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ORIGINAL

Detection of wood failure by image processing method: influence of algorithm, adhesive and wood species

Lanying Lin[1] · Sheng He[2] · Feng Fu[3] · Xiping Wang[4]

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Abstract Wood failure percentage (WFP) is an important index for evaluating the bond strength of plywood. Currently, the method used for detecting WFP is visual inspection, which lacks efficiency. In order to improve it, image processing methods are applied to wood failure detection. The present study used thresholding and K-means clustering algorithms in wood failure detection, and four kinds of plywood were manufactured to analyze the influences of wood species and adhesive. Results show that the detection by K-means clustering method is more accurate than thresholding method; it could better correlate with visual inspection results, while the detection results by thresholding method could not reflect the fluctuation of visual inspection results with types of plywood. Moreover, both analyses of the influence of adhesive and wood species show that thresholding method based detection results are more affected by adhesive color, veneer color and permeability of poplar and eucalyptus veneer (mean absolute error compared with visual inspection: PF-Eucalyptus: 15.77 %; PF-Poplar: 25.42 %; UF-Eucalyptus: 30.55 %; UF-Poplar: 21.48 %); whereas K-means clustering method based detection results show no significant change as adhesive and wood species varies (PF-Eucalyptus: 11.07 %; PF-Poplar: 10.22 %; UF-Eucalyptus: 14.77 %; UF-Poplar: 8.50 %). It can be concluded that K-means clustering method has better compatibility for different adhesive and wood species in wood failure detection.

✉ Feng Fu
feng@caf.ac.cn

1 Research Institute of Forestry New Technology, Chinese Academy of Forestry, Xiangshan Road, Haidian District, Beijing, People's Republic of China

2 China National Bamboo Research Center, No.310, Wenyi Road, Xihu District, Hangzhou, Zhejiang, People's Republic of China

3 Research Institute of Wood Industry, Chinese Academy of Forestry, Xiangshan Road, Haidian District, Beijing, People's Republic of China

4 USDA Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726-2398, USA

1 Introduction

With more than 81 million m^3 production and a market value of approximately 19 billion dollars in exports and imports in 2010, plywood is one of the most important wood based composites (Demirkir et al. 2013). It has been widely used in construction, decoration, manufacture of furniture, transportation, package etc (Zhan 2000).

Bond strength is an important property in order to evaluate the quality of plywood. A traditional method for evaluating is to measure the bond strength in shear mechanically and estimate the wood failure percentage (WFP) on the test specimen surfaces visually (Zink and Kartunova 1998). However, as it is based on visual inspection, there are problems such as inefficiency, subjectivity and difficult to compare between other studies (Zhang et al. 2003; Hu et al. 2011; Jiang et al. 2011).

Image processing method has the advantage of relatively low cost, high efficiency and precision. It has been applied to products' flaw detection (Yuan et al. 2012), biomedical and diagnostic imaging (Dhawan 1990; Xu et al. 2010) and item counting (Friedland et al. 2005), etc. In the field of wood science and technology, image processing has been applied to wood defects detection (Funck et al. 2003; Mekhtiev and Torgovnikov 2004; Christy 2005; Gonzalo et al. 2005, 2009; Gu et al. 2010), wood identification

(Kennel et al. 2010; Harjoko and Gasim 2010; Wooten et al. 2011), lumber grading (Conners et al. 1992; Kline et al. 2003) etc.

Few studies have been done on assessing WFP by image processing methods. McMillin was the first to introduce image processing method to wood failure detection (McMillin 1982). However, he did not illustrate the procedure and principle of the method. Zink and Kartunova presented the thresholding method for the measurement of wood failure in phenol–formaldehyde (PF) glued plywood in detail. It separates the wood failure regions from the background based on different brightness of wood or glue on images. As the wood and glue exhibited a distinctly different brightness character, threshold gray value for image segmentation could be determined (Zink and Kartunova 1998). However, the method still does not analyze the influence of wood species and adhesives on the accuracy of the detection results since different wood species and adhesives might affect the threshold gray value for image segmentation. Therefore, in order to develop a universally adapted image processing method for wood failure detection, it is necessary to investigate the effects of wood species and adhesives on detection results.

Image processing mainly consists of five stages: image acquisition, image enhancement, image segmentation, feature extraction and classification (Pham et al. 2006). Image segmentation is the most important stage. It divides an image into multiple segments based on different algorithms. Extensive studies have been done in the area of image segmentation algorithms. A vast majority of image processing methods applied to wood science and technology are based on thresholding algorithms. The key point of the algorithm is to find the proper threshold gray value for segmenting the image. Many improved algorithms were developed to achieve a better detection of wood failure. For instance, Yang et al. (2008) developed an improved algorithm for wood failure detection based on the image bimodality concept. Besides, clustering based algorithms are also useful for image segmentation. A cluster is a collection of objects which are "similar" between them, and "dissimilar" objects belong to other clusters. It is suitable for separating wood failure region from the background that is, achieving the purpose of wood failure detection. A variety of clustering methods have been proposed. As K-means clustering is the widely used algorithm that solves the clustering problem, it is therefore meaningful to explore its possibility for wood failure detection.

Due to the deficiency of visual inspection, the image processing techniques are used to make the wood failure detection more efficient and scientific. The present study uses two most extensively used methods based on thresholding and K-means clustering algorithm in wood failure detection. Effects of these two methods are compared. In addition, with two kinds of veneer (*Poplar* spp. and *Eucalyptus* spp.) and two kinds of adhesive [phenol–formaldehyde (PF) and urea–formaldehyde (UF)], four kinds of plywood were manufactured to examine the influence of wood species and glue on the final detection results. After that, the accuracy of wood failure detection through image processing method was evaluated and compared with visual inspection, and a suitable image processing method for wood failure detection could be determined.

2 Materials and methods

2.1 Material preparation

Two kinds of widely used adhesive (PF, UF) and two kinds of veneer (*Poplar* spp. and *Eucalyptus* spp.) were used for the manufacture of four kinds of three-layered plywood. The thickness of the veneer was 1.8 mm with a moisture content (MC) of 8–10 %. Parameters of hot pressing were 140 °C, 1 min/mm, 1 MPa for PF and 100 °C, 1 min/mm, 1 MPa for UF. After the panels had been prepared, specimens for bond strength test were cut and bond strength tests were carried out according to the Voluntary Product Standard PS1-95 for construction and industrial plywood. WFP for each specimen was inspected and recorded by experienced personnel from Chinese National Center for Quality Supervision and Testing of Wood and Bamboo Products. A series of 30 plywood shear specimens were tested for each kind of plywood. The tested specimens were scanned (HP Scanjet G3010) with a resolution of 200 dpi. Scanned RGB images were used in the image processing process to realize the automatic detection of wood failure.

2.2 Procedures and algorithms

2.2.1 Image processing procedures

Image processing procedure consists of five main stages: image acquisition, image enhancement, image segmentation, feature extraction and classification. The first stage is included in the material preparation process. Shear zones were cut from scanned images (Fig. 1) and then processed in the subsequent operations. In the image enhancement stage, steps of image type conversion, contrast enhancing were carried out. In the stages of image segmentation and feature extraction, wood failure region of the specimen was separated from the image background based on pixels' gray value. A binary image was obtained where wood failure regions are shown in white with a black background, which represents the undamaged regions. After that, WFP was calculated according to the white area percentage of the total area of the processed image (Eq. 1).

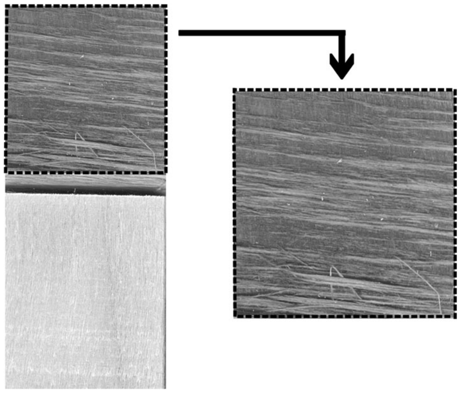

Fig. 1 Scanned image of plywood bond strength test specimen and its shear zone

$$\mathrm{WFP}\,(\%) = \frac{A_{woodfailure}}{A_{shearzone}} \times 100 \tag{1}$$

where $A_{woodfailure}$ is the number of pixels in white, and $A_{shearzone}$ is the total number of pixels for the shear zone of the bond strength test specimen.

The procedures used for image processing is written and run in Matlab R2011b software.

2.2.2 Image segmentation algorithms

2.2.2.1 Thresholding based algorithm Thresholding algorithm is comprised of finding the proper threshold gray value for segmenting the images. The threshold gray value can be determined from gray-level histogram for each single image. There are two basic types of histogram: unimodal and multimodal. In the present study of wood failure detection, mainly bimodal histogram exists. Finding the threshold value from bimodal histogram has been widely studied. Researchers have reported that the threshold gray value should be placed at the valley of histogram (Gonzalez and Woods 1992), which means that the right peak represents failed wood pixels while the left peak represent the glue pixels. As shown in Fig. 2, the threshold gray value could be determined as 90.

2.2.2.2 K-means clustering algorithm K-means is one of the widely used algorithms which solves the clustering problem. The procedure follows a simple and easy way to classify a given data set through a certain number of clusters (assume k clusters). This algorithm aims at minimizing an objective Eq. (2).

$$J = \sum_{j=1}^{k} \sum_{i=1}^{x} \left\| x^{j} - c_{j} \right\|^{2} \tag{2}$$

where $\left\| x^{j} - c_{j} \right\|^{2}$ is a chosen distance measure between a data point x^j and the cluster center c_j, which is an indicator of the distance of n data points from their respective cluster centers.

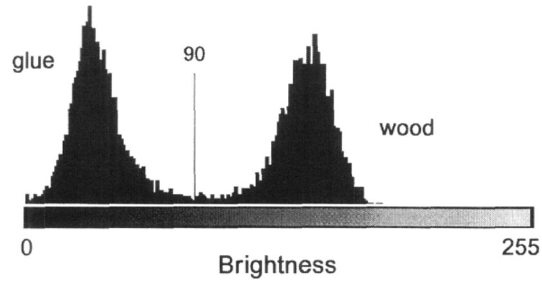

Fig. 2 Bimodal histogram for establishing threshold to separate failed wood from glue (Zink and Kartunova 1998)

The algorithm is composed of the following steps:

1. Place K points into the space represented by the objects that are being clustered (e.g., in the present study, K = 3, and the initial points of three clusters were set as pixels with gray value of 40, 140, 180, while 140 and 180 gray level represent the wood failure region according to gray-level histogram of the images to be processed). These points represent initial group centroids.
2. Assign each object to the group that has the closest centroid.
3. When all objects have been assigned, recalculate the positions of the K centroids. Repeat steps 2 and 3 until the centroids no longer move. This produces a separation of the objects into groups from which the metric to be minimized can be calculated (Sathya and Manavalan 2011).

In the case of wood failure detection, since wood failure regions have different color compared to glue, the regions with similar color are assigned to one cluster while "dissimilar" regions belong to other clusters. After that, one cluster or several clusters [two clusters (140, 180) were taken for the present study] representing wood failure region is designated as white shows in binary image, while the remaining region shows in black. Therefore, wood failure region is separated from image background.

Compared with thresholding and K-means clustering methods, visual inspection method has no mathematical definition for the calculation of WFP. It is only based on the estimation of the detection personnel which is subjective.

3 Results and discussion

3.1 Detection results by image processing methods

WFP detection results by both image processing and visual inspection methods are shown in Table 1 and Fig. 3. It is

Table 1 WFP detection results by image processing methods and errors between image processing and visual inspection methods

Type of plywood	Wood failure percentage (%)			Mean absolute error [% (±STD.)]	
	Thresholding method	K-means clustering	Visual inspection	Thresholding method	K-means clustering
PF-Eucalyptus	43.9	47.1	51.2	15.8 (13.3)	11.1 (9.9)
PF-Poplar	44.0	44.3	42.8	22.4 (13.7)	10.2 (8.2)
UF-Eucalyptus	44.1	61.7	74.7	30.6 (11.8)	14.8 (9.3)
UF-Poplar	43.5	38.2	36.6	21.5 (11.8)	8.5 (6.0)

WFP in table are arithmetic means from 30 samples (n = 30). Mean absolute error is the arithmetic means of difference between image processing methods and visual inspection

Numbers in parentheses are the standard deviations

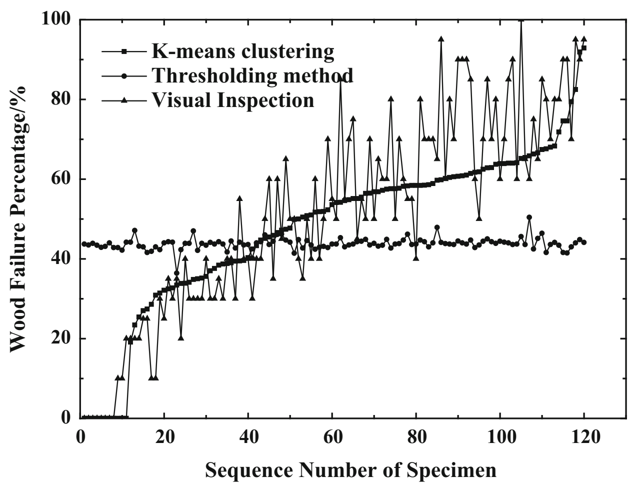

Fig. 3 Wood failure detection result by image processing and visual inspection methods. *Abscissa* represents the sequence of 120 specimens according to WFP ranking by K-means clustering method

indicated that the detection results by K-means clustering could better correlate with the visual inspection results, while the detection results by thresholding method could not reflect the fluctuation of visual inspection results with types of plywood (Fig. 3). Besides, higher mean absolute error is observed for thresholding method than K-means clustering method, while both thresholding and K-means clustering method showed high standard deviation in mean absolute error for each series of samples (Table 1).

Taking the WFP detection of PF bonded eucalyptus plywood as example, Fig. 4 shows the image segmentation results by thresholding and K-means clustering algorithms. According to the detection results, the WFP of this specimen is 63.7 and 43.9 % for K-means clustering and thresholding method, respectively. Compared with the original image, the wood failure regions are almost completely included by K-means clustering method, whereas some small regions have been skipped by the thresholding method. Thus, the detection result by K-means clustering method is more accurate than by the thresholding method. However, the visual inspection result is 85 % for this specimen. There is a great discrepancy between the image processing and visual inspection results, especially for thresholding method. Three major reasons may account for the discrepancy. First, the adjacent regions of failure wood are always regarded as the wood failure if they are surrounded by the wood failure regions in visual inspection. Second, image processing methods lack the sensitivity to fine bundles of fiber projecting out of the plane of the specimen which should be regarded as wood failure (Zink and Kartunova 1998). Third, as the image segmentation is based on similarity of different parts in plywood specimen when resin penetrate to the veneer, wood failure regions may not have significant differences compared with the undamaged region. Thus the image processing result is lower than the visual inspection.

Besides, image processing methods lack the consistency for detecting wood failure at different ranges, especially for thresholding method, which cannot reflect the fluctuation between different specimens (Fig. 3). As to K-means clustering method, although it could well reflect the fluctuation, the detection error is relatively high for specimen with high WFP, such as the limitation to detect the specimen with 100 % wood failure (Zink and Kartunova 1998). Therefore, the standard deviation of mean absolute error between specimens in the same group is quite high (Fig. 5).

3.2 Effect of adhesive

The comparison of wood failure detection results by image processing methods between PF and UF plywood is carried out to examine the effects of adhesive. Figure 5 indicates that for thresholding method, compared with visual inspection, the mean absolute error is higher for UF-Eucalyptus plywood than for PF-Eucalyptus plywood (Table 1), whereas it is almost the same for PF-Poplar plywood and UF-Poplar plywood; the same phenomenon is also found in results of K-means clustering method (Table 1).

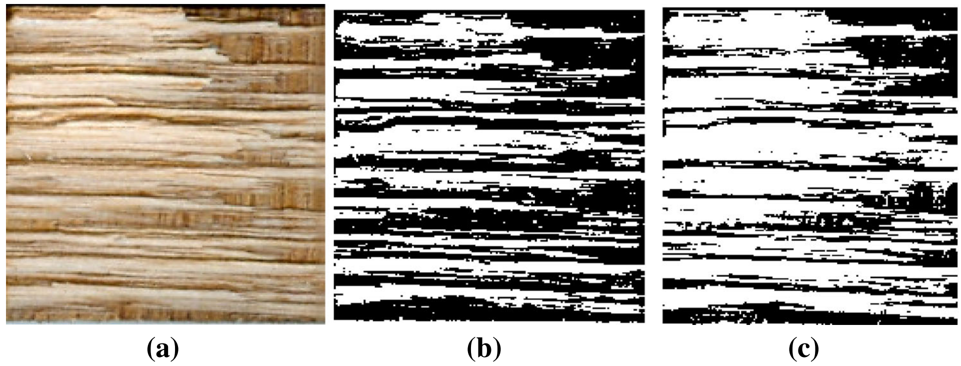

Fig. 4 Image segmentation by thresholding and K-means clustering method. **a** Original image, **b** thresholding method, **c** K-means clustering method

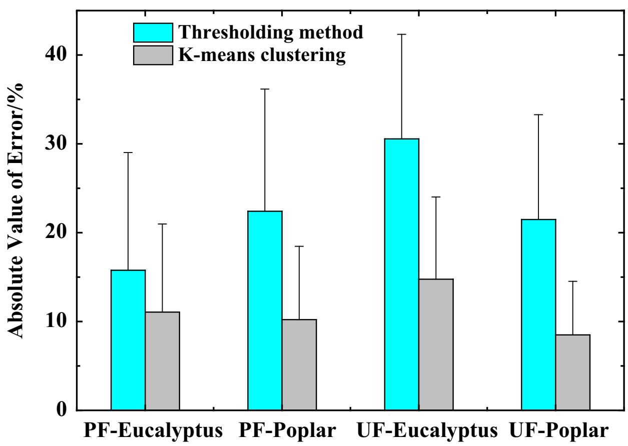

Fig. 5 Mean absolute error compared with visual inspection

As the color of cured PF (red) and UF (white) is different, the contrast between the cured adhesive and veneer is also different. PF has larger contrast for both eucalyptus and poplar veneer than UF in the present study (Fig. 6). The low contrast between wood failure areas and UF adhesive add errors to determine the threshold gray value. Especially for UF-Poplar plywood, as the color of poplar veneer has no significant difference compared with cured UF resin, the gray-level distribution is almost unimodal. It is most likely that the assumption of bimodal distribution for this UF plywood is not appropriate. Thus it is reasonable that the error between image processing method and visual inspection is higher for UF plywood than PF plywood.

3.3 Effect of wood species

Wood species is also an important factor which affects the wood failure detection results of image processing. The contrast between veneer and wood failure area varies as the color of veneer changes. Also, adhesive penetration into the veneer would affect the contrast between veneer and wood failure regions, which finally influence the image processing results.

In the present study, the color of eucalyptus veneer is darker than that of poplar veneer. Therefore, when bonded with PF, which is reflected in the dark color (red), the contrast between cured adhesive and wood failure regions is lower than that in PF-poplar plywood (Fig. 6). It is reasonable that the detection of wood failure is more accurate for PF-Poplar plywood than PF-Eucalyptus plywood by general sense. However, as shown in Fig. 4, when taking the thresholding method for wood failure detection, the mean absolute error is higher for PF-Poplar plywood than that of PF-Eucalyptus plywood (Table 1). This phenomenon could be explained by different permeability of *Eucalyptus* spp. and Poplar veneers. As reported by Dhamodaran and Gnanaharan (2007), *Eucalyptus* spp. wood is refractory in nature and is difficult to be penetrated whereas poplar wood is easy to be penetrated (liquid permeability coefficient K = 13.19 darcy) (Bao and Lu 1992). Thus, poplar veneer is easier to be penetrated than *Eucalyptus* spp. veneer. As the adhesive penetrates into the veneer the contrast decreases between wood failure region and cured adhesive. Figure 6 indicates parts of wood failure areas

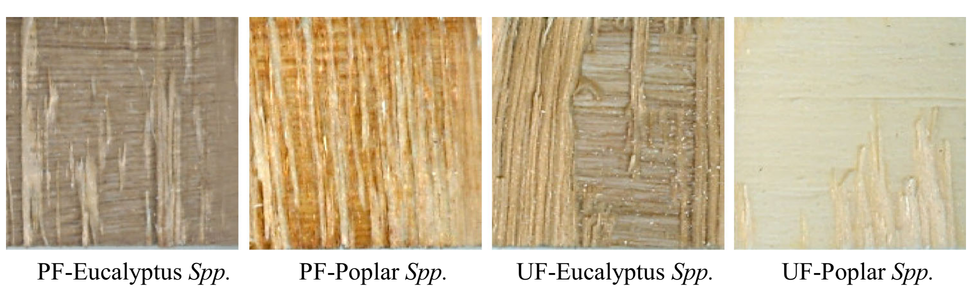

Fig. 6 Shear zones of four kinds of plywood

almost have the same color as the adhesive. Since the contrast decreased, the precision of threshold gray value determined by thresholding method would also be affected. Eventually, the precision of threshold gray value determined by thresholding method would also be affected, which is manifested in higher errors of WFP for PF-Poplar plywood. As to UF bonded plywood, the contrast between cured UF adhesive and *Eucalyptus* spp. veneer is higher than that of poplar veneer, and the permeability of poplar veneer is better than *Eucalyptus* spp. veneer. Although the mean absolute error is higher for UF-Eucalyptus plywood than UF-Poplar plywood (Table 1), the error to visual inspection results is relatively lower for UF-Eucalyptus plywood than UF-Poplar plywood (Table 1).

As to K-means clustering method, the errors between eucalyptus and poplar plywood are relatively smaller (Table 1). It is further indicated that K-means clustering method is more tolerable for different wood species than the thresholding method.

4 Conclusion

WFP of four kinds of plywood is detected based on image processing methods of thresholding and K-means clustering method. Comparison between results of two image processing methods and visual inspection method revealed that the detection by K-means clustering method is more accurate than by thresholding method, it could better correlate with the visual inspection results, while the detection results by thresholding method could not reflect the fluctuation of visual inspection results with types of plywood. Besides, higher errors are observed for thresholding method compared with K-means clustering method. However, large discrepancy still exists between the results of image processing methods and visual inspection, especially for thresholding method.

Analyses of adhesive's influence on image processing results showed that for thresholding method, the mean absolute error is higher for UF plywood than for PF plywood; as to K-means clustering method, there is no significant difference for PF and UF plywood. It can be concluded that K-means clustering method has better compatibility for different adhesive.

Wood species affects the image processing results since different color and permeability of *Poplar* and *Eucalyptus* spp. veneer affect the contrast between veneer and wood failure regions. Wood failure detection by thresholding method revealed that the mean absolute error to WFP by visual inspection is higher for poplar plywood than for eucalyptus plywood. As to K-means clustering method, the errors between eucalyptus and poplar plywood are smaller. It is mainly because the gray level distribution of some specimens (e.g., UF-Poplar) is almost unimodal, which is inappropriate for the processing by the present bimodal thresholding method. For a better correlation with the results of K-means clustering method, or visual inspection, it is recommended to use different thresholding methods (both unimodal and bimodal) for different images.

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