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ORIGINAL

Investigating face veneer check development in decorative plywood panels: the impact of four common manufacturing factors

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Abstract
An optical method based on digital image correlation was used to investigate the impact of four decorative plywood manufacturing factors (core type, veneer type, adhesive type and lathe check orientation) on face veneer checking. The four core types were: combination core, medium density fibreboard, particleboard, and veneer core. The four veneer types were: peeled 0.604 mm, peeled 0.706 mm, sliced 0.508 mm, and sliced 0.564 mm. Both loose-side out and tight-side out lathe check orientations were used. The adhesive systems were urea–formaldehyde, polyvinyl acetate, and soy-protein based. 96 treatment combinations with 8 replicates were tested. All specimens were exposed to harsh but realistic drying conditions (approximately 30°C and 26% relative humidity) for 4 h during inspection. Checks were detected on 428 out of a total of 765 specimens (56%). The estimated mean check densities (area of checking per unit area) indicated some unfavourable factor combinations. All factors had some degree of interaction with one another and check development could not be attributed to a single factor examined in this study. The data were fit to a generalized linear mixed model based on Tweedie's compound Poisson distribution. Confidence intervals were calculated via bootstrapping. The check density estimates produced by this model can be used to cautiously guide manufacturers as they decide on panel components. The broader use of the model is to highlight the complexity of the problem and guide future research in this area.

1 Introduction

Decorative hardwood plywood panels are wood-based composites comprised of hardwood veneers bonded to centre layers (or "cores") which may be veneer, lumber, particleboard, medium density fibreboard (MDF), hardboard, or a combination of these materials (Stark et al. 2010). They are commonly used in applications where quality appearance is desired, including cabinetry, furniture, fixtures, wall and ceiling panels. In uses where appearance is most critical, any defect in the face veneer can lead to complaints by the customer. For many years a common and costly customer complaint has been checking in the face veneer (Holcombe 1952; Cassens et al. 2003; Leavengood et al. 2011). No standard stipulates the minimum wood-tissue separation to qualify as a check, and no study has assessed end-user views on acceptable levels of checking in finished panel products. Therefore, based on physical examination of panels that produced customer complaints, checks in this study were defined as separations of the wood tissue along the fibre direction, greater than 0.2 mm across (i.e. in width) and longer than 1 mm (Burnard 2012). When the surface is exposed to a low humidity environment, moisture gradients between the face veneer and core materials develop; variable shrinkage rates between the face veneer and the core material generate drying stresses, which are the principal cause of checking in hardwood plywood products (Gilmore and Hanover 1990; Forbes 1997; Schramm 2003; Cassens et al.

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2003; Christiansen and Knaebe 2004; Leavengood et al. 2011). While decorative surfaces may only occasionally be exposed to drying conditions severe enough to induce checking, it takes only one such event to generate an irreversible damage resulting in an expensive claim.

Checking in decorative hardwood plywood veneers is commonly believed to depend on specific panel construction and many manufacturing options such as adhesive properties and choice, core materials, component moisture content at time of pressing, veneer cutting and drying methods, etc. (Holcombe 1952; Feihl and Godin 1970; Gilmore and Hanover 1990; Forbes 1997; Cassens et al. 2003; Schramm 2003; Christiansen and Knaebe 2004; Leavengood et al. 2011).

1.1 Panel construction and manufacturing options

The selection of specific wood species and finishes for face veneers is subject to consumer choices and fashion. Sugar maple (*Acer saccharum*, a hard maple), the species examined in this study, has been a common choice for many years and accounts for approximately 43% of North American unfinished materials and 70% of prefinished materials (Schramm 2003; HPVA 2011, 2018). Common core materials are medium density fibreboard (MDF), particleboard (PB), veneer (V), and combination core (typically softwood veneer with a thin layer of MDF on the front and back). Common adhesive systems used to bond the decorative veneers on the core include urea formaldehyde based adhesives (UF), soy-based adhesives (Soy), and polyvinyl acetate based adhesives (PVA). There are other manufacturing options such as log source region and conditioning treatment, veneer cutting method, veneer thickness and grain angle, moisture content and lathe check orientation of the veneer, pressing time and temperature, specific adhesive formulations, panel storage and handling, surface coatings, and others. Previous studies and reports conclude or suggest the factors discussed in the following subsections have significant impact on check formation.

Veneer properties and lathe-check orientation Veneer properties including cutting method, (e.g., sliced or peeled), lathe check orientation, veneer thickness, moisture content at time of pressing, and thickness are all believed to play a role in check development of decorative hardwood panels (Forbes 1997; Schramm 2003; Christiansen and Knaebe 2004). Even the wide variability of properties within veneers of the same type due to features of wood (e.g., grain angle, reaction wood) may contribute to differential checking severity.

Cutting method affects checking because rotary peeling (also called rotary cutting) tends to expose mostly the tangential plane in wood, while slicing may produce veneers with radial faces as well. With the tangential shrinkage rates approximately double the radial shrinkage rates (9.9% compared to 4.9% in sugar maple; Glass and Zelinka 2010), faces made of peeled veneers may experience more severe stress built up during exposure to drying conditions than sliced veneers.

One of the key, and much discussed, options in panel construction is whether the veneer is attached to the panel with its tight- or loose-side out (Cassens et al. 2003; Leavengood et al. 2011). Loose-side refers to the side of the veneer that was in contact with the knife blade during the slicing or peeling process, the opposite side is the tight-side. For many years it has been common practice to place the veneer loose-side down to limit check development (Holcombe 1952; Batey 1955; Feihl and Godin 1970; Cassens et al. 2003; Schramm 2003; Christiansen and Knaebe 2004). However, limited evidence indicates that orienting face veneers loose-side out reduced the propensity for development of new checks in panels with oak veneers (Cassens et al. 2003), while conflicting conclusions have been reported on similar effect in panels with maple veneer (compare Leavengood et al. 2011; Cassens et al. 2003). Lathe-check orientation is thought to be important because more pre-existing cracks are present on the loose-side. The severity of pre-existing cracks and the causes for them have been examined by many researchers (recently, Buchelt et al. 2018; Rohumaa et al. 2018). While research examining the causes and severity of pre-existing cracks exist, their association with the development of surfacing checking in products is limited to lathe-check orientation. No rapid method of characterising pre-existing cracks in large surface areas is known to exist.

Veneer thickness also contributes to check development: checks formed in thicker veneers tend to be fewer but are often wider and more readily apparent than shallow and narrower checks in thinner veneers (Christiansen and Knaebe 2004).

Controlling the moisture content of the face and back veneers at the time of pressing is thought to be one effective method of mitigating check development (Christiansen and Knaebe 2004; Schramm 2003; Cassens et al. 2003). Cassens et al. (2003) recommend conditioning the veneer and core components to the average equilibrium moisture content at the service location to reduce excessive swelling or shrinking after installation. Wilson (2018) found no relationship between checking and the difference between core MC and surface veneer MC at the time of pressing.

Adhesive choice is commonly believed to affect check development (Gilmore and Hanover 1990; Forbes 1997), however there have been very few studies documenting or explaining this effect. It is certain however, that adhesives applied as water solutions contribute moisture to veneers and to the core surfaces. Overall, more checks have been observed in panels constructed with UF adhesive compared to those using PVA (Tremblay and Bouffard 2012). Cassens et al. (2003) found strong evidence that adhesive choice was part of multiple two-way interactions that influenced check development. Of the 16 treatment combinations examined, the one that checked the most was maple veneered panels bonded with PVA, with the loose-side of the veneer facing out, veneer MC at the time of pressing at 12% and a 10 min assembly. A significant 4-way interaction was also reported, increasing the difficulty of isolating any single factor or a simple combination of factors as the cause (Cassens et al. 2003).

Core materials are typically mentioned in *best practice manuals* as a factor contributing to the surface checking effect, along with other components, attributes or panel construction methods (e.g., the moisture content of the veneer, or the adhesive used in combination with the panel type, balanced construction). Little has been reported regarding the performance of specific core types, except for a study by Tremblay and Bouffard (2012), who examined particleboard, veneer, and MDF cores and concluded that panels with veneer cores were more prone to checking than those with particleboard and MDF cores.

This study is motivated as much by the persistent pressure from manufacturers for a comprehensive solution to the problem of check formation, as by the challenge the complexity of this problem and the apparent contradictions between previous studies have been posing to the research community for so long. The complex interactions reported by Cassens et al. (2003) mean that the problem may not be removed by altering individual factors. Another important conclusion from previous studies is that the problem cannot be properly resolved by analysing a small selection of the many variables that may influence check development at a time. Most of the methods used in previous studies may not be well positioned to process large number of specimens necessary to address multiple variables at a time. They may also limit accurate detection and resolution of differences in check development indicators and patterns between panels. For example, measuring checks at specific time intervals, rather than as they form, is likely to lead to significantly underestimated checking measurements given that checks in face veneer may close as the core material equilibrates to the ambient conditions.

Recently, Burnard et al. (2018) developed a new automated optical method for detection and measurement of checks based on check detection concept proposed by Kang et al. (2006). This method was based on the digital image correlation principle, which allowed identification of checks as small as 0.2 mm wide and 1 mm long. Continuous measurement allowed reliable check counts, and measurement of check dimensions as they develop during exposure to drying conditions. Check density, the summed area of check per panel area, was proposed as an indicator of check severity. The method was validated in exposure tests conducted in harsh but realistic conditions, to increase the likelihood of checking and reduce the test duration to 4 h. The test setup allowed near simultaneous monitoring of check development in up to 48 panel specimens sized 300 mm × 300 mm. The efficiency of the method allows studies to examine a large number of treatments and replicates and overcomes most of the limitations discussed in relation to earlier methods.

1.2 Objectives

The objective of this study was to use the check detection and measurement methodology developed by Burnard et al. (2018) to determine the effect of four factors related to manufacturing of the decorative hardwood plywood commonly believed to affect checking: veneer characteristics, lathe orientation, core material and adhesive type, as well as combinations of these factors in maple plywood.

2 Materials and methods

The investigation was performed using 8 replicates of laboratory-fabricated test specimens of each of the 96 combinations of the 4 factors selected for this study. The test procedure, including the panel construction, preparation for testing, exposure to rapid drying conditions, data collection and analysis, followed the methodology developed earlier by Burnard et al. (2018). Factors and levels of factors thought to contribute significantly to check development in maple veneer plywood panels were identified based on literature review and by consultation with industry advisors. Statistical analysis of the data (e.g., checking severity) followed utilising robust methods appropriate for the observed data and experimental design.

2.1 Experimental design

The test variables included: (1) veneer cutting method and thickness; (2) lathe check orientation; (3) core material; and (4) adhesive type. Specific values for each of these variables were determined based on a survey conducted among decorative panel producers in the U.S. producing panels with sugar maple veneer faces (Burnard 2012):

1. In practice, peeled and sliced veneers are produced in different thicknesses. Oregon hardwood plywood manufacturers use peeled veneer in thicknesses between 0.604 and 0.706 mm (in US industry these are, 1/32″ and 1/36″), and sliced veneer between 0.508 mm and 0.564 mm (in US industry these are, 1/45″ and 1/50″; Burnard 2012). Therefore, in this study, veneer cutting method and thickness (the factor further referred to as “veneer”) are treated as a single factor with 4 values: (a) peeled 0.604 mm; (b) peeled 0.706 mm; (c) sliced

0.508 mm; and (d) sliced 0.564 mm (thickness values are nominal). Sliced veneers were slip-matched, rather than book-matched, to ensure lathe-check orientations were the same for all spliced components.

2. Two lathe check orientations were used: (a) tight-side out and (b) loose-side out. About half of the veneers had their tight- and loose-side labelled by the companies donating the material. The orientation of the unlabelled veneers was determined by the research team in a two-step procedure where two researchers physically inspected each sheet, identified the tight and loose sides, then compared results (Burnard, 2012).
3. Four core materials most commonly used by hardwood plywood manufacturers were tested: (a) Veneer core (VC); (b) MDF (medium density fibreboard); (c) "combination core" (CC): plywood with a combination of veneer core and thin layers of MDF adjacent to the decorative face veneer on both sides; and (d) particleboard (PB).
4. Three types of adhesives most commonly used by hardwood plywood manufacturers were investigated: (a) soy-based (S); (b) urea formaldehyde adhesive (UF); and (c) polyvinyl acetate (PVA) adhesive.

The manufacturing variables (factors) and their specific values (levels) examined in this study are summarised in Table 1. The resulting test matrix included 96 different manufacturing combinations (or treatments) with 8 replicates per treatment (a total of 768 test panels).

The experimental design in this study was a randomized block split-plot factorial design. Split-plots are generalisations of the factorial design when a factor cannot be entirely randomised. Blocking is used to help account for a known and controllable source of variation, such as any differences that may occur between panel manufacturing runs. In this study, one replication was produced per day so the production day constituted the blocking factor. Only one adhesive could be used at a time because of limitations to the stability of the adhesive at room temperature (i.e., its pot life), the availability of a single glue spreader in the laboratory, mixing, and clean-up times. Therefore, all treatments using a single adhesive type were made consecutively within each block and adhesive was treated as a split-plot factor in the analysis. Replications of the remaining factors (veneer type and thickness, veneer orientation, and core type) were randomly assigned within each replication of the adhesive. The number of observations per block and the number of levels for different combinations of the factors are presented in Table 2.

Table 1 Factors and levels of manufacturing variables

Factors	No. of levels	Levels
Veneer cutting method and thickness (veneer)	4	Peeled, 0.706 mm
		Peeled, 0.604 mm
		Sliced, 0.564 mm
		Sliced, 0.508 mm
Veneer orientation	2	Tight-side out (TSO)
		Loose-side out (LSO)
Core	4	Veneer (V)
		Medium density fibreboard (MDF)
		Combination core (CC)
		Particleboard (PB)
Adhesive	3	Soy-based (Soy)
		Urea Formaldehyde (UF)
		Polyvinyl Acetate (PVA)

*These thicknesses correspond to commonly produced thickness in the US, which are customarily measured in inches, (e.g. 0.706 mm = 1/36″)

2.2 Manufacturing and conditioning panels

Sample specimens were prepared from pre-cut 300 mm × 300 mm cores and veneer sheets donated by cooperating companies, resulting in panels of the same size. Materials were conditioned at ambient lab environment at a mean temperature of 21.4 ± 0.6 °C and mean relative humidity 31.3 ± 5.9% (solid wood EMC between 5.4 and 7.3%) for at least 7 days before being assembled and pressed.

The PVA adhesive was received pre-mixed by the manufacturer. The pot life was sufficient to last throughout the entire production phase. The UF adhesive was mixed in the lab according to manufacturer instructions before each production cycle. The soy-based adhesive was received pre-mixed by the company and delivered in small batches, which were refrigerated between production cycles. Per manufacturers' recommendations all adhesives were applied with a target spread rate of 177 g/m^2 (15.9 g per glue line) using a laboratory-scale adhesive spreader. All test panel cores were weighed before and after applying the adhesive. The average measured spread rate for all panels was confirmed at 15.9 ± 1.3 g per glue line.

Manufacturing procedures Specimen production order was randomized ahead of production which included consideration for the adhesive split-plot factor. The adhesive for the production day was prepared and applied to the spreader, then all specimens using that adhesive within the current block were produced pulling veneers and cores at random from the available stock.

Due to damaged sliced veneers, only 7 out of 8 planned replicates of 0.508 mm sliced veneer with loose-side out veneer orientation, particleboard core, and UF adhesive, and

Table 2 Factor combinations, treatments, and observations

Factors and factor combinations	No. of levels per factor or combination of factors	No. of observations for each combination in one block
Veneer	4	24
Veneer orientation	2	48
Core type	4	24
Adhesive	3	3[a]
Veneer × core type	16	6
Veneer × adhesive	12	8
Veneer × veneer orientation	8	12
Core × adhesive	12	8
Core × veneer orientation	8	12
Adhesive × veneer orientation	6	16
Veneer × core × adhesive	48	2
Veneer × core × veneer orientation	32	3
Core × adhesive × veneer orientation	24	4
Veneer × core × adhesive × veneer orientation	96	1

[a]The average of checking values for all 32 panels made with a single adhesive type constituted an observation

7 replicates of 0.508 mm sliced veneer, tight-side out, MDF, UF adhesive were produced. As a result, 766 test panels were produced rather than the target of 768.

All panels were assembled with only the face veneer (no back veneer was applied) to speed up the assembly. No significant buckling or bending was observed at pressing time or prior to exposure, however this was not measured.

In the sample preparation process, face veneers on veneer cores were inadvertently applied with the grain direction oriented parallel to the grain direction in the core faces. While some commercial panels are assembled this way, it is rare, and this is thought to contribute to the severity of checking (Tremblay and Bouffard 2012).

Pressing procedure and conditions followed manufacturer recommendations: all panels were pre-pressed at room temperature for 5 min at 0.930 MPa in a CP SPX 55T ECN Press 1851, and then hot-pressed for 2 min at 0.930 MPa with the face veneer oriented toward the top platen set to 113 °C in a Clifton Hydraulic Press 1500.

After pressing, sample panels were cooled and stored at conditions of 20 °C and 65% relative humidity (i.e., solid wood equilibrium moisture content of approximately 12.0%) for a minimum of 72 h.

Twenty-four hours before testing, a random speckle pattern (a sparse spray of white and black acrylic matte paint) was applied to all veneered surfaces to enhance optical measurement of surface strain development (Burnard et al. 2018). Samples were then moved to a conditioning chamber set to 30 °C and 90% relative humidity (solid wood EMC of approximately 20%) for 24 h.

2.3 Measuring check severity

Check severity was measured using the optical method developed by Burnard et al. (2018). In this method, small surface checks were detected and measured by means of an optical full-field strain analysis based on the digital image correlation (DIC) principle. Kang et al. (2006, 2011) demonstrated that even very small checks may be detected and monitored as apparent local peak in magnitude of strains measured perpendicular to the surface grain.

Tests were performed on groups of 32 panels simultaneously. Test panels were exposed to relatively harsh but realistic drying conditions (approximately 30 °C and 26% RH which for solid wood is equivalent to EMC of 5.39 ± 0.21%) maintained for 240 min. The final group consisted of 30 specimens. During the exposure, an automated image acquisition system with a digital camera (5 megapixel monochrome Grasshoper 2) mounted on an 8 m horizontal linear positioning track system allowed sequential examination of all test specimens in 10 min intervals. Finally, automated identification of checks allowed batch processing of the data collected during the exposure tests. The system used a custom image capture and track control system, as well as a custom check detection and measurement system. The check detection and measurement system used displacement and strain measurements exported from ARAMIS 5.4.3 by GOM, mbH (2004). A detailed description of the system is presented in Burnard et al. (2018).

The system was calibrated to detect checks at least 0.2 mm wide, with a precision of ± 0.03 mm (Burnard et al.

2018). The check metrics returned by the system included check count, dimensions (width and length) and position of all detected checks as they developed over the exposure time.

In order to allow quick quantitative comparison of checking severity observed on sample surfaces of varying dimensions, check density (CD) was calculated as a ratio of the total area of all checks detected on a panel (A_{ck}) expressed in square millimetres to the examined area of interest (A_{ROI}, Eq. 1) expressed in square meters (Burnard et al. 2018).

$$CD = \frac{A_{ck}}{A_{ROI}} \left[\frac{mm^2}{m^2} \right] \tag{1}$$

In this study, as in the system validation study (Burnard et al. 2018), CD was observed over a 4-h exposure in order to capture the check development dynamics in panels. In the validation study, the gradual accumulation of checks with increasing moisture gradient through the thickness of the panel was reflected as gradual build-up of CD until a peak, beyond which the moisture begins to equilibrate and the CD decreased as the checks gradually closed. Since the rate of check formation was shown to be different for individual panels and between the test layups, comparing the CDs for all test samples at some arbitrary time snapshot would not yield meaningful assessment. Instead, the peak CD values observed in panels over the exposure times were compared and analysed.

2.4 Statistical analysis

A substantial number of panels survived the exposure tests without detectable checks (> 0.2 mm in width and longer than 1 mm) while the distribution of the observed, non-zero check densities was heavily right-skewed. Both conditions violated the assumption of a normal distribution with homogeneity of variance and therefore common ANOVA methods could not be used.

The observed data met the assumptions of the Tweedie compound Poisson distribution (Zhang 2013), which allowed us to use a linear mixed model. In this model, the number of observed checks, X, is a Poisson distributed random variable with mean λ (Eq. 2):

$$X \sim Pois(\lambda); X = 0, 1, 2, 3, 4, \ldots \tag{2}$$

and the area of an individual check, Y_i, is a Gamma random variable with mean α and variance $\alpha\beta^2$ (Eq. 3):

$$Y_i \sim Ga(\alpha\beta), for\ Y > 0; \tag{3}$$

A_{ck}, the total area of observed checks in a single panel at a specific stage, is defined as:

$$A_{ck} = \sum_{i=1}^{X} Y_i, \tag{4}$$

So that the check density, CD, is as defined in Eq. (1). In this case, the CD reported is the maximum observed within the test period.

A generalized linear mixed model based on the Tweedie compound Poisson distribution was fitted to the observed data using a logarithm link function for the mean CD. The linear model included fixed effects for the factors (veneer type and thickness, lathe check orientation, core, and adhesive types) and all 2, 3, and 4-way interactions. In addition, assessed models included random effects of day (block variation) and adhesive*day (whole plot variation).

Estimation of standard errors, and functions of standard errors such as statistical hypothesis tests and uncertainty measures for this model are not well estimated (Zhang 2013). Instead analysis must be based on the ordered arrangement of estimated means for each combination of factors and their associated 95% confidence intervals (CIs).

Furthermore, 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 estimated means, making estimates of standard normal confidence intervals unreliable. To address this issue, the bootstrap method was employed to extract point estimates of the mean of each treatment and their associated confidence intervals, and to confirm model parameters.

The bootstrap method is a non-parametric computational method used in place of theoretical approaches that rely on strong distributional assumptions to estimate precision and confidence intervals from observed experimental data (Efron and Tibshirani 1986). The bootstrap method proceeds as follows: resample the observed data with replacement, recalculate the statistic(s) of interest, record, and repeat n times. From these results, accurate confidence intervals can be calculated by various methods, including several non-parametric methods which do not rely on distributional assumptions about the data (Efron 1984; Efron and Tibshirani 1986; DiCiccio and Efron 1996; Davidson and Kuonen 2003; Haukoos and Lewis 2005).

In the current implementation, the model parameters, means, and their confidence intervals were calculated based on 10,000 bootstrap repititions. In addition to estimates for each observation, estimates of the index and dispersion parameters of the fitted gamma distribution, as well as the variance of the whole plot and residual random effect were recorded. The blocking random effect was not included in the bootstrapped Tweedie compound Poisson model, as it was considered to be an insignificantly small source of variation in the model and prevented resampling for the bootstrap.

Following this procedure, confidence intervals were calculated using bias-corrected accelerated confidence intervals (BC_a, DiCiccio and Efron 1996).

Statistical analysis was performed using R (version 3.3.3; R Core Team 2017), in RStudio (version 1.0.136; RStudio, Inc. 2016) with the cplm package for fitting the Tweedie compound Poisson distribution (version 0.7.5; Zhang 2013, 2017). Bootstrapping was implemented and BC_a confidence intervals were calculated using the boot R package (version 1.3.18; Davison and Hinkley 1997; Canty and Ripley 2019). Plots were created with the ggplot2 R package (version 2.2.1; Wickham 2009), the scales R package (version 0.4.1, Wickham 2016), and the gridExtra R package (Auguie 2016). Data cleaning and preparation utilised the tidyr and dplyr R packages (Wickham 2017; Wickham and Francois 2016). Documentation of the statistical analysis with the bootstrap script and the input and output data are available as supplemental material to this publication (Burnard and Ganio 2019).

3 Results

3.1 General observations

Of the 766 panels tested, detectable checks developed in 429. One panel was rejected from the data set because the suspiciously wide check regions determined by the system could not be corroborated with direct observation of the surface. It is likely that this error was caused by a local disturbance in the speckle pattern. The remaining 428 panels with detectable checks constituted 56% of the total 765 qualified panels. Panel checking status, that is the binary condition of having checked or not, was similar among the levels of each factor (Fig. 1, bars). Core type is the notable exception to this observation; checking occurred in 71% of panels (136 out of 192) with veneer core, in 60% of panels with combination cores, 49% in panels with MDF cores and 44% in panels with particleboard cores. However, the proportion of overall CD accounted for by each factor level varied significantly (Fig. 1, dots). For example, while 71% of veneer core panels checked, 47% of the total CD was accounted for by veneer core panels compared to 45% and 10% for particleboard, respectively. This may indicate some of the tested panel components are likely to contribute to check severity (increase CD).

Figures 2a, b summarize observed peak check densities (CD). The CD histogram in Fig. 2 shows that the observed CDs were mostly within 100 mm^2/m^2. The distribution was heavily right skewed (Fig. 2a), with few severe cases between 3000 and 7200 mm^2/m^2 (between 2 and 13 checks detected). These distributions are much easier to examine on a natural logarithmic scale as in Fig. 2b.

Check progression varied greatly over time even among replicated panels from the same treatment groups. In all cases where checking occurred, the maximum detected CD occurred after the 120th minute of the test period, and in many cases CD was observed to decrease following the peak. In 56% of all panels with detectable checks, the maximum CD occurred prior to the 240th, and final, minute of

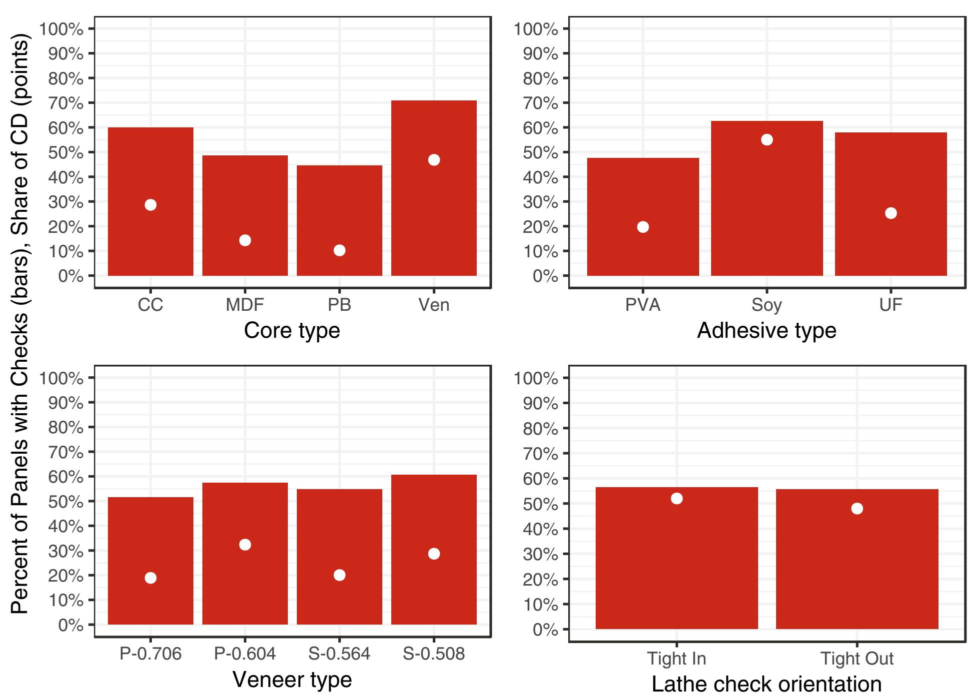

Fig. 1 Panel checking state and observed share of total CD by factor and level. Bars are proportion of panels of a given factor level with observed checking. Points indicate the proportion of total observed CD accounted for by factor level (total of 100% per factor)

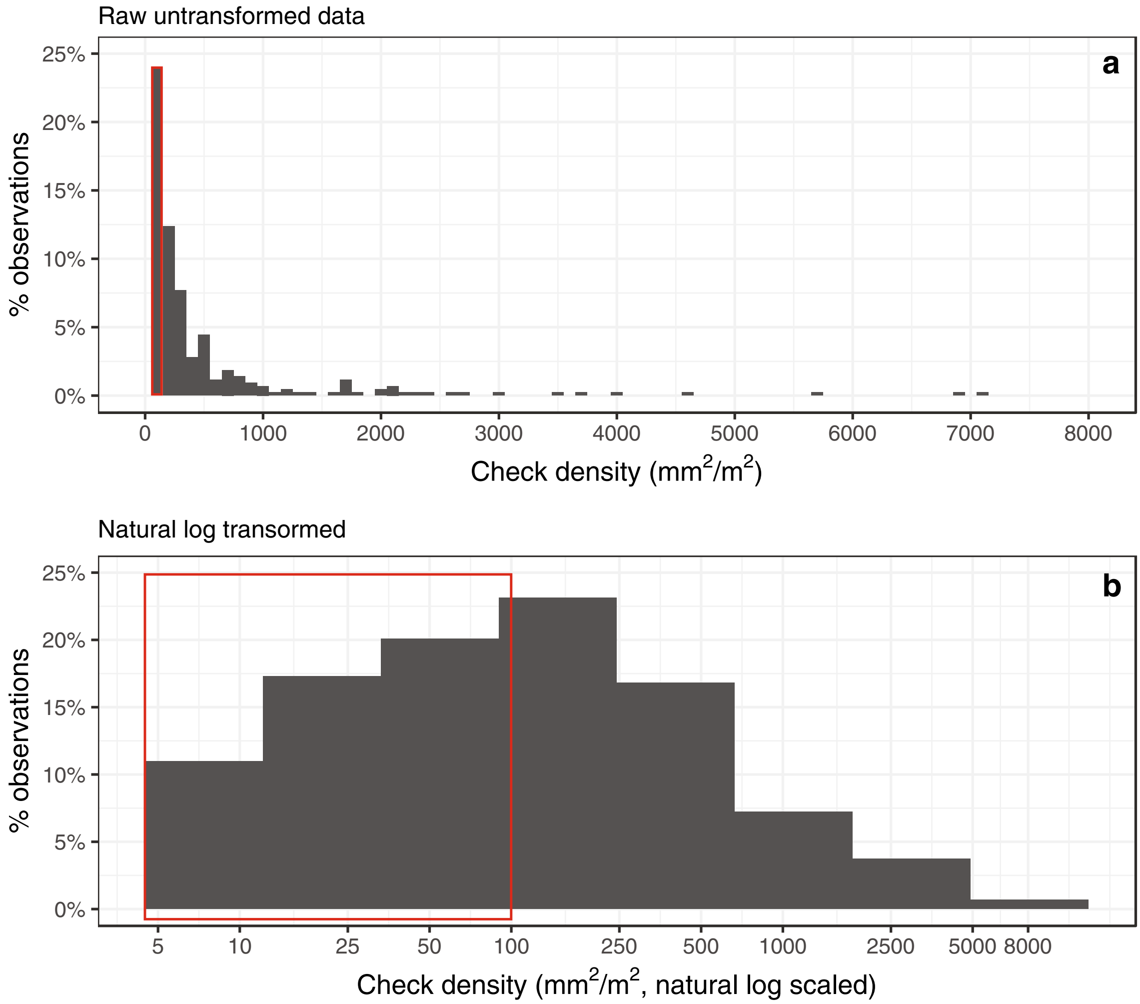

Fig. 2 Histogram of CD on the original scale (**a**) and the natural log scale (**b**) used as the link to the mean in the data model. On the original scale, each bar covers a range of 100 mm^2/m^2. On the natural log scale, each bar covers e^x, where x is an integer between 2 and 9. For example, the first bar is e^2 mm^2/m^2 or ~ 7.4 mm^2/m^2 wide, and the fourth bar is e^5 mm^2/m^2 or ~ 148 mm^2/m^2 wide. The areas highlighted in red are the same ranges (0–100 mm^2/m^2) of CD (color figure online)

the test. The variation in check progression patterns becomes apparent when comparing them between replicate panels for a specific combination of factors, then altering only one factor. For example, Fig. 3 shows the check progression patterns for all panels manufactured using sliced 0.564 mm veneer, tight-side out lathe check orientation, urea–formaldehyde adhesive, for each of the four core types. The patterns vary between and within core type, and clearly demonstrate the need to consider the point in time at which a checking indicator is recorded. To address this, the maximum observed checking for each panel, the maximum CD, was used as the indicator of checking for comparison.

Examination of the cumulative distribution of CD by factor level of an individual variable shown in Fig. 4 reveals virtually no difference between factor levels for the adhesive type and lathe check orientation, and only minor differences between various veneer types. The most notable difference is between core types. For example, particleboard core panels generally have a higher position on the y-axis than veneer core panels, indicating there are fewer particleboard core panels with a given CD than veneer core panels (Fig. 4).

Only one treatment combination (of 96) had no detectable checks in any of the eight replicates; no samples with peeled, 0.706 mm veneer on particleboard core using soy adhesive with loose-side out face veneer had detectable checks. Only four treatment combinations, all of them with veneer cores, had detectable checks on all replicates (highlighted with bold face in Table 3).

Very small check densities (in the first quartile, less than 52 mm^2/m^2) were observed on panels with 1 or 2 small checks, which may have been as short as 1 mm, and as narrow as 0.2 mm. The longest observed checks were over 100 mm long and the widest were more than 1 mm wide.

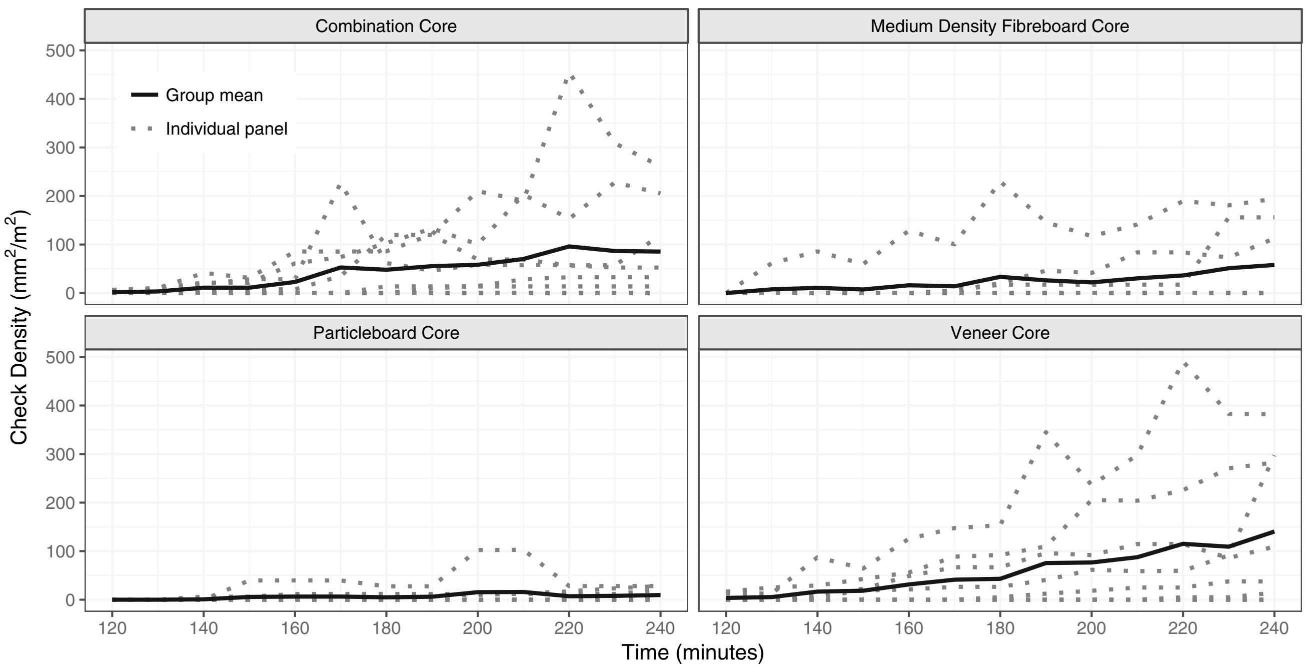

Fig. 3 CD progression for all samples with sliced 0.564 mm veneer, tight-side out lathe check orientation, urea–formaldehyde adhesive, and each of the core types from the 120th minute through the end of the test period (240th minute). Eight replicates are depicted per plot. Where it appears there are less than 8 individual panel curves in each plot, multiple panels with no checking (zero CD value) are overlaid

3.2 Data model and analysis

A generalized linear mixed model based on the Tweedie compound Poisson distribution was fitted to the observed check densities using a logarithmic link function. Model fit for generalised linear mixed models is not easily assessed by a single metric (i.e., there is no equivalent of R^2). However, model results were assessed by comparing estimated values with observations.

Only in two cases, the observed mean CD fell outside the 95% confidence interval of the estimated mean. One case was the specimen group that had no observed checking, yet the model produced very small estimated checking values. The second case was for specimens with sliced 0.508 mm face veneer, veneer core, soy adhesive, and loose-side out lathe check orientation. In this case, the observed mean CD was lower than the lower bound of the 95% confidence interval of the estimated mean (observed mean CD: 230 mm^2/m^2, estimated lower bound: 297 mm^2/m^2). Other than these isolated incidences, the observed mean CD fell within the 95% confidence interval of the estimated mean, indicated the model performed well.

The CD values estimated by the model for each treatment are presented on the original and natural logarithmic scale in Fig. 5. Again, when the results are shown with natural CD values on the vertical axis (background chart), the differences between the measured values and the estimated means for individual treatments and between treatments are overwhelmed by the large values at the higher end of the distribution. The superimposed foreground chart shows the same information with CD values in natural logarithmic scale. The adhesive types are coded with marker shape and the core types with marker colors. Even though the data points represent all four veneer types and lathe check orientations these treatment levels could not be simultaneously visually distinguished without risking confusion. The error bars represent the estimated 95% confidence intervals for individual treatments. For comparison, the experimental CD values for each treatment are shown as grey square markers.

The model revealed the presence of a four-way interaction between factors (drop in deviance between the full model with all four-way interactions and reduced model with all three-way interactions: drop in deviance = 60, df = 18, $p < 0.001$). That is, the effect of any factor depends on the levels of the other factors being used. Therefore, the simple effects of a factor cannot be separated from the effects of other factors. This makes it impractical, and indeed untenable, to offer simple, straightforward recommendations on the use of individual factors (e.g., using a specific adhesive or a specific adhesive with a specific core type). Although checking was observed to be more severe in panels with veneer core, statistical analysis indicated the degree of checking was dependent on a combination of factors that varied by level of the other factors. This observation about treatment combinations may, to some extent, explain the confusion

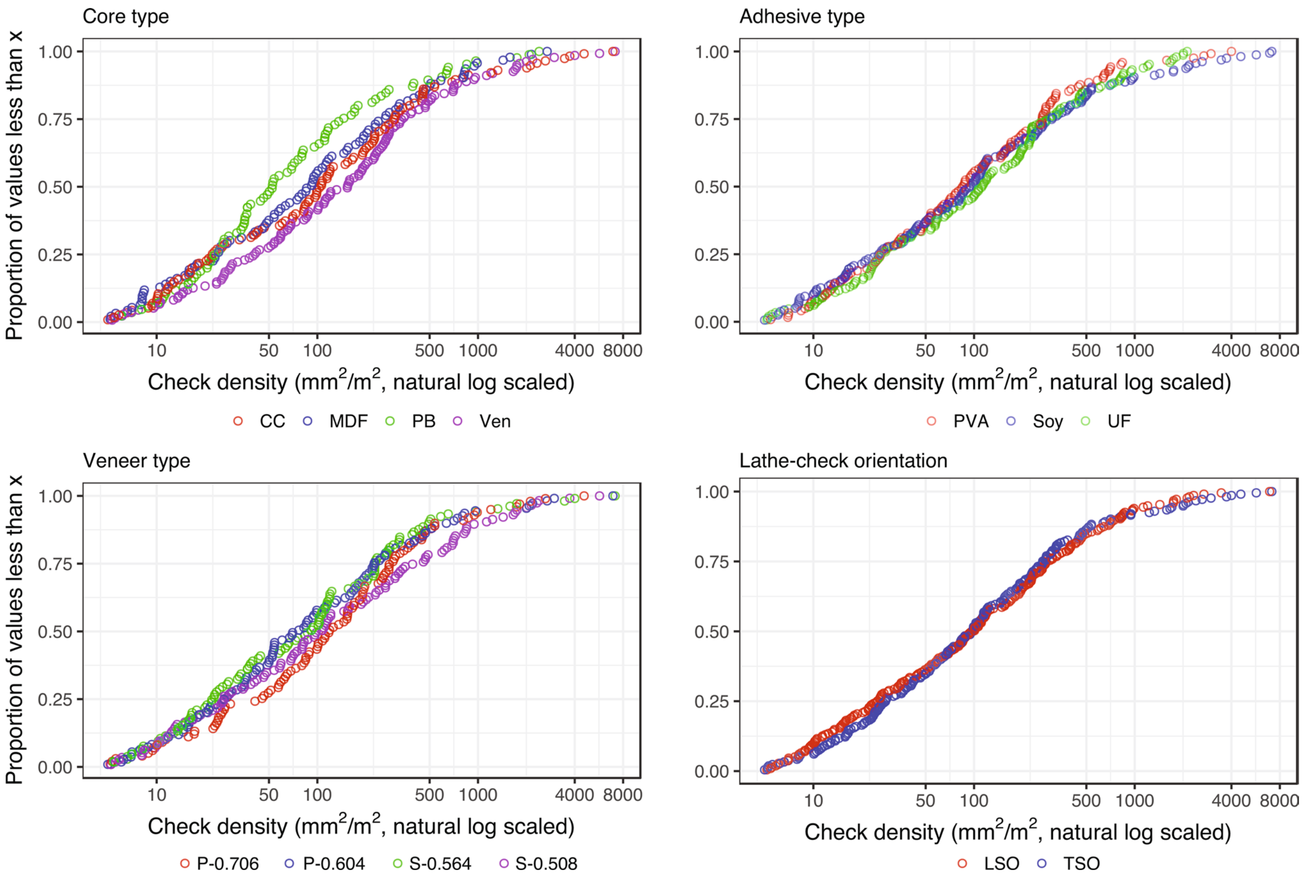

Fig. 4 Cumulative distributions of observed CD for each factor level grouped by factor. Each chart includes all panels with detected checks ($n = 428$ for each chart). Each point indicates a single replicate

and apparent contradictions in earlier studies examining a limited number of treatments.

Check density is strongly right-skewed, reflecting large variation. The random effect of whole plot only accounted for a small portion of the variance in the data (1.06), and the residual variance was much greater (17.8, the dispersion parameter estimated to be equivalent to the residual variance) (Table 4). This indicates other factors not included (e.g., log harvest location and time, log preparation, drying method, other veneer properties, etc.) in the experiment may contribute to check development as well as those in the experiment.

The complexity and variability exposed through the model is best explored in Fig. 5 where the estimated mean CD for each of the 95 treatments are presented in order of increasing severity. The rank, full description of the treatments, observed mean check density, number of panels with observed checks, as well as the model estimated CDs and associated bootstrapped CIs for each treatment are presented in Table 3.

The estimated mean check densities for the individual treatments range from approximately 0 to 1343 mm^2/m^2 (Table 3, Fig. 5).

One practical way of assessing the effect of individual factors used in this study is to examine how the mean CD values for individual combinations rank among other all other mean CD values, or, in somewhat reduced way, how many panels representing specific variable levels fall in one of the four quartiles of the distribution. The following sections present this information for each of the key factors examined.

3.3 Effect of veneer

Panels constructed with all four veneer types have check densities dispersed throughout the entire range of estimated mean check densities. This suggests that the propensity for checks to develop cannot be attributed to veneer preparation method/thickness alone. Estimated mean check densities for panels manufactured with sliced, 0.508 mm veneer, were

Table 3 Observed and bootstrapped estimated mean check density with 95% BC_a CI's for all treatments; number of panels with detected checks for each treatment combination

Rank	Veneer	Lathe checks	Core	Adhesive	Observed mean	No. panels with checks	Boot-strapped mean	95% CI lower bound	95% CI upper bound
1	Peeled, 0.706	LSO	PB	Soy	0.000	0	0	0	0
2	Peeled, 0.604	TSO	MDF	PVA	2.903	1	1.387	0	6.476
3	Peeled, 0.604	TSO	MDF	UF	10.22	2	6.599	0	20.41
4	Sliced, 0.508	TSO	PB	UF	7.107	1	6.907	0	37.92
5	Peeled, 0.706	LSO	MDF	PVA	14.73	1	7.038	0	32.99
6	Sliced, 0.564	LSO	CC	PVA	4.553	3	7.383	1.817	28.87
7	Peeled, 0.604	LSO	PB	UF	8.703	1	9.208	0	43.80
8	Peeled, 0.604	LSO	Veneer	PVA	26.49	3	14.83	0.651	83.15
9	Peeled, 0.706	TSO	PB	UF	15.78	4	16.16	4.225	38.26
10	Peeled, 0.706	LSO	PB	PVA	36.02	2	18.11	0	84.90
11	Sliced, 0.564	LSO	PB	UF	22.27	4	18.69	4.762	57.02
12	Sliced, 0.564	TSO	PB	UF	18.92	3	18.76	2.845	54.11
13	Sliced, 0.508	LSO	MDF	UF	34.53	2	23.40	0	106.8
14	Peeled, 0.706	TSO	PB	PVA	33.41	3	28.39	4.370	101.6
15	Peeled, 0.604	LSO	CC	UF	34.26	5	28.74	6.237	108.0
16	Peeled, 0.604	LSO	PB	PVA	32.71	4	35.29	13.51	96.59
17	Peeled, 0.706	TSO	MDF	PVA	20.27	3	36.47	5.590	136.6
18	Sliced, 0.508	TSO	MDF	UF	38.96	3	38.20	2.151	130.1
19	Peeled, 0.706	LSO	PB	UF	58.41	3	40.76	3.185	185.0
20	Sliced, 0.564	TSO	PB	PVA	83.67	2	41.64	0	194.0
21	Sliced, 0.508	TSO	PB	PVA	57.45	4	43.14	14.70	117.6
22	Peeled, 0.706	LSO	CC	PVA	24.63	3	43.71	0.798	161.0
23	Peeled, 0.604	TSO	CC	PVA	53.00	3	47.73	9.339	162.6
24	Sliced, 0.564	LSO	MDF	UF	48.62	5	51.67	13.20	131.7
25	Sliced, 0.564	TSO	MDF	UF	62.32	3	53.14	8.349	142.1
26	Sliced, 0.564	LSO	MDF	PVA	86.80	3	53.27	1.329	261.0
27	Peeled, 0.604	LSO	PB	Soy	75.00	5	53.46	14.63	162.3
28	Sliced, 0.564	TSO	CC	PVA	43.22	4	53.74	11.13	183.5
29	Sliced, 0.564	TSO	MDF	Soy	59.83	5	53.85	8.191	233.5
30	Peeled, 0.706	TSO	Veneer	PVA	47.28	3	60.36	11.35	228.0
31	Sliced, 0.564	LSO	PB	PVA	42.85	4	60.41	15.99	196.9
32	Peeled, 0.706	TSO	MDF	UF	95.90	4	64.55	8.466	187.6
33	Peeled, 0.604	LSO	MDF	Soy	74.29	4	67.53	12.42	233.9
34	Peeled, 0.604	TSO	PB	PVA	78.39	5	67.96	11.30	305.6
35	Sliced, 0.564	LSO	CC	UF	49.12	5	68.69	19.55	147.5
36	Sliced, 0.508	TSO	CC	PVA	58.69	5	70.46	21.28	209.1
37	Peeled, 0.604	TSO	PB	UF	97.45	5	72.70	20.81	149.6
38	Peeled, 0.706	TSO	CC	UF	72.12	5	74.20	16.46	218.1
39	Sliced, 0.508	LSO	PB	PVA	103.7	6	77.91	16.57	307.8
40	Sliced, 0.564	LSO	Veneer	PVA	95.03	4	84.10	15.46	281.8
41	Sliced, 0.564	TSO	PB	Soy	129.7	3	87.20	13.43	423.3
42	Peeled, 0.706	LSO	MDF	UF	38.63	4	90.92	7.095	416.8
43	Sliced, 0.508	LSO	CC	UF	68.40	4	96.20	4.874	284.2
44	Peeled, 0.706	TSO	PB	Soy	87.05	4	96.67	24.81	329.4
45	Peeled, 0.706	LSO	Veneer	PVA	70.75	4	106.6	25.31	369.0
46	Peeled, 0.604	TSO	MDF	Soy	79.72	7	110.2	44.31	275.6
47	Sliced, 0.508	LSO	MDF	Soy	68.98	3	116.0	2.690	658.4

Table 3 (continued)

Rank	Veneer	Lathe checks	Core	Adhesive	Observed mean	No. panels with checks	Boot-strapped mean	95% CI lower bound	95% CI upper bound
48	Sliced, 0.564	LSO	Veneer	Soy	191.1	4	121.2	39.50	441.1
49	Peeled, 0.604	TSO	Veneer	Soy	95.41	5	125.3	34.41	365.6
50	Sliced, 0.564	LSO	PB	Soy	166.6	5	131.1	26.21	490.9
51	Sliced, 0.508	TSO	PB	Soy	303.0	2	146.4	0	688.4
52	Sliced, 0.508	LSO	CC	Soy	136.8	6	149.2	37.10	533.4
53	Sliced, 0.564	TSO	CC	Soy	273.0	6	152.5	29.70	657.4
54	Sliced, 0.564	TSO	CC	UF	203.1	6	152.6	51.07	373.7
55	Peeled, 0.604	TSO	PB	Soy	186.9	4	152.9	6.390	875.1
56	Sliced, 0.508	LSO	MDF	PVA	154.0	5	154.8	28.57	540.8
57	**Peeled, 0.706**	**TSO**	**Veneer**	**UF**	**134.5**	**8**	**154.9**	**71.76**	**313.3**
58	Peeled, 0.604	TSO	CC	UF	225.0	4	155.0	34.18	411.4
59	Sliced, 0.564	TSO	MDF	PVA	98.66	3	158.8	18.10	754.1
60	Sliced, 0.508	LSO	PB	UF	218.1	4	161.5	14.03	473.5
61	Sliced, 0.508	LSO	Veneer	PVA	133.5	6	162.3	75.56	356.5
62	Sliced, 0.564	TSO	Veneer	UF	154.7	6	172.8	60.59	329.9
63	Peeled, 0.604	TSO	CC	Soy	84.91	7	183.6	80.08	614.6
64	Peeled, 0.604	LSO	MDF	PVA	277.3	4	192.4	8.630	847.9
65	Sliced, 0.508	TSO	CC	UF	357.4	5	196.8	17.46	930.7
66	Sliced, 0.508	TSO	MDF	Soy	312.2	5	201.6	21.56	1015
67	Peeled, 0.706	LSO	MDF	Soy	197.4	5	207.5	48.82	736.1
68	Peeled, 0.604	LSO	Veneer	Soy	338.9	6	210.4	15.21	1109
69	Peeled, 0.706	LSO	Veneer	Soy	269.9	6	215.8	46.62	884.8
70	Peeled, 0.604	LSO	CC	PVA	145.6	7	224.1	101.3	450.6
71	Sliced, 0.508	TSO	MDF	PVA	160.1	7	228.6	83.01	623.6
72	Sliced, 0.564	LSO	MDF	Soy	183.6	5	231.6	64.88	688.7
73	Peeled, 0.706	TSO	MDF	Soy	184.2	5	240.6	46.35	971.6
74	Peeled, 0.604	LSO	MDF	UF	222.4	4	250.5	60.51	685.9
75	Sliced, 0.564	LSO	CC	Soy	460.3	5	252.7	11.27	1429
76	Sliced, 0.508	TSO	Veneer	PVA	133.9	3	258.8	66.21	932.3
77	Peeled, 0.706	TSO	CC	PVA	155.0	4	268.0	104.5	787.9
78	Sliced, 0.508	TSO	CC	Soy	510.7	4	292.0	12.72	1627
79	Peeled, 0.706	LSO	CC	Soy	178.8	4	300.5	95.20	865.7
80	Sliced, 0.564	LSO	Veneer	UF	553.3	7	311.0	112.6	884.5
81	Sliced, 0.564	TSO	Veneer	PVA	359.9	5	314.9	18.14	1772
82	Peeled, 0.706	TSO	Veneer	Soy	215.1	7	349.1	155.0	861.0
83	**Peeled, 0.604**	**LSO**	**Veneer**	**UF**	**297.0**	**8**	**374.7**	**159.9**	**750.4**
84	Peeled, 0.706	LSO	Veneer	UF	332.2	7	382.4	119.7	1244
85	Peeled, 0.706	LSO	CC	UF	498.2	5	459.2	124.7	1172
86	Sliced, 0.508	LSO	PB	Soy	368.1	7	481.1	172.7	1300
87	Sliced, 0.508	LSO	CC	PVA	442.8	4	506.1	116.1	1740
88	Sliced, 0.564	TSO	Veneer	Soy	935.5	5	509.2	21.18	2294
89	Peeled, 0.604	TSO	Veneer	UF	354.7	6	540.2	132.7	1771
90	**Sliced, 0.508**	**LSO**	**Veneer**	**Soy**	**230.4**	**8**	**564.6**	**297.4**	**1625**
91	Sliced, 0.508	LSO	Veneer	UF	415.6	6	594.5	238.1	1182
92	Peeled, 0.604	TSO	Veneer	PVA	548.8	4	748.9	216.7	2362
93	**Sliced, 0.508**	**TSO**	**Veneer**	**UF**	**769.9**	**8**	**784.4**	**336.9**	**1363**
94	Peeled, 0.706	TSO	CC	Soy	1005	5	908.9	158.7	2858
95	Peeled, 0.604	LSO	CC	Soy	990.1	6	1236	115.0	4947

Table 3 (continued)

Rank	Veneer	Lathe checks	Core	Adhesive	Observed mean	No. panels with checks	Boot-strapped mean	95% CI lower bound	95% CI upper bound
96	Sliced, 0.508	TSO	Veneer	Soy	816.2	7	1343	232.6	6242

LSO loose-side out; *TSO* tight-side out, *CC* combination core, *PB* particleboard, *MDF* medium density fibreboard, *PVA* polyvinyl acetate, *UF* urea formaldehyde

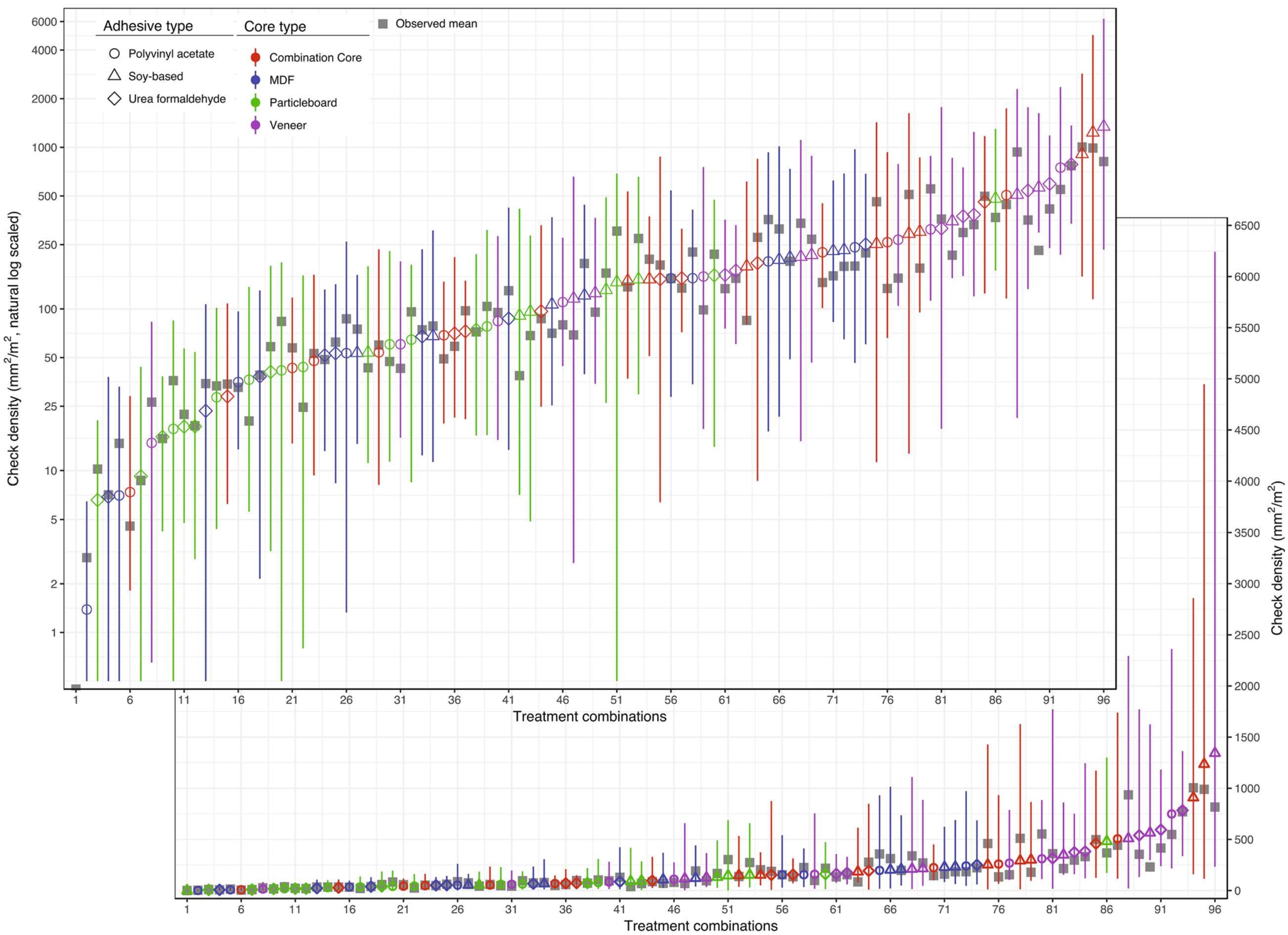

Fig. 5 Observed and estimated CD means with 95% BC_a confidence intervals by treatment ordered from least to greatest. The top panel is on a natural log scale, and the bottom panel is on the raw scale. Estimated means and confidence intervals are bootstrapped. 1 treatment is removed from the natural log scale panel to simplify display (the treatment ranked 1)

Table 4 Parameters from the Tweedie compound Poisson model fit to the observed data and the values extracted from the bootstrap, with 95% BC_a CI's

Parameter	Data model	Bootstrap value	Bootstrap 95% CI
Index	1.58	1.58	1.58–1.60
Dispersion/ residual variance	17.2	17.2	16.2–20.3
Whole plot	1.09	1.09	0.71–1.31

highest, with 66% of estimated check means falling into the 3rd and 4th quartiles, or above 121 mm^2/m^2 (Table 5, Fig. 5).

3.4 Effect of lathe check orientation

Panels constructed with both lathe check orientations (tight-side out and lose-side out) have mean check densities distributed throughout the full range of estimated check densities (Fig. 5, Table 6). The observed data and resulting model provide no evidence that lathe check orientation alone contributes to check development in maple veneered decorative panels. These observations contradict the conclusions of previous studies that lathe check orientation effect can be isolated from other complex interactions (Cassens et al. 2003; Leavengood et al. 2011). The authors` model suggests lathe check orientation is entangled in 4-way interactions with other variables, and therefore, based on their data, it cannot be concluded that one lathe check orientation will lead to greater probability or degree of checking than the other. It is important to note that the characteristics and quantity of any pre-existing cracks were not studied here, only the lathe-check orientation of the face veneer at the time of assembly.

3.5 Effect of core material

Panels with veneer core tended to have high estimated mean check densities (54% of estimated CDs fall in the 4th quartile). Panels with particleboard core tended to have low estimated mean check densities, indicating they performed the best in terms of checking (50% of estimated CDs fall in the 1st quartile) (Table 7, Fig. 5). The high check densities for panels with veneer cores is likely attributable to the fact that these panels were produced with the face veneer grain orientation parallel to the grain orientation of the veneer core. However, recent research in which the face veneer was oriented perpendicular to the grain orientation of the veneer core also confirms that there is a greater tendency for checking on veneer core material (Wilson 2018).

Based on this analysis, in panels with checks, the decorative plywood panels with particleboard cores seemed to mitigate the amount of checking.

3.6 Effect of adhesive type

The range of estimated mean CD separated by the adhesive type (Table 8) shows interesting trends. While 66% of estimated mean CD values for PVA bonded panels and 56% of the UF bonded panels fall into the two lower quartiles (i.e., are likely to check at CD levels below 121 mm^2/m^2), 72% of panels bonded with soy adhesive fall in the two higher quartiles of estimated mean CD (i.e., above 121 mm^2/m^2),

Table 5 Percent of panels of each type falling into quartiles of all estimated means by veneer type

Veneer type	Quartile			
	1st (CD < 52 mm^2/m^2) (%)	2nd (CD ≤ 121 mm^2/m^2) (%)	3rd (CD ≤ 232 mm^2/m^2) (%)	4th (CD ≤ 1343 mm^2/m^2) (%)
Peeled, 0.706 mm	33	25	13	29
Peeled, 0.604 mm	29	21	29	21
Sliced, 0.564 mm	21	38	25	17
Sliced, 0.508 mm	17	17	33	33

Table 6 Percent of panels of each type falling into quartiles of all estimated means by lathe check orientation

Lathe check orientation	Quartiles			
	1st (CD < 52 mm^2/m^2) (%)	2nd (CD ≤ 121 mm^2/m^2) (%)	3rd (CD ≤ 232 mm^2/m^2) (%)	4th (CD ≤ 1343 mm^2/m^2) (%)
Tight-side out	27	25	23	25
Loose-side out	23	25	27	25

Table 7 Percent of panels of each type falling into quartiles of all estimated means by core type

Core type	Quartiles			
	1st (CD < 52 mm^2/m^2) (%)	2nd (CD ≤ 121 mm^2/m^2) (%)	3rd (CD ≤ 232 mm^2/m^2) (%)	4th (CD ≤ 1343 mm^2/m^2) (%)
Combination core	17	21	29	33
MDF	29	33	29	8
Particleboard	50	29	17	4
Veneer	4	17	25	54

Table 8 Percent of panels of each type falling into quartiles of all estimated means by adhesive type

Adhesive type	Quartiles			
	1st (CD < 52 mm^2/m^2) (%)	2nd (CD ≤ 121 mm^2/m^2) (%)	3rd (CD ≤ 232 mm^2/m^2) (%)	4th (CD ≤ 1343 mm^2/m^2) (%)
Polyvinyl acetate	38	28	19	16
Soy	3	25	38	34
Urea formaldehyde	34	22	19	25

with 33% likely to check above 232 mm^2/m^2 (i.e., in the 4th quartile).

Figures 6 and 7 show the estimated mean CD for all combinations sorted by the core material: particleboard (Fig. 6a), MDF (Fig. 6b), combination (Fig. 7a), and veneer core (Fig. 7b), respectively. In these charts, the adhesive and core types are coded by marker shape and colour, respectively, and lathe orientation is indicated by the type of the error bar line (solid line for loose side out, dashed line for tight side out). These charts may be of some practical use for manufacturers to weigh decisions regarding panel lay-up, if they have selected a particular type of core material. The results of this study can be used in a similar way for assessing the levels of other factors examined, or for any combination of them. The relatively small differences between some combinations indicate only minor gains or losses when selecting specific manufacturing variables.

4 Discussion

Customer complaints related to checking are more likely when the severity of checking increases, and there is no standard definition of an acceptable amount of checking. Therefore, examining the range of estimated check densities from the model provides the most straightforward insight into which treatments are more or less likely to perform well in case of occasional severe drying exposures.

As in prior research (Cassens et al. 2003; Leavengood et al. 2011), the results suggest significant interactions among factors. The complexity of the interactions should prompt caution in attributing checking propensity in decorative maple plywood to any single factor of panel construction. For example, a manufacturer should not decide to change adhesive types to avoid check formation without considering the concurrent effects of other factors.

While entangled four-way interactions are not easy to interpret, the reduced data and charts parsed by selected variables generated by the model may be a useful tool for estimating the propensity of selected combinations for checking at severe drying exposure events.

Manufacturers may consider Table 3 or Figs. 5, 6, 7, which present the ordered mean check densities and provide an index of increasing risk of a claim. The variability associated with the estimates, as represented by 95% confidence intervals, indicate that check development in decorative maple veneer panels may be related to factors beyond those included in this study. That is, the examined factors do not provide a complete understanding of check development. No factor or factor level can easily be dismissed from consideration either.

It should be stressed that this study has not addressed all possible factors, which may and should be explored in future studies. Examples include the moisture content of the core and veneer components at the time of pressing, log/flitch conditioning method, veneer source region and harvest season, veneer drying method, etc. In addition, the variability inherent within panel components (i.e., veneers, adhesives, cores) is likely to contribute to the degree of checking as well. Accordingly, in future research the test methodology used in this study should be employed to investigate the variability within panel components and the effects of other factors discussed in the rich literature of the subject in order to confirm or dismiss earlier hypotheses. Currently, the bottleneck of the method seems to be the fabrication of test specimens in lab environment.

5 Conclusion

An innovative optical method was successfully used for investigation of the impact of four decorative plywood panel manufacturing factors (core type, veneer type, adhesive type and lathe check orientation) commonly believed to affect face veneer checking. This method allowed automated examination of a large number of panels and measurement of detailed checking information as checking occurred. One particular advantage of this method was that it allowed detecting the peak check densities as they occurred in panels at different times of exposure. That in turn allowed for meaningful comparisons of check densities not possible when surfaces are examined at an arbitrary point in time. In 56% of panels with detectable checks, peak CDs occurred before the end of the 240-min testing period.

Checks were detected on 56% of all inspected specimens. Only one treatment—peeled 0.706 mm veneer on

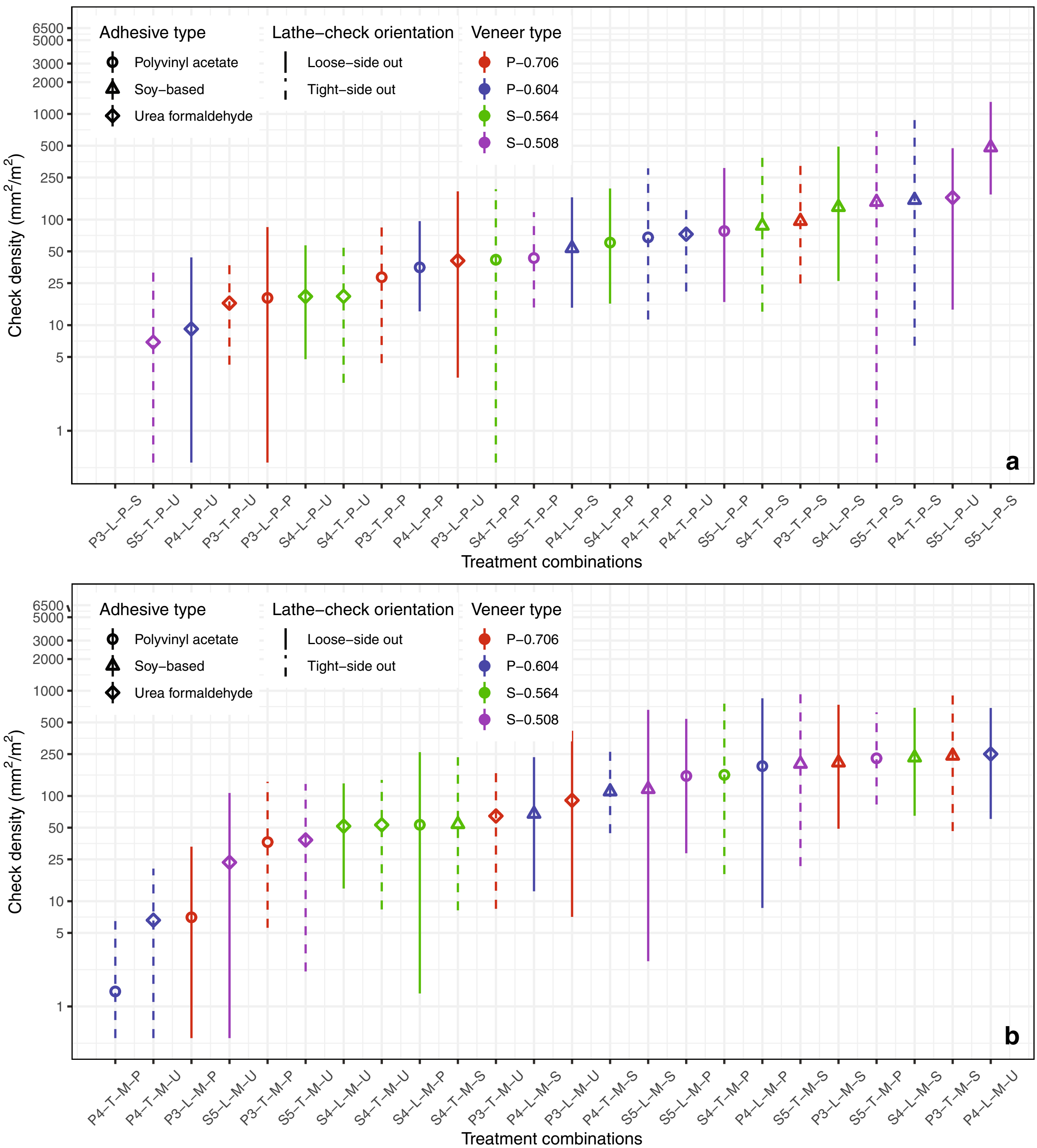

Fig. 6 Estimated CD means with 95% BC_a confidence intervals for all panels made with particleboard core (**a**) and MDF core (**b**), and all other manufacturing factors noted. X-axis label key: indicator order is: Veneer type—Lathe check orientation—Core type—Adhesive type. Values are: P3 = peeled, 0.706 mm, P4 = peeled, 0.604, S4 = sliced, 0.564, S5 = sliced 0.508; L = loose-side out, T = tight side out; P = particleboard; M = MDF, P = polyvinyl acetate, S = soy-based, U = urea formaldehyde

particleboard core using soy-based adhesive with the lathe checks oriented out (loose side out)—had no detectable checks on any of the eight replicates examined. In only four treatment, checks were detected in all 8 of the replicates investigated. The complexity of the checking process and the number of variables that may affect it make generalisations

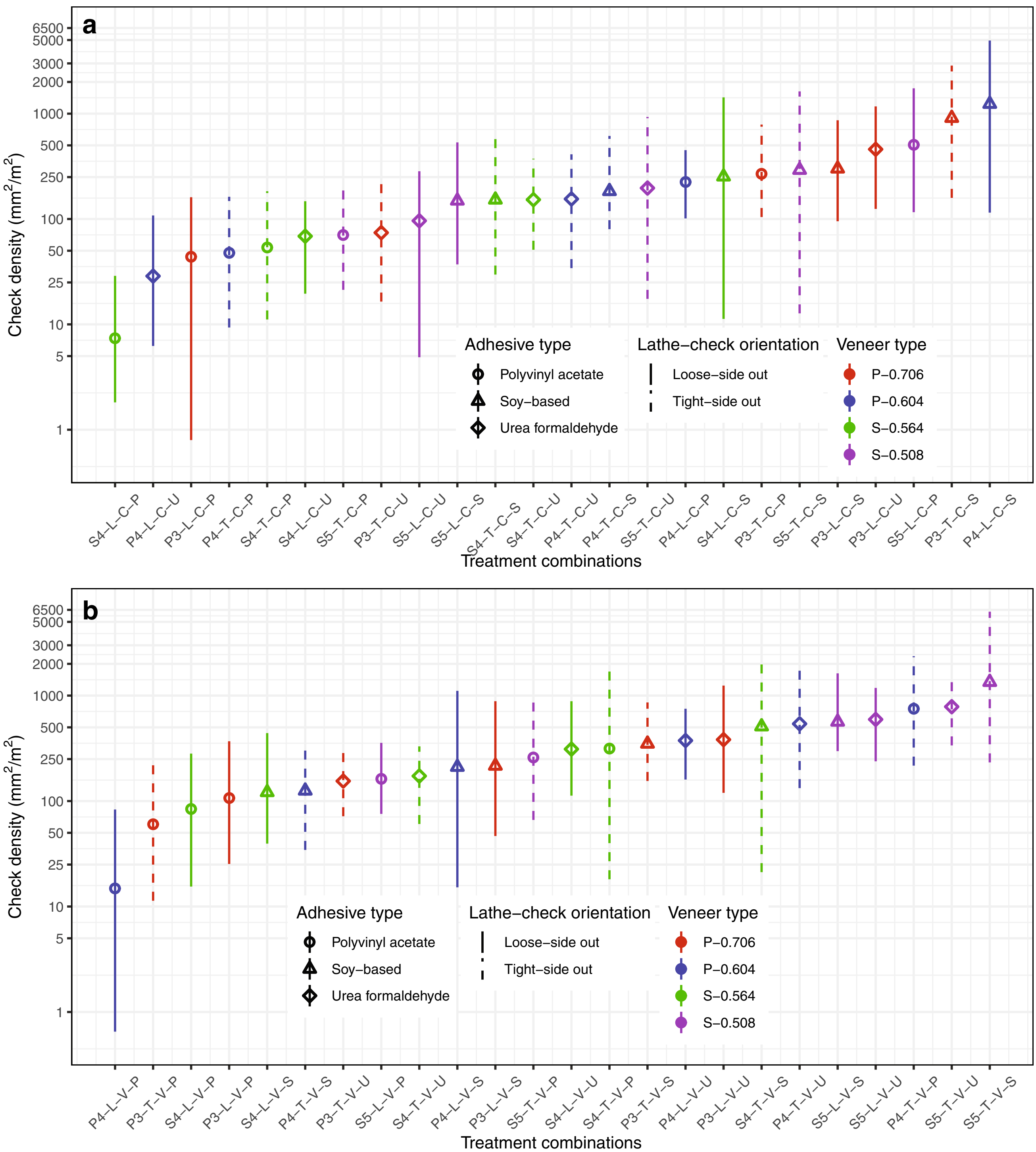

Fig. 7 Estimated CD means with 95% BC_a confidence intervals for all panels made with combination core (**a**) and veneer core (**b**), and all other manufacturing factors noted. X-axis label key: indicator order is: Veneer type—Lathe check orientation—Core type—Adhesive type. Values are: P3 = peeled, 0.706 mm, P4 = peeled, 0.604, S4 = sliced, 0.564, S5 = sliced 0.508; L = loose-side out, T = tight side out; C = combination core; V = veneer core; P = polyvinyl acetate, S = soy-based, U = urea formaldehyde

beyond the specific materials and processes represented by the 96 combinations of factors studied here difficult to support. However, the most generalizable conclusion may be that conventional wisdom related to the best lathe check orientation to reduce checking, and indeed previous research results, cannot be supported by the evidence in this study.

This suggests that check development may be more directly related to the characteristics and quantity of pre-existing cracks in the veneer than can be attributed only to the lathe-check orientation of the veneer in the assembled panel. The presence of checks and the observed check densities were nearly equal between lathe check orientations.

The model used to estimate the probability of high level of check densities in products with specific manufacturing options is charged with substantial uncertainties. At the current stage, practitioners should use it with caution. However, the tools used here for exploring and comparing check densities do allow isolation of the most suitable panel types within individual manufacturer's constraints.

The test method used in this study allows larger and more comprehensive investigations as well as a more accurate way to detect and measure check intensity at any time throughout the checking process. In future research this method should be employed to investigate the effects of other factors discussed in the rich literature of the subject in order to confirm or dismiss earlier hypotheses. This check characterisation methodology, particularly in combination with rapid veneer characterisation methods such as those demonstrated in Rohumaa et al. (2018) and other useful assessment methodologies can help shed light on a greater range of potential check development factors, especially those related to the characterisation and quantification of pre-existing cracks which are hypothesised to contribute to the degree of checking in the final panel.

A qualitative study examining the extent of checking (number, size, visibility) acceptable to end users may be helpful to provide manufacturers with some indicator of the tolerance end users have regarding checking.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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