shown in Fig. 3. Fragments of tracheids (*W*) torn out of the face veneer remain attached to the glue on the core surface. This means that in these areas, either the wood was weakened, or the glue bond was stronger than the wood itself. Figure 3 also shows that wood failure occurred in the forms of intrawall failure and transwall failure parallel with the tracheid axis.

Adhesive failure can be identified by the impression the face veneer leaves in the glue on the core surface. Representative examples are seen in Figs. 4 and 6. These imprints are fairly accurate replicas formed of the tracheid surfaces exposed on the face veneer. In Fig. 4, for example, the parallel microfibrillar structure of the S_1 layer is accurately reproduced, while in Fig. 6 a cast of the fiber lumen is produced with the inner surface of the lumen lining accurately replicated. These micrographs suggest that in these areas fairly close contacts have been established between the wood and glue, but probably specific adhesion was not produced because of the inability of the prehardened glue to wet the fiber surface.

Unbonded area represents the glue surface without any imprint of the face veneer in it. In these regions, no contact has been established between the face veneer and glue spread core. Therefore, in the shear tests no failure occurs in these regions. Scanning electron micrographs of the glue spread core veneer (Figs. 3 and 4 at *G*) reveal that these areas possess undisturbed and smooth glue-covered veneer surfaces, except for the variations in overall surface topography. Under incident light illumination, these glue-coated areas appear highly shiny and somewhat glazed.

The presence of unbonded areas in the glue line has been confirmed by Fig. 5, which was taken from an area where there was a knothole in the face veneer. As a result this was an open glue line on the core without any contact with the face veneer. As expected, the surface morphology of the glue line in the knothole area (Fig. 5) was identical to those in the unbonded areas of dry-out glue joint (Figs. 3 and 4).

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FIG. 1. Scanning electron micrograph (SEM) of Douglas fir-plywood failure in the tangential plane showing transwall failure parallel with the tracheid axis, tracheids with spirals (*L*), and intrawall failure (*I*) indicated by tracheids without spirals. All scales are in micrometers (μm).

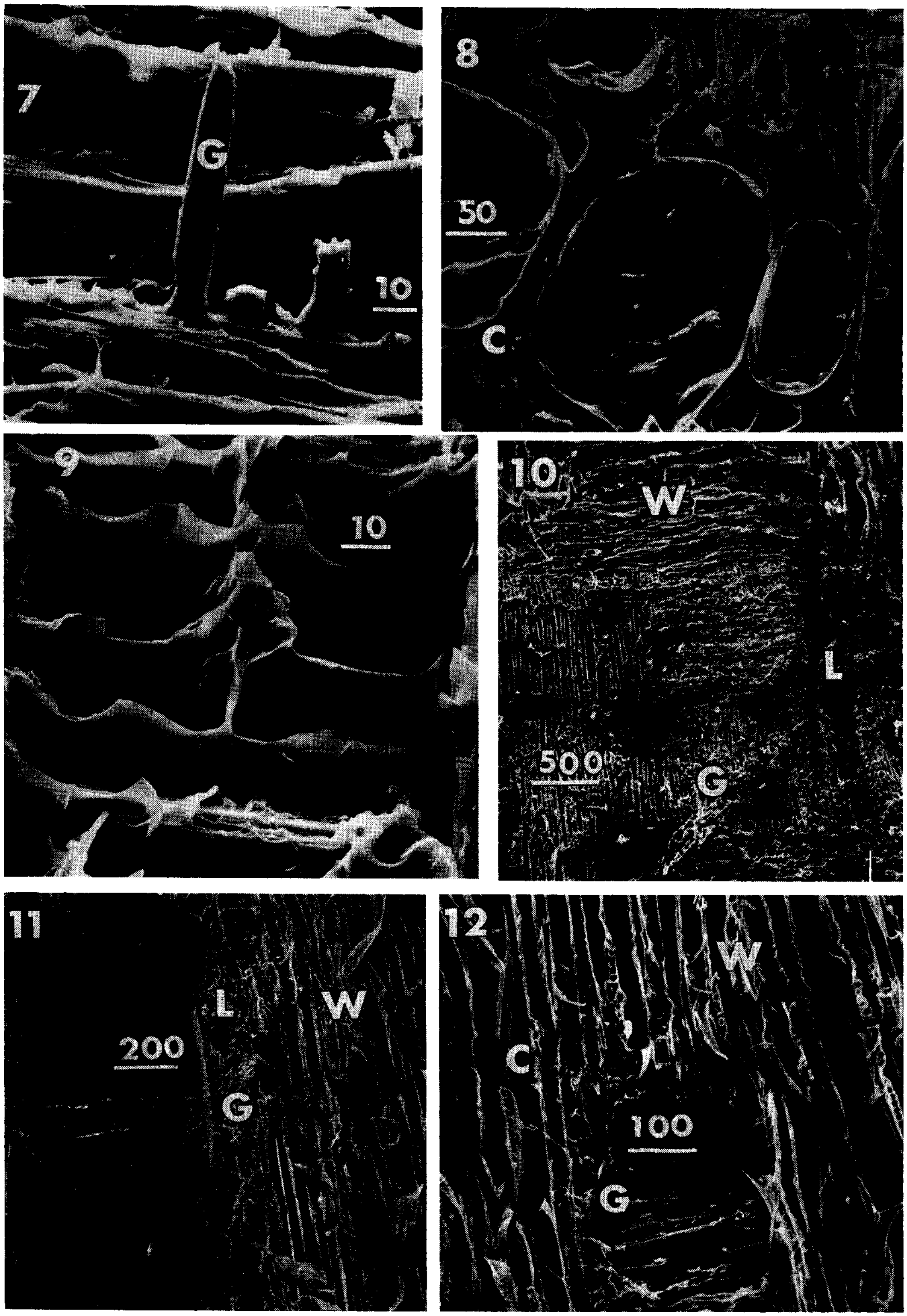
FIG. 2. Transwall failure perpendicular to the tracheid axis exposing the cross walls and lumens of tracheids (*A*).

FIG. 3. Dried-out glue joint showing wood failure (*W*) and adhesive failure consisting mostly of unbonded areas (*G*).

FIG. 4. Dried-out glue line showing adhesive failure with imprints of the tracheid wall (S_1), unbonded areas (*G*) and steam vents (*V*).

FIG. 5. Dried-out glue line consisting entirely of unbonded glue on the core veneer just below a knothole in the face veneer. Note that the glue exposes smooth and undisturbed surface topography.

FIG. 6. Dried-out glue line in which the spiral thickenings of Douglas-fir tracheids are accurately replicated.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Starved glue joint

This glue line was formed of veneer with high-moisture content which caused much of the glue to penetrate into the veneer surface, thus leaving an insufficient amount of glue to form a continuous glue line. Studies made on panels possessing starved glue joint revealed: (1) low shear stress values, (2) low percentage of wood failure (12%), (3) numerous blisters, (4) the absence of a continuous glue line, and (5) the presence of deep glue penetration into the wood, but not enough glue to fill completely the openings on the veneer surface.

The deep glue penetration was especially apparent in the wood rays where glue penetration was several cells deep. This is illustrated in the scanning electron micrograph of Fig. 7 where the polelike structures in the center of the picture are solid glue bodies pulled out of the ray cells from the opposite surface during the shear test. In Fig. 7 the tall glue pole is 45 μm in height, which means a minimum of 45 μm penetration into the opposite surface. In general, glue penetration was deeper into the core surface than into the face veneer.

Microscopic examination of the exposed fracture surfaces revealed uniform glue coverage on both the face and core veneer surfaces. However, these surfaces exhibited a highly washed-out appearance, with little glue remaining on the surface. This means that glue transfer from the spread core onto the unspread face veneer was generally complete, but since most of the glue penetrated into the veneer surface, little glue remained to form the final glue bond.

Another common feature of the high-moisture glue bond is the formation of steam pockets in the glue line during the hot press operation at 340 F. Although much of the steam escapes during the pressing operation, part of the steam becomes captured within the glue line in steam pockets, such as the one observed in Fig. 8. These pockets vary in size and shape (Fig. 8), and the larger ones may develop into blisters upon the release of pressure. Other forms of steam pockets are observed in Fig. 9. In such cases, the entire glue line seems to possess a uniform foamlike texture, indicating the presence of an excessive amount of steam throughout the glue bond during pressing.

Undercured glue line

In undercured plywood panels, the formation of glue bond is normal up to the pressing operation. However, in the hot press, the pressure is released before the complete polymerization of the glue is achieved, that is, before maximum strength is developed in the glue bond. Therefore, in undercured plywood panels, the glue bond fails in many areas upon the release of pressure. This is because the partially cured glue bond is not able to withstand the localized tensile forces upon the springback of the veneer.

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FIG. 7. Glue line formed on veneer with high-moisture content. The depth of glue penetration is indicated by the height of glue casts (*G*) pulled out of some ray cells in the shear test. All scales are in micrometers (μm).

FIG. 8. Glue line formed of high-moisture veneer. Cohesive failure (*C*) in glue is clearly apparent between the steam pockets, which weaken the glue line.

FIG. 9. Glue line formed of veneer with high-moisture content, showing foamlike structure and cohesive failure between the steam pockets.

FIG. 10. Wood failure (*W*) and glue failure (*G*) in undercured glue line. Note also the accumulation of glue in the lathe check (*L*).

FIG. 11. Rough veneer glue line showing the accumulation of glue in the lathe check (*L*), glue failure (*G*) and wood failure (*W*).

FIG. 12. Transverse compression folds (*C*) in the walls of tracheids immediately adjacent to the glue line which causes their formation as a result of existing compressive stresses.

In this study the undercured plywood panels possessed low shear strength and a low percentage (50%) of wood failure. SEM observations revealed an equally uniform glue coverage and penetration on both veneer surfaces and the presence of a continuous glue line. Figure 10 is a low-magnification view of an undercured glue bond exposing surfaces of both wood (*W*) and glue (*G*) failure. Closer examination of the glue failure reveals both cohesive and adhesive failures.

Figure 12 shows an area containing glue failure (*G*) and wood failure (*W*). In the latter, transverse compression folds (*C*) can be observed in the tracheid walls immediately above the glue line. These folds were introduced during hot pressing and are now maintained by the glue line just below the wood surface. This proves that localized stresses are set up during the pressing operations and these stress zones are maintained in the plywood panels by the resisting effect of the glue line.

Rough veneer joint

In many respects the glue line of plywood panels formed of rough veneer is similar to the dried-out glue line. When glue is spread onto the rough core veneer surface, it tends to flow into the depressions, cracks, lathe checks (Fig. 11 at *L*), accumulate in these areas and leave relatively little glue in the high areas. In the hot press, direct contact is made only in the high areas where some bond is formed, while in the depressions where most of the glue accumulates, no contact is made. Here, the glue simply dries onto the core veneer surface and cures without forming any bond. This type of panel possesses starved localized joints in the high areas and dried-out, unbonded glue line in the low areas.

In many cases the glue in the unbonded areas contained large bubbles, similar to those in Figs. 8 and 9. In other areas of the fracture surface, impressions of the face veneer were formed in the glue surface of the core veneer, such as the type observed in Figs. 4 and 6. These probably originated from the intermediate pressure areas in the plywood, where pressure was not high enough to establish a complete bonding between wood and glue.

In general, plywood formed of rough veneer possessed low shear strength and low percentage of wood failure (15%).

CONCLUSIONS

Plywood panels formed of veneer with high-moisture contents, rough surface topography, dried-out glue on the core surface, and undercured glue line are characterized by low shear strength and low percentage of wood failure.

Good bonds possess a continuous glue line that is stronger than the wood itself. In shear test this type of bond produces nearly 100% wood failure, which occurs preferentially in springwood or at the growth ring boundary. Wood failure occurs in the forms of intrawall failure, transwall failure parallel with the grain direction, and transwall failure perpendicular to the tracheid axis. Failure types of the first two kinds are of about equal occurrence, while the last is rather rare.

Dried-out bonds are characterized by the lack of glue transfer, glue flow, wetting and penetration, and by the lack of a continuous glue line. The shear fracture surface of dried-out bond displays high percentages of adhesive failure and unbonded areas and a low percentage (15%) of wood failure.

Glue joints formed of veneer with high moisture content reveal good glue transfer from core onto face, overpenetration of glue into wood, excessive squeeze-out of glue in the hot press, the formation of numerous air bubbles in a rather discontinuous, starved glue line, and a low percentage of wood failure (12%).

Shear failure surfaces of rough veneer joints are characterized by adhesive failure with imprints in the glue, cohesive failure in glue, unbonded glue areas, and by a low percentage of wood failure (15%).

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