Comparison of Damage to Wood Pallets in Use with Damages Occurring Using the Virginia Tech FasTrack Simulation of Pallet Use

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The durability of a pallet affects the amount of use a pallet can withstand before functionality is lost. A reliable prediction of durability can be used to determine the effect of pallet performance on supply chain operating costs. The objective of this research was to correlate damage modes, location, severity, and frequency observed for pallet in the field, to damages observed during Virginia Tech's FasTrack simulation system. Several 1219 mm x 1016 mm (48 x 40 inch) stringer class wooden pallets used in the field were inspected for damages, and the results were compared to historical pallet damage information from FasTrack. The pallet damage behavior did not change for different levels of damage severity, which indicates that pallets fail as the initial damage worsens due to prolonged use. Inspected pallets from the field showed high damage occurrence on the stringer notches and bottom lead deckboards. Pallets tested *via* FasTrack exhibited significantly more top deck and end board damage and less stringer damage than observed in the field.

DOI: 10.15376/biores.18.3.6044-6056

Keywords: Pallet durability; Pallet damage; Durability simulation; FasTrack; Wood pallet

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INTRODUCTION

Pallets are crucial components of unit load-based supply chains. Pallets are horizontal, rigid structures, used as bases for assembling, storing, stacking, handling, and transporting goods as unit loads (MH1 Committee 2005). According to the Freedonia Group, wood is the predominant material with 84% of the total pallet stock in 2019 and 93% of sales (The Freedonia Group 2015). Other materials such as plastic and metal are gaining market shares due to characteristics such as improved strength and resistance to environmental hazards such as mold and insects.

Pallet performance is measured by strength and functionality. Durability is a functionality characteristic. Durability is the ability of the pallet to resist damages from impacts experienced in shipping and handling environments. One pallet durability metric is the number of trips, or supply chain cycles, that a pallet remains functional, prior to requiring repairs (MH1 Committee 2005). Wallin (1984) defines durability in terms of the economic life of a pallet. When the pallet is treated as a capital asset that is amortized, it should be replaced when the average cost per use is at a minimum. Past this point, the cost of continued maintenance is greater than the cost of a replacement pallet (Wallin and Whitenack 1984).

To understand the relationship between pallet design and performance, the National Wooden Pallet Manufacturers Association (now NWPCA) partnered with the USDA Forest Service, Virginia Tech, and Better Management Services of New York to conduct the Pallet Exchange Program (PEP) study (Wallin *et al*. 1972; Wallin and Sardo 1974). Between 1968 and 1971, the damages to 877 pallets of 17 different designs, used in five different supply chains, was recorded after each use. This resulted in 150,206 pallet handlings (White and Wallin 1987). The primary metrics used to evaluate the effect of pallet design were damage frequency and severity (White and Wallin 1987). Damage frequency is defined as the number of damages sustained by a pallet during its lifetime, whereas, damage severity represents the extent of the damage that the pallet experiences (Wallin and Whitenack 1984). Wood species selection, reinforcement of end deck boards, wood moisture content, and the number and quality of fasteners were the factors that most affected pallet durability (White and Wallin 1987). Using the correlation between these factors, the damage frequency and severity, and the elements mentioned before, an empirical model for predicting durability was created (Wallin and Whitenack 1984).

The model outlined in the MH1, 1997 standard includes nine different factors that can predict the economic life of a pallet from damage severity and frequency. Fastener shear and withdrawal resistance, connection-splitting resistance, pallet part (shook) quality and placement, flexural strength for stringers and deckboards, deck construction, and handling environment are all included in the model (American Society of Mechanical Engineers 1997). Pallet durability predictions in commercial pallet design software that are used today are based, in part, on the data and models from the PEP study.

Virginia Tech and Procter and Gamble partnered to develop an accelerated rough-handling test that simulated pallet handling in unit load supply chains (Cao 1993). The Virginia Tech FasTrack procedure subjects pallets to common stresses related to the handling environment. A forklift and a pallet jack are used to simulate handling movements on a pallet, which holds a 1500 lb dummy load, positioned with an underhang of 2 in. Material handling steps such as loading pallets into and out of a trailer with both a forklift and pallet jack, warehouse racking, double stacking, and floor storage along with the pallet being pushed on the floor and slued where the pallet is turned 90-degrees using the top of the forktines. During field handling, the pallet also experiences other impacts such as free fall drops and impacts to the lead bottom deck. However, the frequency of these impacts is really low, and thus they are only conducted every 5 or 10 cycles during the simulation. Each cycle contains 15 handling steps where handling is defined as a single lifting, transporting, and putting down of the unit load. The pallet is inspected, and damages are recorded after each FasTrack cycle, until the simulation ends, or the pallet is considered to no longer be in working condition or failed. Cao estimated that 30 FasTrack cycles would simulate five years of service for a pallet in the grocery industry (Cao 1993).

Part 3 of *MH1 Pallets Slip Sheets and Other Bases for Unit Loads* (2016) lists pallet damage limits that significantly reduce a wood pallet's strength and functionality. Also included are recommended repair practices that restore pallet strength and functionality. These criteria are used as a reference during the VPI FasTrack procedure to determine whether the pallet can continue being tested or if it should be discarded after a specific number of cycles.

The VPI FasTrack has been used to compare the performance of different pallet designs and to identify design changes that could improve pallets' resistance to rough handling. Examples of FasTrack use are found in the research conducted by Clarke, White, and Araman (Clarke *et al*. 2005). During this research, the VPI FasTrack was used to compare the performance of new and repaired pallets of three different qualities (A, B, C). Clarke *et al.* (2005) found that new, remanufactured, and grade A pallets were similar in resistance to rough handling. Moreover, the authors identified top end deckboards and stringers as the main focus for initial repairable damage in the pallets subject to testing.

Material handling practices and pallet designs have significantly evolved since the early studies, including the PEP study. Industries are automating their manufacturing and warehousing activities, continuously improving their efficiency (Mejías 2019). Based on this research, 3% of warehouses and storage facilities around the United States are fully automated, and 20%-to-30% are now semi-automated.

Research Objectives

The objective of this research was to quantify common damage modes, damage severity, and damage frequency for common pallet designs used in the industry and compare them to the damage modes simulated by FasTrack. A description of the damage mode behavior seen for pallets used in the field can be used to design cost-effective pallets, capable of withstanding the effect of rough handling in supply chain. By identifying the most vulnerable components of the pallet and the manner in which these components fail, equipment manufacturers can evaluate tolerance levels for the equipment that interacts with pallets, especially for automated and semi-automated facilities. A description of the most common damages seen in pallets can be used to evaluate the applicability of the standards, and drive improvements to durability simulations such as the VPI FasTrack.

EXPERIMENTAL

To quantify the damages during pallet inspection, a data collection tool was developed. This tool can be used to gather information about the different pallet components: top lead deckboards (TLD), top interior deckboards (TDB), bottom lead deckboards (BLD), bottom interior deckboards (BDB), and stringers (SS). These pallet components are shown in Fig. 1.

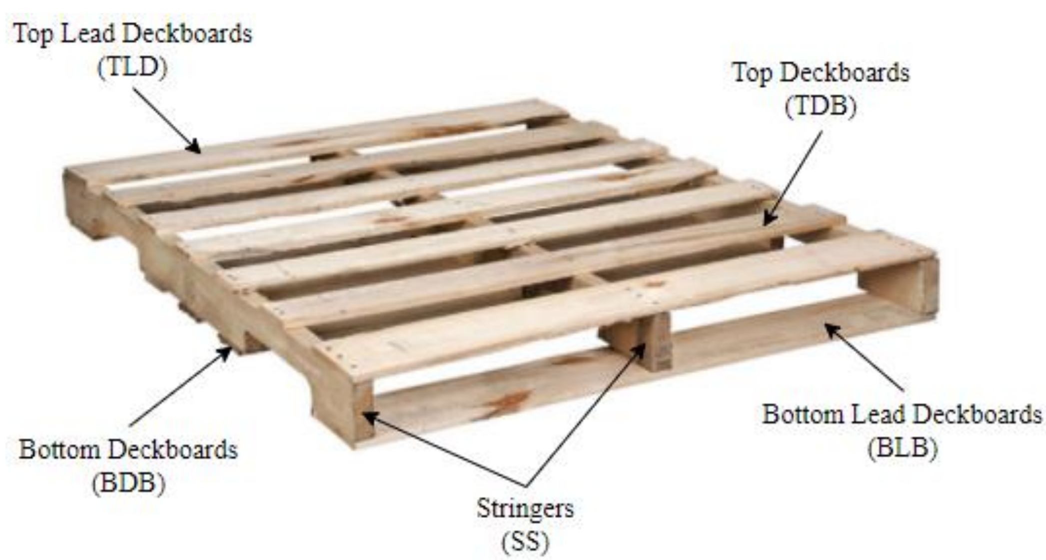

Fig. 1. Investigated pallet components

Three major damage categories were investigated: splits, breaks, and missing wood, as described below.

a. Split: Separation of a component in any direction, though commonly along the length. Also referred to as a crack (Cao 1993).

b. Break: A partial or full separation of the component, either obliquely or across.

c. Missing wood: A portion of, or a complete component, is missing from the pallet.

Representative pictures for each damage type are presented in Fig. 2.

Fig. 2. Representative picture of missing wood (left), break (middle), & split (right) damage modes

For each damage type, a severity scale was developed, containing two levels: medium and high severity. Damages ranked high severity are those that compromise the strength or functionality of the pallet, thus requiring the pallet to be repaired. The damage levels that warrant pallet repair in Part 3 of the Uniform Standard for Wood Pallets (National Wooden Pallet and Container Association 2014) and ISO 18613:2014 (International Organization for Standardization, 2014) were used as a reference to develop the damage descriptions for the high severity level. Meanwhile, damages with a medium severity level do not compromise the strength or functionality of a pallet, but their presence suggests that the component is being hit consistently.

Table 1. Description of the Damages for Each of the Damage Modes and Pallet Components Included in the Medium Severity Level

Damage mode	Component	Damage Description
Split	Deckboards	More than ½ the length or width, but it can be securely fastened. Splits extending through a nailed joint, greater than 1/3 of length/width and cannot be securely fastened.
	Stringers	Splits along the stringer, more than 1/3 of length and 1/2 the height or width
Missing wood	Deckboards	1 connection compromised, exposing 1 or more shanks, Not broken yet. Missing wood along 1/4 the length, more than 1/4 board width
	Stringers	1 shank is visible at a joint. More than 1/3 of the width and height of the stringer
Breaks	Deckboards	One deckboard is broken along 1/2 of its width, but the deckboard is still attached to the pallet
	Stringers	Breaks are present in the stringer, but the stringer is still in place and no nails are visible. Up to one exposed shank.

A description of damages in each severity level is in Tables 1 and 2. Examples of the damages considered at medium and high severity levels of the damage scale are presented in Fig. 3.

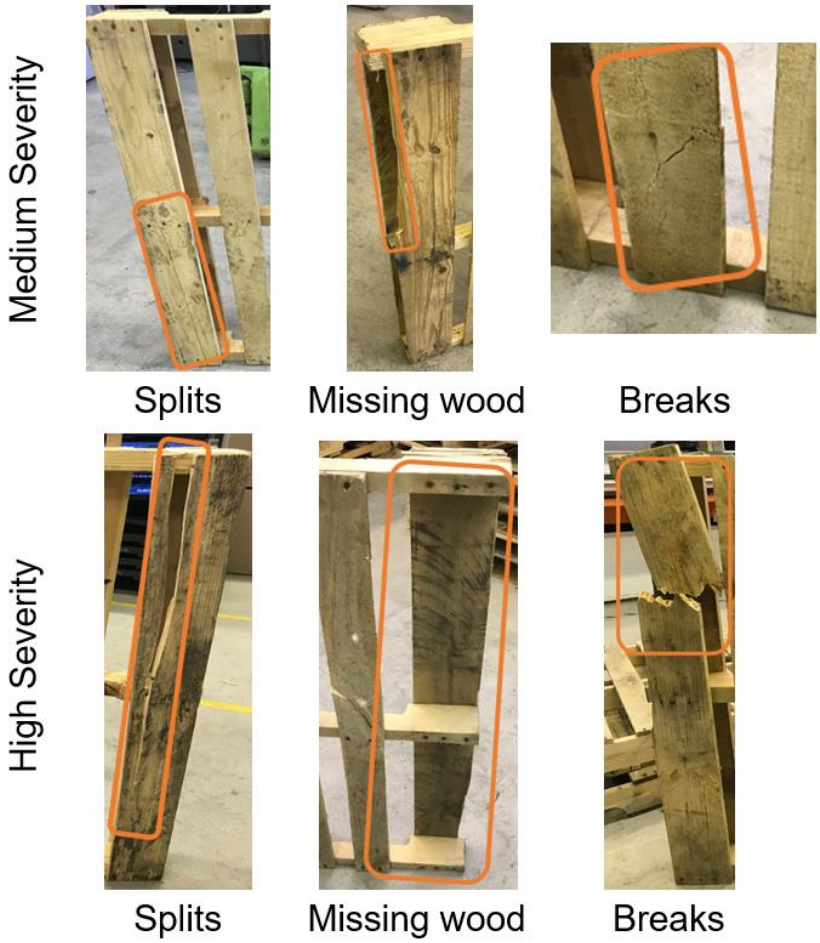

Fig. 3. Representative picture of splits (left), missing wood (middle), and breaks (right) based on severity scale

Table 2. Description of the Damages for Each of the Damage Modes and Pallet Components Included in the High Severity Level

Damage mode	Component	Damage Description
Splits	Deckboards	More than 1/2 the length or width, which cannot be securely fastened
	Stringers	More than 1/2 the height or width and more than half the length. Notches: Full width splits of any length in stringer notches
Missing wood	Deckboards	More than 2 connections of the same component, exposing 1 or more shanks or 1 connection completely broken. More than 1/4 of the board width and ½ the length.
	Stringers	If more than one nail shank is visible at any one joint. More than 1/2 of the width and height of the stringer and full length of the foot
Breaks	Deckboards	Completely broken deckboards, stringers, blocks, or stringer boards. One deckboard is broken, either obliquely or across
	Stringers	A stringer/block is broken to such an extent that more than one nail is visible

Pallet Inspection

This study included only the current version of the GMA/GPC style pallet design shown in Fig. 1, which is a 1219 mm x 1016 mm (48 X 40 inch), three-stringer, partial four-way, double-faced, non-reversible, flush, wooden pallet design (Stern 1979). The pallets had a different number of top and bottom deckboards, different component dimensions and quality, and were manufactured from different lumber species. Pallets from two different sources were investigated: FasTrack and the field. To obtain representative pallet data from the FasTrack simulation, the damage found on pallets tested in the FasTrack simulation between 2017 and 2020 was quantified. Pallets evaluated using the FasTrack simulation were tested until the damages caused by the simulation required the repair of the pallet. The pallets were grouped into three quality grades (grade A, B, or C). Overall, 152 grade A, 69 grade B, and 98 grade C pallets were investigated. The descriptions of the quality grades are listed below:

a. Grade A**:** Pallets with stringer metal plate repairs, but no companion members (a full or half-length supplementary stringer placed next to a damaged stringer during pallet repair(MH1 Committee, 2005)). Deckboard repairs are acceptable, but the top and bottom lead boards are a nominal 6 inches wide.

b. Grade B: Pallets with at least one (but no more than two) full/half-length companion member (s). Plugs are not acceptable, but metal and deckboard repairs are accepted.

c. Grade C: Pallets that did not meet the above criteria for an A or B grade.

To obtain representative pallet damage data from the field, used pallets were collected from three different retail facilities in North Carolina. The pallets were picked-up from a pallet repair facility; they were randomly pulled from the incoming cores prior to any pallet repair operation. The pallets were classified based on the same grade categories as the FasTrack pallets. Overall, 201 grade A, 187 grade B, and 42 grade C pallets were investigated from the field.

Statistical Methods

The output of damages per pallet was analyzed for each source (field and FasTrack) with Minitab 19 (Minitab LLC, State College, PA). Additional processing of the data and elaboration through graphics used to evaluate trends and the behavior of the data were done with Microsoft Excel (Microsoft Corporation, Redmond, WA). The historical data used for the FasTrack inspections was aggregated using a weighted average, based on the number of pallets inspected from each quality grade group (A-C).

RESULTS AND DISCUSSION

Pallet Damages Observed in the Field

The inspection results for the investigated damage locations and severity levels are presented in Fig. 4. The observed trend of the damage locations for both medium and high severity damages was similar. The exception is the damages observed for stringers (SS), which sustained high severity damages (22.2%) much more frequently than medium severity damages (4.1%). Bottom end deckboards (BLB) also experienced a greater number of high severity damages (15.7%) than medium severity damages (8.8%). The damages observed for top end deck boards (TLD), top interior deck boards (TDB), and bottom deckboards (BDB) are all similar in magnitude.

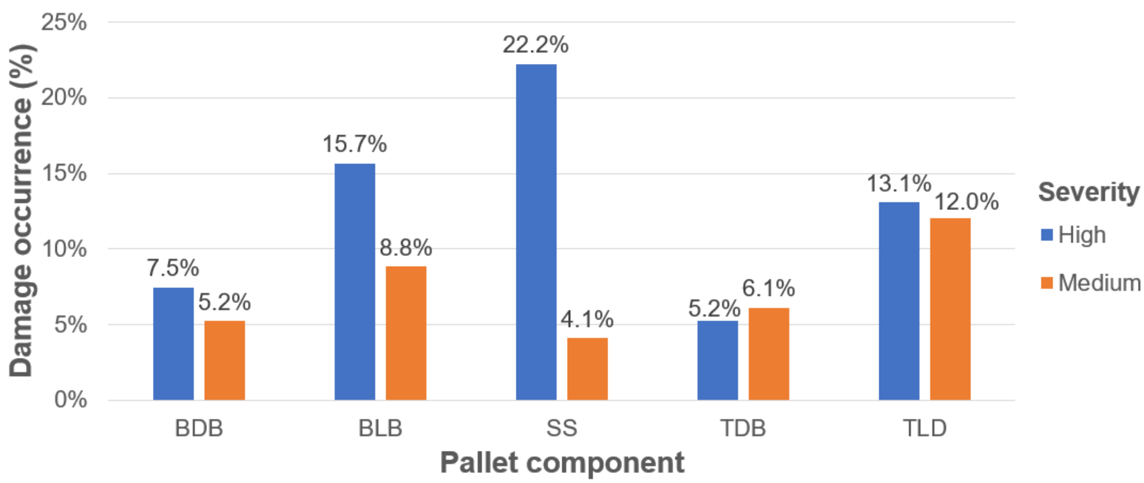

Fig. 4. Damage occurrence from pallets in the field, by severity level

Damage modes by severity level are shown in Fig. 5. Splits are the most frequent damage, followed by missing wood and breaks. High severity damages occur 8 to 10% more often than medium severity damages.

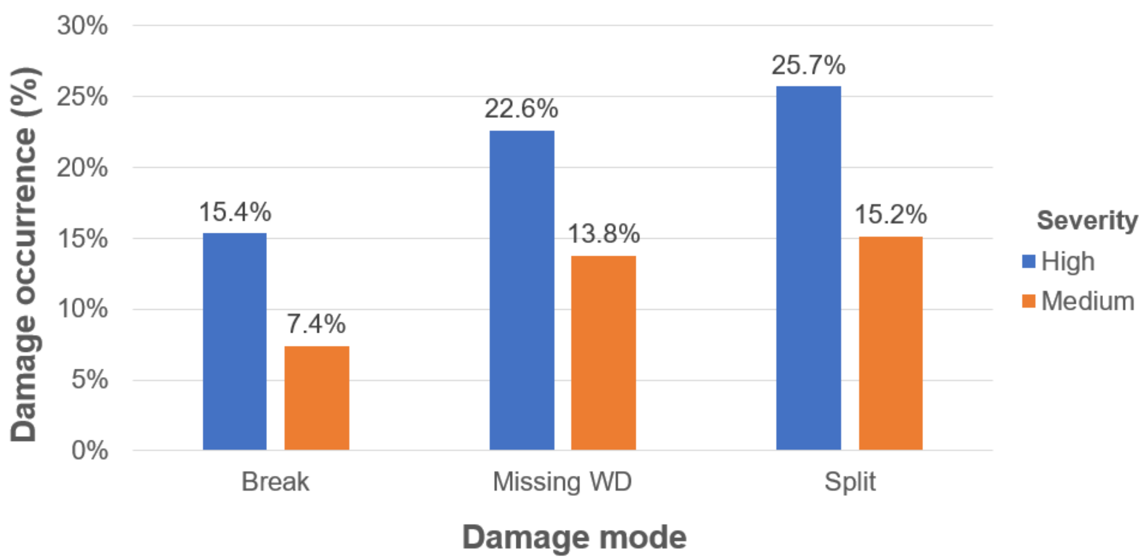

Fig. 5. Damage mode occurrence percentage by severity level

Figure 6 shows the mode of damage by pallet component. Only high severity damages are presented. The most commonly damaged component at this severity level was found to be the stringer (SS). For stringers, splits are the most frequent damage mode (19.5%), followed by breaks (8.8%) and missing wood (6.5%). Breaks are more common in stringers than in the rest of the components of a pallet. Missing wood (10.2% - 13.5%) followed by splits (6.4% to 7.7%) and breaks (3.4% to 3.9%) were more common in top (TLD) and bottom end deckboards (BLB).

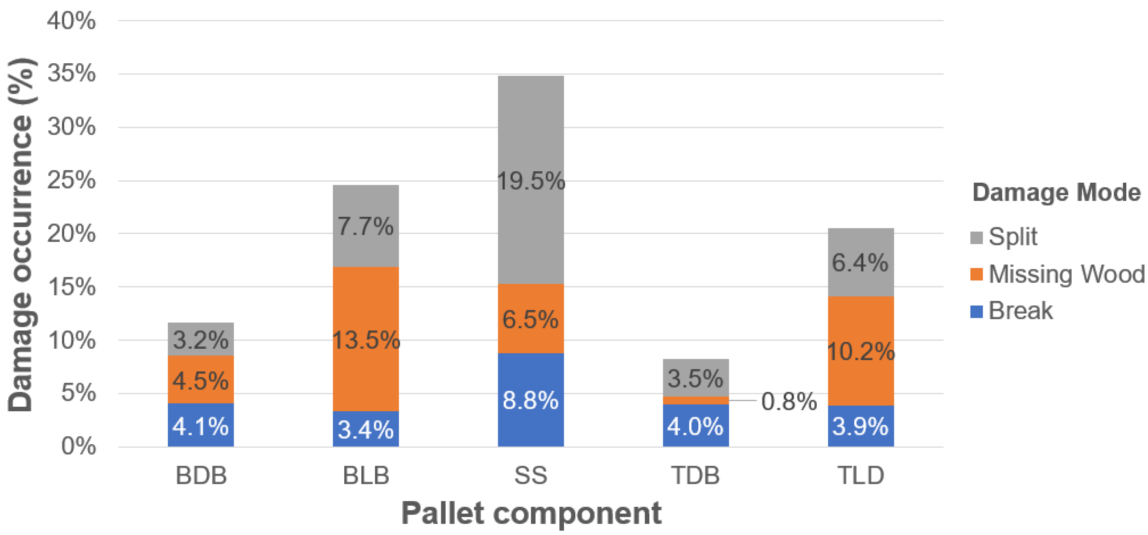

Fig. 6. Damage mode by pallet component (high severity only)

Most of the damage to pallets is caused by impacts during forklift or pallet jack handling or when a pallet is dropped. However, splitting at pallet notches can be the result of bending stresses when pallets are placed in storage racks (Mejías 2019). Additionally, lead deckboards are damaged due to banding, especially in scenarios where the end boards are not covered by packaging (ABF Freight System Inc. 2017). Tension of the strapping will lift and fracture end deckboards, especially when the load does not cover the end board.

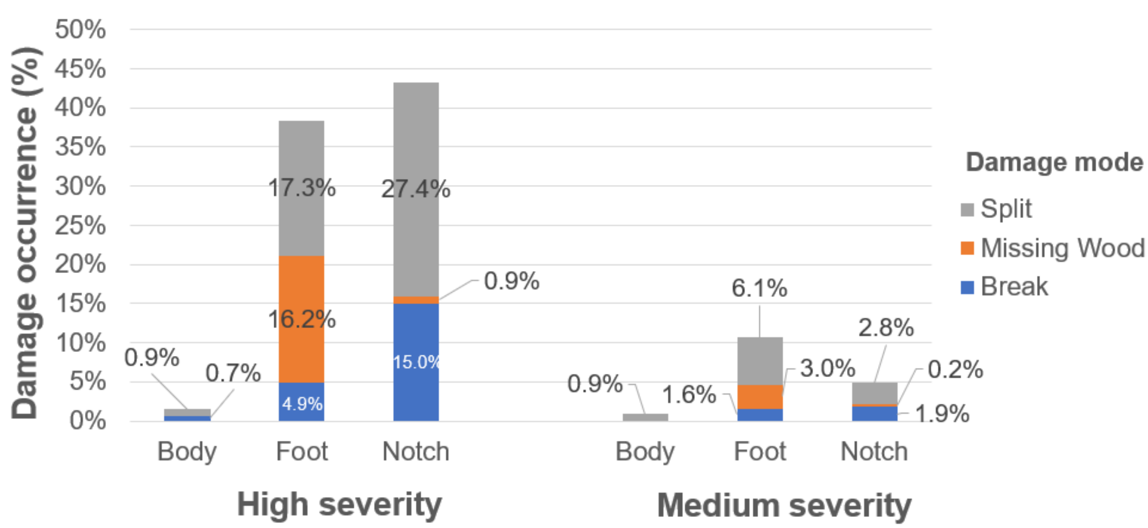

Fig. 7. Damage mode by damaged stringer location according to severity level

Figure 7 shows the results of observed damage modes according to specific regions of the stringers. These regions are defined in Fig. 8. At medium severity levels, the foot of the stringer is the most frequently damaged location at 10.7% and splits the most common damage mode (6.1%), followed by missing wood (3%), and then breaks (1.6%). Notches are the second most commonly damaged location at 4.9%. This location is affected mostly by splits (2.8%) and breaks (1.9%). As damage severity increases, there is a dramatic increase in the occurrence of damages at the stringer foot (38.4%) and notch (43.3%) respectively. In the case of the stringer foot, splits (17.3%) and missing wood (16.2%) are the most common damages. In the case of the notches, splits (27.4%) and breaks (15%) are the most common damages. Regardless of the severity level, the body of the stringer is rarely affected. In addition, the main causes of damages are the same, independent of severity level.

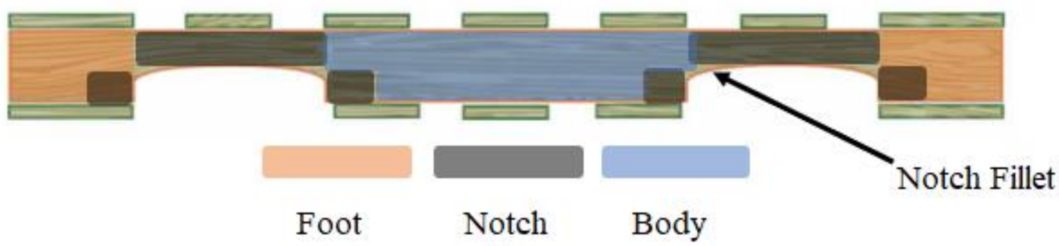

Fig. 8. Identification of stringer regions used during pallet inspection

Damages to the stringer foot are usually from a direct impact of a forklift tine at the moment of entry (Clarke *et al*. 1993). Storage and transportation of a loaded pallet can result in damages to the body and the notch of the stringer. As Clarke *et al.* mention, failure modes are generally localized splits along the grain when they occur on the body of the stringer, while bending-type failures are more common in the notches.

To create a cost effective and sustainable pallet design, pallet designers need to use the available material wisely and only add extra materials to the most critical locations where the additional durability will make the biggest effect on the life of the pallet. The results indicate that pallet designers need to focus on improving the durability of the side stringers and the lead deckboards of the pallet because most damages concentrate to these components. Also, for stringers, the location and size of the notch is a critical dimension because it will have the greatest effect on the durability of the pallet foot and notch area.

Comparison of Pallet Damages between the Field and FasTrack

The FasTrack simulation is stopped when the damage to the pallet requires repair. To establish an equivalent comparison with pallets from the field, the assessment for FasTrack and field compares the behavior for high severity damages only. Therefore, the damage percentage in the figures does not add to 100%.

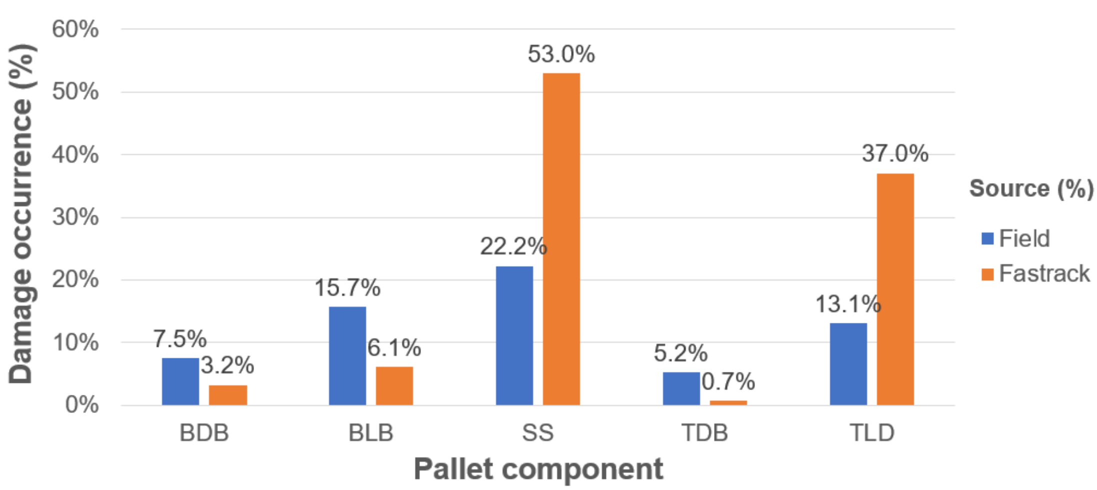

Fig. 9. Damage occurrence percentage by damaged pallet component for Fastrack and Field (high severity)

Figure 9 shows the results of the damage, by component, from the pallets used in the field compared to similar the pallets tested in the FasTrack simulation. There are similar trends. The stringers (SS) are the most damaged components in both. For FasTrack, top lead deckboard (TLD) damage is more frequent while the bottom lead deckboards are more frequently damaged in the field.

The differences between FasTrack and the field are more prominent in terms of damage occurrence rates. Damages observed from Fastrack reflect an emphasis in top end deckboards (TLD) (37% > 13%) and stringers (SS) (53% > 22%), while the damages to the bottom lead (BLB), top (TDB) and bottom (BDB) interior deckboards were less prominent from FasTrack than the field.

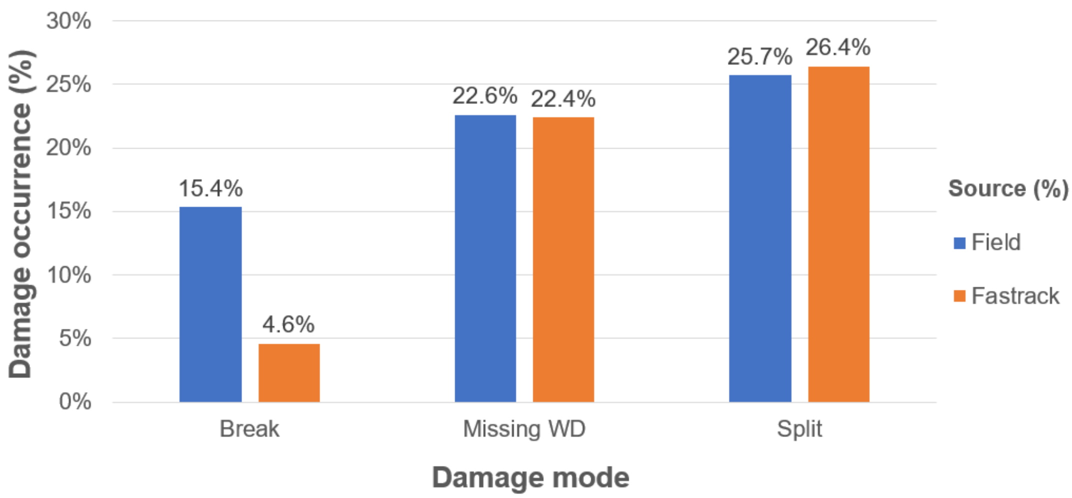

Fig. 10. Comparison of damage mode for pallets tested in the FasTrack and observed in the field (high severity)

Figure 10 shows the damage modes, compared between the field and Fastrack. Splits were the most common damage mode (25.7% in the field, 26.4% in FasTrack) followed by missing wood (22% to 23%). The results observed for the pallets tested with the FasTrack procedure are similar to those observed in the field for splits and missing wood. However, there was a significant difference in the percentage of breaks. Breaks rarely occurred during the FasTrack simulation, but they were common in pallets used in the field (5% for FasTrack, 15% in the field).

The lower frequency of breaks during the FasTrack simulation could be explained by the conditions simulated by FasTrack. While considered in the procedure, the racking and stacking conditions in the simulation might not put enough stress in the pallets tested. It is important to remember that this is an accelerated durability simulation during which the pallet carries a 1,500 lb. payload (Cao, 1993). Greater loads may be placed on pallets in the field. Also, FasTrack cannot simulate misuse, which may occur in the field.

Figure 11 shows the observed location of stringer damages from the field and the FasTrack. The results indicate similar damage rates for the stringer foot and body. The most significant difference between FasTrack and the field was seen in the damages to the notches of the stringers. The notches were damaged in 52% of the pallets from the field. However, FasTrack notch damage is only 19.2%. The FasTrack procedure accurately represents damages in the foot and the body of the stringer, but it underestimates the damages to the stringer notches.

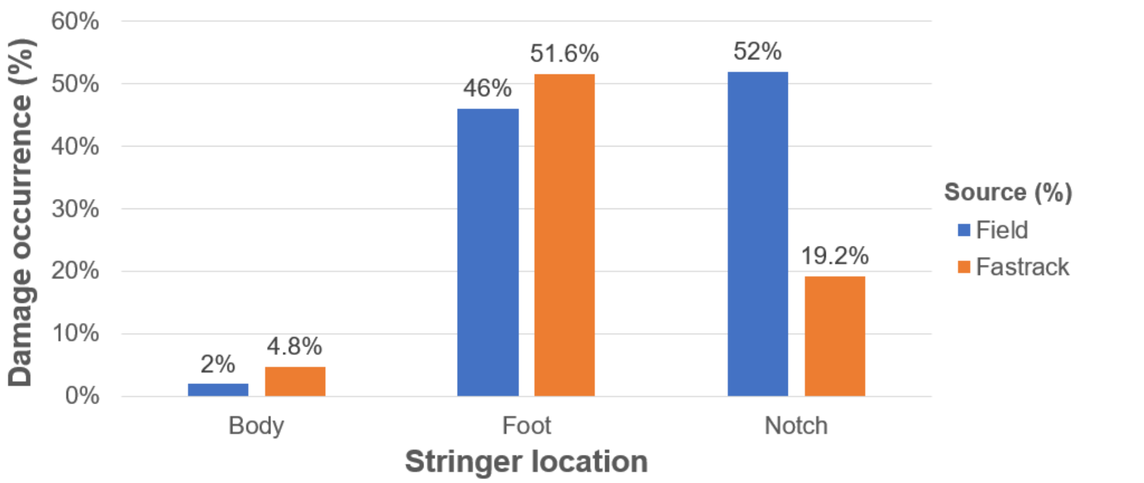

Fig. 11. Location of stringer damages from filed observations and FasTrack testing. (High severity)

The fillet of the notch is shown in Fig. 8, and it is a location of concentrated stress that is a function of the radius of curvature. The less the curvature, the greater the stress at that location when the stringer is subjected to bending. In supply chains, the bending stresses occur when pallets are placed in free-span storage racks or when empty pallets are dropped and hit the floor at an angle. However, both of these are simulated during FasTrack.

In the U.S. supply chain, only 34% of the pallets are 48 in. x 40 in. pallet (Gerber *et al.* 2020), forklift drivers cannot use a fork tine spacing that is optimized for 48 in. x 40 in. pallets. Therefore, if the fork tines spacing is too narrow or too wide than the chances of fork tines colliding with the notch area of pallets increases. This phenomenon is not incorporated into the FasTrack simulation thus to simulate the notch damage from fork tine impacts, the spacing of the fork tines during the simulation needs to be changed. The intensity or frequency of these handlings during FasTrack may have to be increased to reflect the damages occurring in the field.

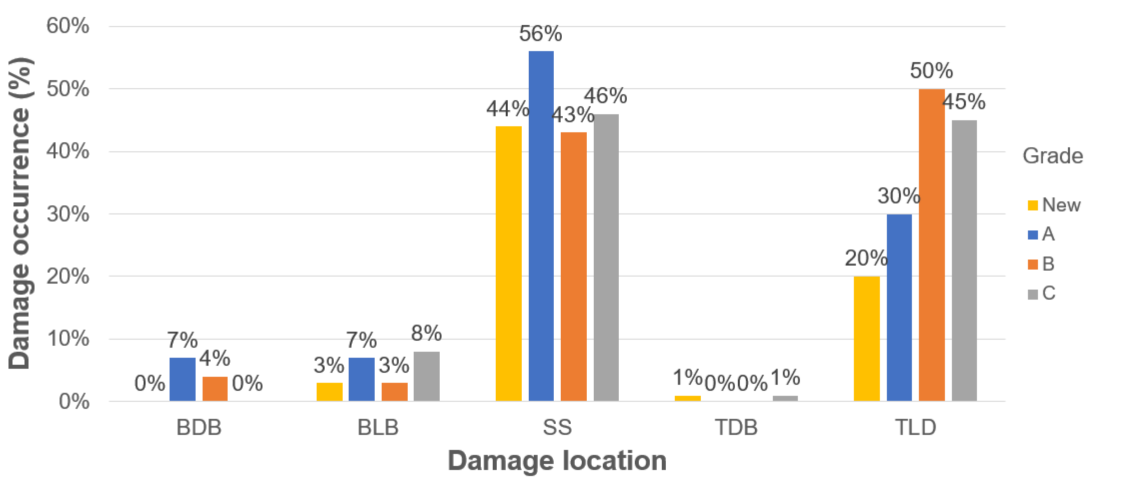

Fig. 12. Damaged location percentage by pallet quality in FasTrack

The results of the inspections conducted on pallets with different repair grades (New, A, B, C) tested with the FasTrack procedure are presented in Fig. 12. In general, stringers (SS) are the most damaged components (43% to 56%), followed by top end deckboards (TLD) (30%-50%). Bottom end deckboards (BLB) are damaged less (3% to 8%). Interior components of the pallet are rarely damaged, with bottom deckboards (BDB) in grade A and B used pallets exhibiting slightly more damage (4%-7%).

There is a slightly greater tendency of stringer damage in Grade A pallets, while top end deckboards seem to be more damaged in the B and C grades. Bottom deckboards are less damaged in all grades than stringers and top end deckboards.

CONCLUSIONS

1. The high percentage of damage occurrence in the stringers reflects that this component is the most vulnerable in the pallet.
2. The medium and high severity damage location distribution on pallets from the field shows that components fail due to continuous impacts during handling. In the stringers, the difference between medium and high severity indicates that this component can fail after it is exposed to less damage during handling and distribution.
3. The FasTrack simulation causes more damage to the stringers and lead deckboards, and less damage to the rest of the components of the pallet than the damages observed in the field.
4. The higher rate of damage to the stringers and top lead deckboards suggests that interactions with the forklift cause greater stress to these components in the FasTrack than in pallets during use in the field.
5. The lower frequency of damages product by Fastrack around the notch and pallet fee area indicate that the FasTrack simulation should incorporate changes to increase the frequency of these damages. The authors suggest changing spacing between the fork tines to increase the probability of fork tine collision with the notch area.
6. Testing repaired pallets in FasTrack shows that top lead deckboards and stringers are the most damaged components. This shows that FasTrack will yield consistent results regardless of pallet repair quality.

ACKNOWLEDGMENTS

This project was financially supported by the Industrial Affiliate Membership program of the Center for Packaging and Unit Load Design (CPULD) at Virginia Tech.

REFERENCES CITED

ABF Freight System Inc. (2017). “General packaging recommendations for the less-than-truckload (LTL) environment,” (https://arcb.com/sites/default/files/forms_and_documents/ABF_Packaging_Guideline_11.17.pdf), accessed January 23, 2023.

ANSI MH1-05 (2005). “Pallets, slip sheets, and other bases for unit loads,” MHI, Charlotte, NC.

ASME MH1-1997 (1997). “Pallets, slip sheets, and other bases for unit loads,” MHI, Charlotte, NC.

Cao, J. (1993). *The Development of a Durability Procedure for Pallets with Structural Panel Decking*, Master’s Thesis, Virginia Tech, Blacksburg, VA, USA.

Clarke, J. W., Mclain, T., White, M. S., and Araman, P. A. (1993) “Evaluation of metal connector plates for repair of wood pallet stringers,” *For. Prod. J.* 43(10), 15-22.

Clarke, J. W., White, M. S., and Araman, P. A. (2005). “Comparative performance of new, repaired, and remanufactured 48- By 40-inch GMA-style wood pallets,” *For. Prod. J.* 55(12), 83-88.

Freedonia Group (2015). *Pallets: US Industry Study with Forecasts for 2019 to 2024*, Freedonia Group, Cleveland, OH, USA. DOI: 10.1007/b99099

Gerber, N., Horvath, L., Araman, P., and Gething, B. (2020). “Investigation of new and recovered wood shipping platforms in the United States,” *BioResources* 15(2), 2818-2838. DOI: 10.15376/biores.15.2.2818-2838

ISO 18613-2014 (2014). “Pallets for materials handling - Repair of flat wooded pallets,” International Organization for Standardization, Geneva, Switzerland.

Mejías, A. (2019). *Case Study: The Effect of Pallet Design on the Performance of Semi-Automatic and Fully Automatic Warehouses*, Master’s Thesis, Virginia Tech, Blacksburg, VA, USA.

National Wooden Pallet and Container Association (2014). “Uniform standard for wood pallets,” Alexandria, VA, USA.

Stern, E. G. (1979). *Standard Wooden Pallets*, Wood Res Wood Constr Lab. Bulletin No. 164, Virginia Tech, Blacksburg, VA, USA.

Wallin, W. B., and Whitenack, K. R. (1984). "Durability Analysis for Wooden Pallets and Related Structures,” unpublished manuscript, Northern Forest Experimental Station, Forest Science Laboratory, Princeton, VW.

Wallin, W. B., Strobel, J. J., Frost, R. E. R., and Stinson, P. R. (1972). "PEP Research Study Report," unpublished manuscript, Northern Forest Experimental Station, Forest Marketing Laboratory, Princeton, VW.

Wallin, W. B., and Sardo, W. H. J. (1974) "The Performance of Wooden Pallets in Pallet Exchange Programs," Northern Forest Experimental Station, Forest Marketing Laboratory, Princeton, VW.

White, M. S., and Wallin, W. B. (1987). “Effect of wood pallet design on structural durability: A statistical analysis of observed in-service damage,” *For. Prod. J.* 37(11/12), 32-38.

Article submitted: January 20, 2023; Peer review completed: April 1, 2023; Revised version received and accepted: May 16, 2023; Published: July 20, 2023.
DOI: 10.15376/biores.18.3.6044-6056