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The influence of lathe check depth and orientation on the bond quality of phenol-formaldehyde – bonded birch plywood

Abstract: During the rotary peeling of veneer for plywood or the laminated veneer lumber manufacture, checks are formed in the veneer that are as deep as 70–80% of the veneer thickness. The results of this study show that, during adhesive bond testing, deep lathe checks in birch (*Betula pendula* Roth.) veneer significantly reduce the shear strength and the percent wood failure of phenol-formaldehyde (PF) – bonded plywood. The results also show that specimens tested with the checks pulled open or closed can fail by different mechanisms. Dried rotary peeled birch veneers were sanded to create uniform surfaces with lathe check depths varying from 30% to 90% of veneer thickness. Then, 7-ply plywood was manufactured with a commercial PF resin. After the preparation of the test specimens, the check depth of each specimen was measured microscopically. Subsequently, bond quality was measured according to EN 314. The results show that veneer checking alone can bring EN 314 specimens to the brink of failure even with an excellent adhesive. These findings stress the importance of measuring the depth of lathe checks and considering the orientations of checks during the testing to get a better understanding of bond quality in veneer-based products.

Keywords: bond quality, lathe checks, percent wood failure, plywood, share strength

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Introduction

There are numerous factors affecting the plywood bond quality and more than 100 of them have been described by Marra (1992). Generally, the quality of the adhesive bond in plywood is evaluated by testing saw kerfed specimens in tensile shear. The standard testing methods in the United States and Europe are different. The "pass/fail" adhesive bond quality criterion in the U.S. standard PS 1-95 "Construction and Industrial Plywood" (National Institute of Standards and Technology, NIST 1996) is linked to the percentage wood failure (PWF). In the European Standard EN 314 "Plywood Bonding Quality" (The European Standard 1993, 2004), both the PWF and the shear strength are used in assessing the adhesive bond performance. In both standards, wet evaluation is recommended, but the means of evaluating bond quality differs. DeVallance et al. (2006) tested plywood according to PS 1-95 and did not observe any statistical differences between wet and dry bonds in terms of the PWF, although the loads at failure were different. The conclusion was that bonds do not need to be tested wet. On the contrary, dry testing does not detect undercured or overpenetrated bonds. In the case of fully cured bonds, the difference between wet and dry PWF is not statistically significant according to DeVallance et al. (2006), but with undercured resin notable differences may be observed (Black and Olson 1947). In some cases, undercured adhesive bonds can give rise to high dry PWF values but will delaminate during wet testing (Black and Olson 1947). The main objective of wet testing is to verify whether proper bonds are formed based on the "pass/fail" criterion.

Veneer characteristics correlate strongly with adhesive bond quality (Koch 1965a; Christiansen 1990; Fucheng and Shengquan 2001; Aydin et al. 2006). One of the characteristics is surface roughness, which affects the adhesive consumption (Marra 1992; DeVallance et al. 2007; Palubicki et al. 2010) and the long-term bond strength (Sinn et al. 2009). While studying the effect of roughness on bond quality, the importance of lathe checks was noted (Neese et al. 2004). Nevertheless, the depth and the frequency of lathe checks have seldom been taken into account during bond quality evaluation. Neese et al. (2004) found that most plywood bonds tended to fail along the loose side (side toward peeling blade), and this was interpreted to mean that lathe checks and surface roughness interact to diminish the bond performance. DeVallance et al. (2007)

found that reducing veneer surface roughness increased the PWF. Additionally, Neese et al. (2004) noted that the lathe checks played a significant role in determining the PWF. Chow and Warren (1972) suggested that the PWF shows the undercuring of resin and describes the level of adhesion between veneer and adhesive and that the shear strength reflects mainly the quality of veneer. Chow (1974) noted that there is no direct relationship between the shear strength of plywood and the PWF but that shear strength is affected by the depth of the lathe checks.

Not surprisingly, the check depth, check frequency, and bond strength are interrelated. To begin with, deeper checks tend to be less frequent than shallower checks (Koch 1965b; Korpijaakko 1999). According to Korpijaakko (1999), reducing check depth is beneficial because numerous shallower checks have been found to be less detrimental to bond strength than a lower frequency of deep checks. DeVallance et al. (2007), on the contrary, found that, by reducing the frequency of checks, the load at failure can be increased. Koch (1965a) found a significant, but extremely weak, negative relationship between lathe check frequency and PWF. Moreover, the depth of checks did not correlate with the PWF.

A further complication found in the literature relates to whether bonds are pulled open or closed. During peeling, checks form on the surface curving away from the knife and move through the veneer at an angle to the surface. When testing according to European Standard EN 314, the results differ depending on whether the checks are pulled open (Figure 1c) or closed (Figure 1d) (Marra 1992). It has been reported that the shear strength of plywood pulled closed results in higher strength values than when the checks are pulled open; however, the magnitude of the strength difference varies from 14% to 94% (Bethel and Huffman 1950; Koch 1965b; Chow 1974; DeVallance et al. 2006). The variation in strength might be due to check depth, but in most published reports the depth of checks is not presented or the depth variation of checks was obtained by varying the peeling conditions. It is well known that altering peeling conditions (e.g., log temperature and peeling speed) will also cause changes in other veneer surface properties, such as surface roughness or wettability (Bethel and Huffman 1950; Aydin et al. 2006). It is challenging to produce veneer with similar surface properties while having differences in the check depth. One solution to this problem is to evaluate an equal number of open and closed specimens in each test (ASTM Standard D906-98 2004). This solution merely reduces the influence of lathe checks in the final results rather than truly accounting for, or controlling, their impact. DeVallance et al. (2006) found that the orientation did not make

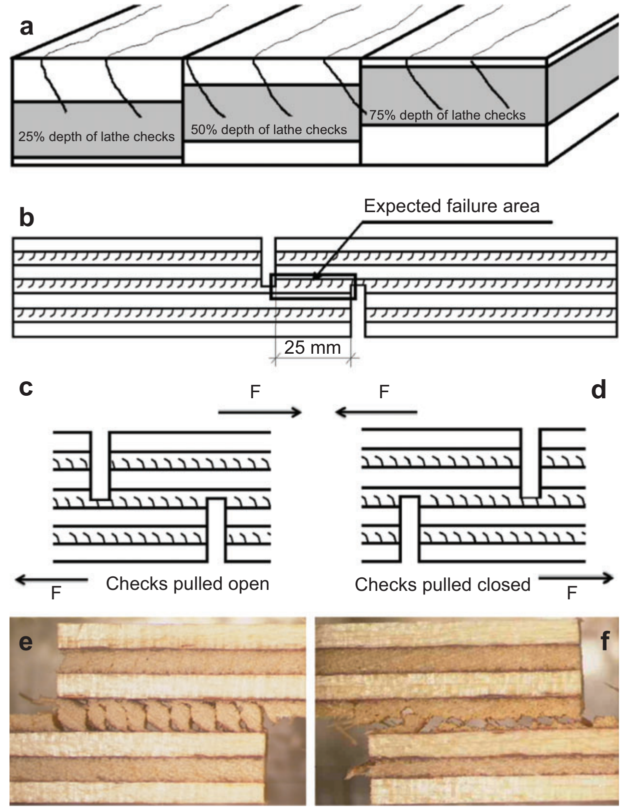

Figure 1 (a) Schematic representation of the three veneer groups to control check depth (the shaded area is the final veneer after sanding). (b) Schematic visualization of plywood shear test configuration and bondline under test. (c) Middle ply with lathe checks pulled open. (d) Middle ply with lathe checks pulled closed. (e) Plywood failure in open fashion. (f) Plywood failure closed fashion. (The loose side of the tested veneer is at the bottom of c–f.)

a significant difference to the PWF and for this reason claimed that, in standard testing, less attention should be paid to the issue of check orientation. However, because EN 314 (The European Standard 1993) takes failure loads into account, the orientation of the checks relative to the testing direction is relevant.

The aim of this work was to evaluate the effect of lathe check depth and check orientation on failure stress and PWF according to EN 314. At present, there is no robust understanding of how the depth of checks affects the bonding quality of plywood. Also, there is a lack of consensus as to the role that both the PWF and the shear strength values play in the determination of bond quality. Because it is practically impossible to peel veneer with different check depths and yet keep all other veneer parameters constant, in the present article, the veneers were peeled and then sanded to different extents on either side. Thus, different check depths could be produced with the same surface quality. Contact angle (CA) measurements were employed to verify that there were no significant differences in the physiochemical properties of veneers surfaces and the depth of checks was evaluated by light microscopy. The veneers were laid up to form plywood and the bond strength was tested according to EN 314, with the checks being pulled open and closed under wet and dry conditions.

Materials and methods

Wood material and preparation

Fresh birch (*Betula pendula* Roth.) logs, felled in the autumn in southern Finland, were soaked in water at 20°C for 48 h before rotary peeling on an industrial size lathe (Model 3HV66; Raute Oyj, Nastola, Finland). After peeling, the veneer was dried at 160°C to an average final moisture content (MC) of 6% in a laboratory-scale veneer drier (Raute Oyj, Nastola, Finland). The target thickness of the veneer was 2 mm and the average depth of the lathe checks was 50%. After drying and conditioning, the veneer sheets were cut to dimensions of 400×400 mm^2 and sanded (Sanding machine type FBA 8, Karl Heesemann Maschinefabrik GmbH & Co., KG, Bad Oeynhausen, Germany) (180 grit) to 1.4 mm thickness. Both sides of the veneer were sanded to obtain three groups of veneer with checks nominally 25%, 50%, and 75% of veneer thickness (Figure 1a). In this way, individual veneer sheets with check depths ranging from ~30% to 90% of the veneer thickness were produced. The veneers were subsequently conditioned before bonding to a final MC of ~3%, because the resin supplier recommends between 2% and 6%. Low veneer MC prior bonding is essential in hot-pressed panels because water in the panel turns to pressurized steam, which can cause blistering and blows during press opening.

Plywood manufacture

The plywood was bonded with a phenol-formaldehyde (PF) resin (Prefere 14J021; Dynea Chemicals Oy, Hamina, Finland). A mixture of the adhesive was prepared 2 h before spreading. The approximate spread rate of the adhesive on the veneer sheets was 155 g m^{-2}. The 7-ply plywood was produced in a laboratory hot press (type LA 63, Robert Bürkle GmbH, Freudenstadt, Germany). After lay-up, the panels were prepressed for 8 min at 0.8 MPa before hot pressing. The hot press time was 7 min, the platen temperature was 128°C, and the press pressure was 1.8 MPa. In total, 18 panels were produced. After hot pressing, the panels were hot stacked and finally conditioned at 20°C and 65% relative humidity for 1 week before machining the specimens. The specimens were produced according to EN 314-1.

Wettability by CA measurements

The wettability of both the tight and the loose sides of the veneer sheets was measured with a CAM 200 (KSV NIMA, Espoo, Finland) goniometer. The volume of the droplet of distilled water was 10 µl. Three measurements were made on each surface. In total, 180 CA measurements were carried out. CA was measured 60 s from the initial contact of the droplet on the veneer surface.

Microscopy of lathe check depth

Before adhesive testing, the check depths of each EN 314 test specimen were measured in the region where the failure would occur (Figure 1b). All specimens were treated with the textile dye "Dylon Tulip red" (Spotless Group, Paris, France) on one side to make the checks visible under an optical microscope (Wild MZ8, Leica, Wetzlar, Germany). To reveal the checks, a slice ~0.5 mm thick was removed from the colored side by sawing. The depths of all checks occurring between the saw kerfs were measured and the average check depth was calculated for each specimen.

Bond quality determination

Bond quality was measured according to EN 314. Half of the specimens was tested according to EN 314-1 by treating them according to class 1 (soaking) and the other half of the samples was tested without prior soaking. Additionally, the shear strength was measured with the checks being pulled open (Figure 1c) and pulled closed (Figure 1d). In such manner, four groups of test samples were prepared: (a) water-soaked samples with open lathe checks, (b) water-soaked samples with closed lathe checks, (c) dry samples with open lathe checks, and (d) dry samples with closed lathe checks. Shear testing was performed on a Zwick universal tester (type 147570) (Zwick Roell Group, Ulm, Germany). The PWF was determined visually and automatically by means of a CCD camera (3-CCD, KY-F55B, JVC, Yokohama, Japan) and an image processing software Vision Assistant 7.1.1 (National Instruments Corp., Austin, TX, USA)

Microscopy and microtensile testing

Specimens with dimensions of 80 mm length×9 mm depth×3 mm width were tested in tension in a bespoke microtensile tester operated under a Leica Wild MZ8 dissecting microscope, which is suitable for the visualization of the failure mechanism during testing.

Analysis of results

In all tests, the significance of the differences between the means of the different groups was evaluated by analysis of variance (ANOVA). The differences among means were compared and segregated by Tukey's test ($P<0.05$). The linear correlations were determined based on the standard Pearson's method.

Results and discussion

Veneer wettability

The results in Table 1 indicate that there is no remarkable difference in the wettability of veneer specimens on the tight side with different depths of lathe checks after sanding. This shows that sanding produces surfaces with closely similar characteristics yet, at the same time,

Table 1 Veneer surface wettability measured in different groups after 60 s of water contact.

Side of veneer	Depth of lathe checks (%)	Average (SD) of CA (°)
Tight	25	85.4 (19.86)
	50	86.3 (10.42)
	75	100.9 (11.57)
Loose	25	104.6 (7.96)
	50	94.5 (14.38)
	75	67.3 (20.39)

CA, contact angle.

yielding veneer with different check depths. The wetting of veneer on the loose side was slightly greater in the case of deeper lathe checks (Table 1). At the same time, the variation in this group increased with depth of checks. Both the declining CA and the increased variability can be explained by deeper checks allowing water to penetrate much more deeply but less uniformly into the veneer.

Lathe checks and bond strength

As shown in Figure 2a, check depth was found to have a strong influence on the measured shear strength when the checks were pulled open, because the shear strength dropped by ~40% when the check depth increased from 40% to 80%. On the contrary, when the checks are pulled closed, limited strength loss is noted over the same interval. As visible in Figure 2a, the strength difference due to the pulling mode is mainly affected by the depth of the checks: the shallower the checks, the smaller the difference between the two values, which agrees with the results presented by Korpijaakko (1999) and Marra (1992). This would also explain the differences in open and

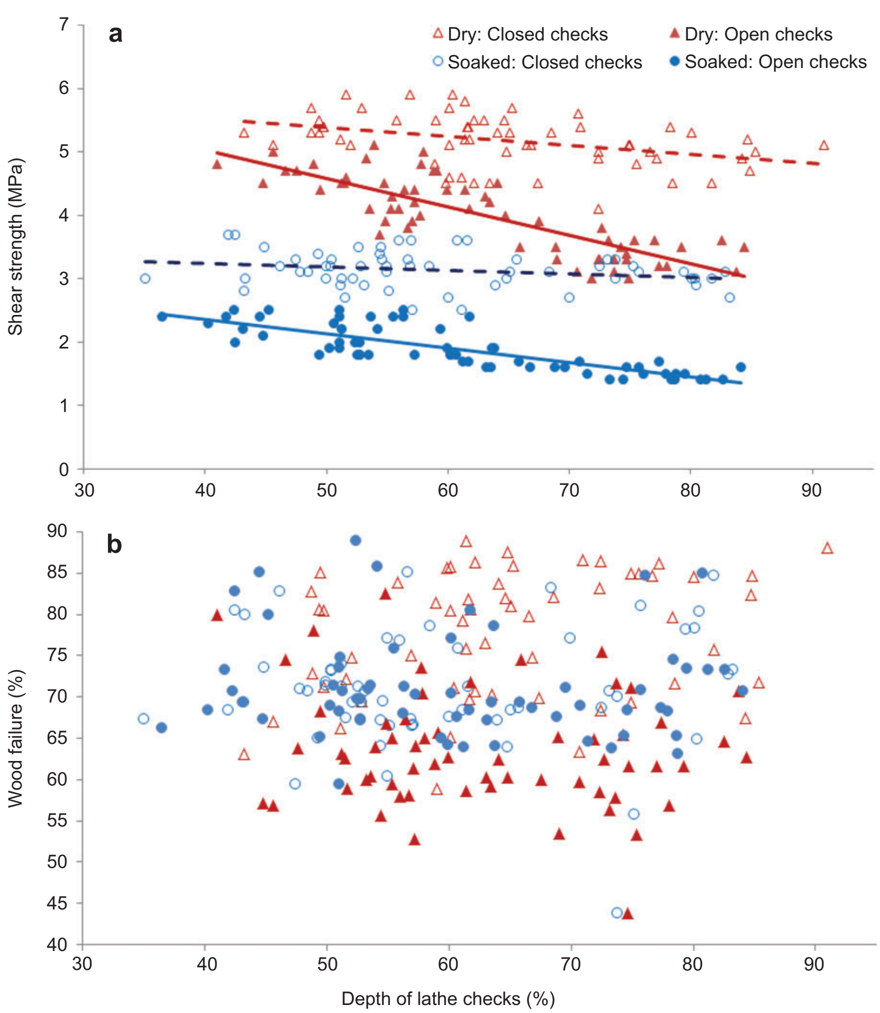

Figure 2 (a) Shear strength values of tested plywood under dry and wet conditions pulling checks open or closed. (b) Effect of depth of lathe checks on percentage of wood failure evaluated by automated image analysis for checks pulled open and closed under wet and dry conditions.

closed strength values presented by other authors (Bethel and Huffman 1950; Koch 1965b; Chow 1974; DeVallance et al. 2006), who did not measure the depth of checks in their study. The results also show that soaking universally lowered shear strength. It does not mean, however, that the bond quality of these samples is unacceptable because all samples met the requirements of EN 314-2. Both soaked and dry specimens with the checks pulled open exhibited decreasing shear strength with increasing check depth.

There were no samples that failed the standard requirements of EN 314 (1 MPa wet strength with no PWF requirements, with 0% wood failure). There is some probability that the 1 MPa threshold would not be achieved in the case of a low-quality veneer with deep checks pulled open, because the trend line in Figure 2a for soaked specimens tested with the checks open already approaches the 1 MPa limit.

Wood failure

PWF was evaluated in two different ways: first by visual inspection and second by computer-based image analysis. As may be seen in Figure 3, the results vary depending on whether the specimens had been tested dry or wet. The two evaluation methods correlated well for dry tests (r=0.85), but no correlation was observed for wet tests (r=0.10).

A visual evaluation is extremely subjective even for experienced evaluators; it is very difficult to distinguish between wood failure and adhesive failure when failure is very shallow and only a thin layer of wood fibers is left on the failure surface. Nevertheless, the visual evaluation shows clearly that the PWF is smaller when pulled open than when pulled closed. There are no statistical differences in the PWF tested wet or dry for pulling in the same direction. Similar results were obtained from the computer-based image analysis of dry specimens. Here, there are statistical differences in the PWF between the open and the closed specimens when tested dry. However, when tested under wet conditions, there are no statistical differences. Also here, the extreme scattering of the PWF was confirmed. It also explains the contradictory results reported in the literature (Chow and Warren 1972; Chow 1974; Neese et al. 2004; DeVallance et al. 2007).

Failure mechanisms

The plywood failure mechanisms were observed under a microscope. From Figure 1e, it can be seen that pulling the checks open leads to a localized mode I (opening mode) failure type, resulting in the middle ply “rolling” off from the bondline. Thus, the strength of the wood and the presence and depth of the checks most probably affects bond strength, because localized opening mode, rather than shearing mode, loading conditions prevail. However, as indicated in Figure 1f, specimens that are pulled closed fail primarily due to global in-plane

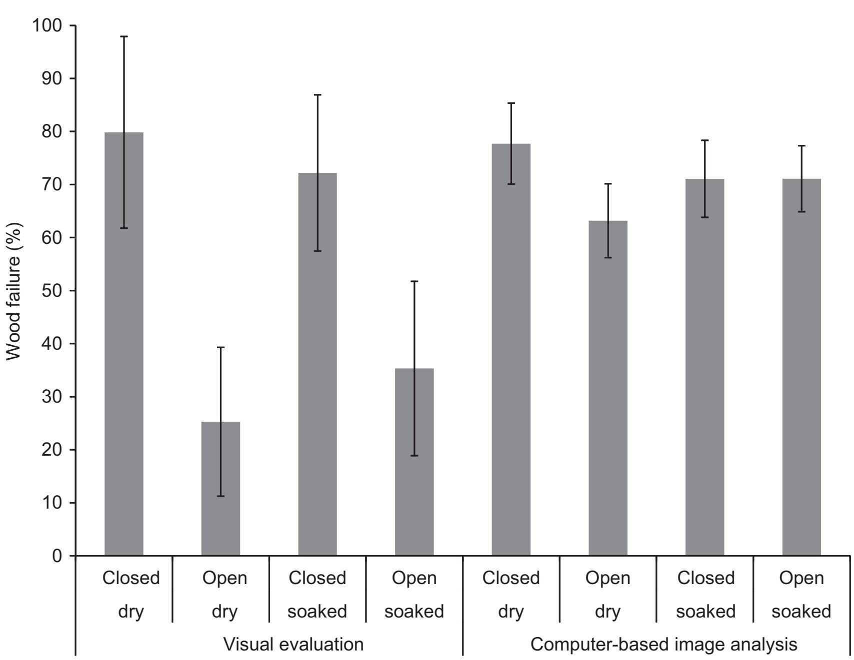

Figure 3 Percentage of wood failure evaluated by different methods. Error bars represent one standard deviation.

shear (mode II), resulting from the propagation of fracture within the veneer itself. It is not surprising, therefore, that the observed strength is almost independent of check depth (Figure 2a) when the checks are pulled closed. When pulled open, on the contrary, the wood on either side of the check moves in opposite directions (i.e., a shearing action occurs), inducing the localized mode I loading conditions at the bondline. This would suggest that larger checks would allow an easier movement and thus provide a mechanism explaining the lower failure load. This hypothesized mechanism would also support the observations of Korpijaakko (1999), namely, a few large checks are more detrimental to bond strength than many small checks. This mechanism also explains why shallow lathe checks pulled open approach the value of specimens pulled closed in Figure 2a. The shallower checks are less effective at instigating mode I failures; therefore, specimens with shallow checks pulled open behave very much like specimens pulled closed.

As noted, the observed PWF was influenced by whether the samples were tested open or closed. When tested open, the failure zone moves closer to the bondline and only a small amount of wood fibers are present in the failure zone. Sometimes this shallow wood failure is interpreted as adhesive failure because of the problems described in the previous section. Samples pulled closed fail mainly along a line delineated by the crack tips of lathe checks. In this case, the failure is clearly further from the bondline, resulting in smaller differences observed visually and by automated evaluation. These mechanisms also tend to drive the wood failure toward the loose side of veneer as described by Koch (1965b) and Neese et al. (2004).

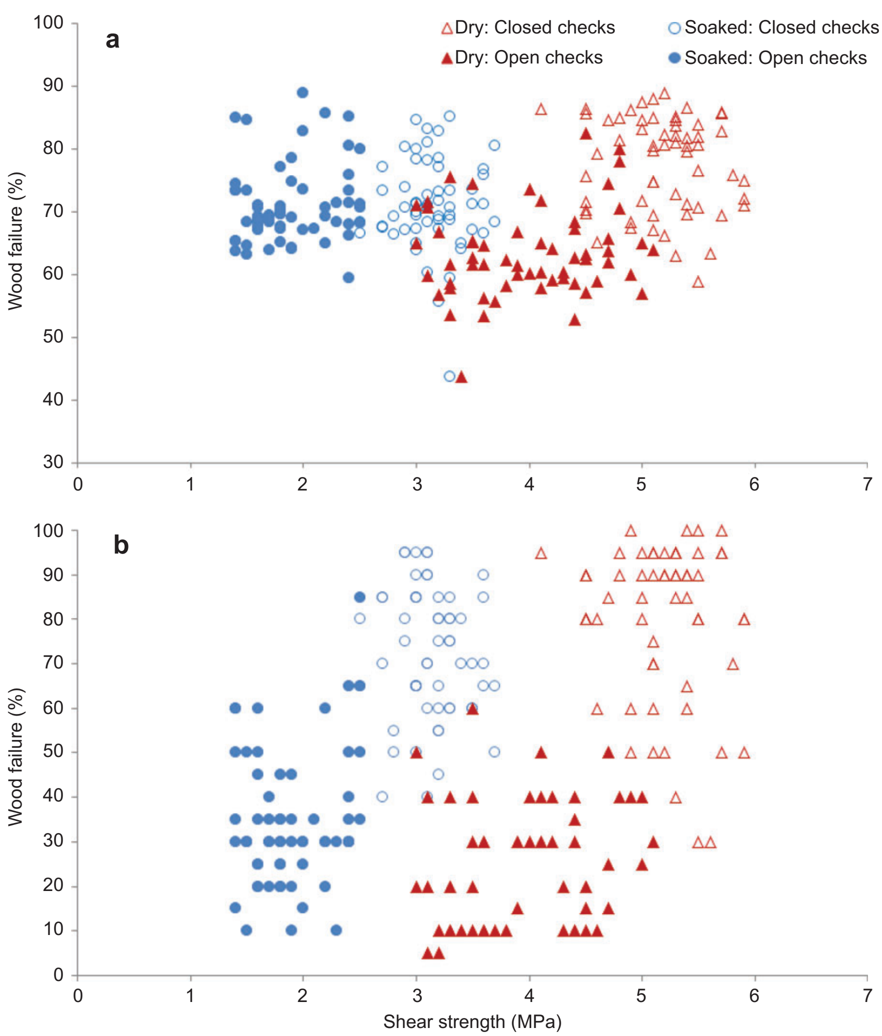

Figure 4 (a) Relationship between shear strength and wood failure of plywood evaluated by an automated image analysis for checks pulled open and closed under wet and dry conditions. (b) Relationship between shear strength and wood failure of plywood evaluated visually for checks pulled open and closed under wet and dry conditions.

Wood failure vs. depth of checks and shear strength

The relation between PWF of specimens and check depth as measured by an automated image analysis is presented in Figure 2b. Clearly, there is no correlation between the PWF and check depth under any conditions, confirming the results of Koch (1965a).

Figure 4a shows the relationship between plywood shear strength and the PWF as evaluated by an automated image analysis and does not reveal any significant correlation within any of the four groups, although the testing mode (open or closed) influences the results. Figure 4b shows the relationship between the PWF and shear strength recorded by the human observer. Again, there is no correlation between shear strength and the PWF within any of these four groups, but again the testing mode (open or closed) has an effect on the results. Chow (1974) described similar results.

Conclusion

Check depth and pulling direction were found to have a major influence on the measured shear strength of plywood tested according to EN 314. Because lathe check depth increased from 40% to 80%, plywood shear strength decreased by ~40% when tested open but was nearly unchanged when tested closed. In addition, failure when testing closed involved a predominantly mode II (shear) mechanism, whereas testing open involved more of a mode I (cleavage) failure type, especially with deeper checks. Testing open resulted in a failure very close to the bondline, giving the perception of a low PWF, although the wood was failing. In contrast, specimens tested closed failed across the tops of the lathe checks and much deeper in the veneer.

Against this background, the large scatter in the published data and some apparently contradictory findings are not surprising. The reported findings not only confirm the importance of minimizing the depth of lathe checks for product quality but also demonstrate how check depth could influence a test (EN 314), which was designed mainly for testing adhesive properties and to evaluate adhesive cure. As demonstrated, the lathe check depth has a very large impact on the results of tests carried out according to EN 314.

The most fastidious approach to dealing with lathe check variability in veneers is to measure them regularly. A faster approach for reducing the variation induced by lathe checks in routine work is to perform the tests only in closed mode. This approach will lower the variability and allow more reliable comparisons between different adhesives and bonding conditions.

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