Small-Diameter Roundwood, Strong-Post W-Beam Guardrail Systems

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Summary

Round guardrail posts may provide an important value-added option for small-diameter thinnings. Such posts require minimum processing and are believed to have higher strength for the equivalent rectangular volume. The resulting value-added product may bring a higher return compared to lumber. The obstacles to immediate utilization of ponderosa pine and Douglas-fir guardrail posts are the need for full-scale crash testing, a visual grading rule, and an installation guide. This paper reports on tests and Barrier VII computer simulations at the Midwest Roadside Safety Facility and the Forest Products Laboratory to determine dynamic and static material properties and correct embedment depths. Grading practices are recommended for round ponderosa pine and Douglas-fir guardrail posts for the new Midwest Guardrail System.

1. Introduction

For many years, there has been ongoing discussion on ways to manage fuel and reduce fire control costs and damages on forested lands. This discussion has led to various strategies aimed at preventing catastrophic fires by reducing fuel loadings (i.e., excess biomass), including prescribed burning, salvage timber operations, pruning, pre-commercial thinning, and mechanical or chemical release. For salvage timber operations and pre-commercial thinning in western forests, fuel loadings are intentionally reduced by small-diameter and low-valued forest thinnings. Although these activities are believed by many to be an effective fire prevention technique, their cost-effectiveness cannot be properly evaluated until all costs have been accurately determined. As more end uses for this traditionally underutilized wood become available, the overall operational costs will be reduced as a result of the financial and societal benefits that are generated. One potential use for forest thinnings is for the round guardrail posts that are used along highways for motorist safety [1]. There are significant opportunities for implementing round posts into W-beam guardrail systems throughout the United States, especially should alternative wood species become available and acceptable for such use in crashworthy barrier systems.

2. Background

For more than 50 years, longitudinal barrier systems have been utilized for preventing errant motorists from colliding with dangerous rigid hazards along highways and roadways. Although several different longitudinal barrier systems can be found throughout the United States, W-beam guardrail systems have historically been the most common. In general, W-beam guardrail systems consist of three major components: a W-beam rail element, evenly spaced support posts, and guardrail blockouts. Guardrail posts are manufactured from either wood or steel. For the wood alternative, 152.4- by 203.2-mm rectangular and 184.1-cm-diameter round post cross sections have been successfully utilized. They are generally manufactured from No. 1 grade southern yellow pine. Wood blockouts are usually incorporated into the design to position the W-beam rail away from the sides of the posts that face traffic. The positioning of the rail forward from the posts reduces the propensity for vehicles to snag on the posts as well as the potential for vehicular instability and/or rollover. Although the price range for round posts is lower than that for steel posts, the implementation of round-post W-beam systems has been primarily limited to Texas.

Several goals were identified for our guardrail post project. First, it was necessary to obtain technical data that would demonstrate whether small-diameter softwoods harvested from fuel reduction projects could be used for highway guardrail applications. As such, we investigated the use of ponderosa pine and Douglas-fir, with southern yellow pine as baseline material. The test variables included post size, grade, and post embedment depth. Second, it was deemed important to determine reasonable grading practices for round guardrail posts manufactured from ponderosa pine, Douglas-fir, and southern yellow pine. Third, researchers were to investigate, design, and make recommendations for the use of round wood posts, including all these species, in the Midwest Guardrail System (MGS) or the use of a new strong-post, W-beam guardrail system, using a proven nonlinear, dynamic vehicle-to-barrier impact analysis computer simulation program. Fourth, full-scale vehicle crash tests were to be conducted at test level 3 according to the impact safety standards of the National Cooperative Highway Research Program [2] to demonstrate the use of wood round post alternatives in longitudinal barrier systems. Finally, at the completion of the project, an installation manual and standard CAD plans were to be prepared for round-post highway guardrail systems using ponderosa pine, Douglas-fir, and southern yellow pine.

3. Testing Program

Phase I—Initial project planning period, component test setup and preparation, and acquisition and grading of wood materials.

Phase II—Static and dynamic evaluation of structural properties for three species (ponderosa pine, Douglas-fir, and southern yellow pine) subjected to cantilevered loading; two rounds of testing used to determine optimum size of round posts.

Phase III—Dynamic post-soil testing on each wood species using cantilevered loading and varying soil embedment depth.

Phase IV—BARRIER VII computer simulation modeling of vehicle-to-barrier impacts for three round post wood alternatives; modeling to evaluate and predict dynamic barrier performance; design modifications, as needed.

Phase V—Full-scale vehicle crash testing; final design of barrier system; preparation of installation manual and standard CAD plans.

This paper summarizes the results of phases I through IV.

4. Test Methods

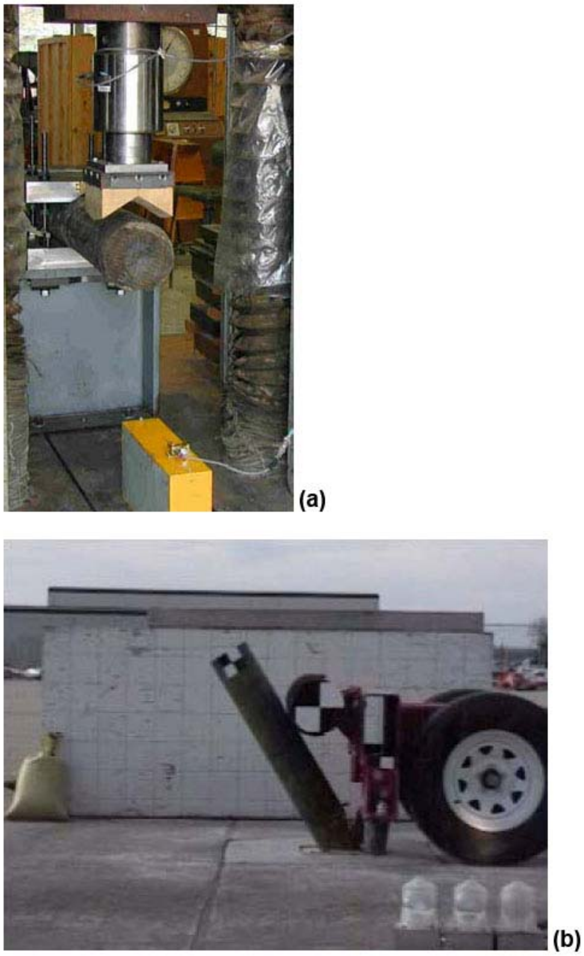

Fig 1 Test setup for (a) static and (b) dynamic tests

Destructive tests were conducted in Phases II, III, and V. When this paper was written, only the tests for Phases II (static/ dynamic cantilever) and III (dynamic soil embedment) had been completed.

The static tests for Phase II were conducted using a million pound (454,000-kg) test frame at the Forest Products Laboratory (FPL) (Fig. 1a), with a loading rate of 0.008 m/min. Loads were recorded on a 22,700-kg load cell in test round 1 and a 13,620-kg load cell in round 2. Deflections were recorded using a linear variable differential transformer.

Phase II dynamic tests were conducted at the Midwest Roadside Safety Facility (MwRSF) using a 728-kg rigid-frame bogie vehicle (Fig. 1b). The bogie traveled at approximately 32 km/h in round 1 and 21.7 km/h in round 2. A pickup truck with a reverse tow system was used to propel the bogie. One triaxial piezoresistive accelerometer system with a range of ±200 *g* was mounted on the bogie near its center of gravity and used to measure acceleration in the longitudinal, lateral, and vertical directions at a sample rate of 3,200 Hz. Three pressure tape switches, spaced at 1-m intervals and placed near the end of the bogie track, were used to determine the speed of the bogie before impact. Two digital video cameras, operating at either 500 or 29.97 frames/second, were used to document the tests. All dynamic tests recorded the force–time profiles using accelerometer data.

The test matrix for the cantilever tests is shown in Table 1. The study was set up so that both static and dynamic tests would be performed on three knot-ring combinations (BKN LRD, SKN LRD, and SKN HRD): two types of knots—big (BKN) and small (SKN), which varied depending on species; two categories of rings-per-inch (rings per 25.4 mm, hereafter referred to as rpi)—low (LRD, ≤4 rpi) and high (HRD, ≥6 rpi). These three combinations were tested both statically and dynamically. Further tests of a larger sample more representative of the expected post population was also tested statically.

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Table 1. Test matrix for Phase II cantilever beam tests[a]

	Number of static (ST) and dynamic (DY) tests in rounds 1 and 2 for various sizes of Douglas- fir (DF) and southern yellow pine (SYP) beams												
	Round 1						Round 2						
	DF 184-mm		SYP 216-mm		SYP 190-mm		DF 178-mm		SYP 184-mm		SYP 171-mm		
Variable[b]	ST	DY	ST	DY	ST	DY	ST	DY	ST	DY	ST	DY	Total
BKN LRD	5	5	5	5	5	5	5	5	5	5	5	5	60
SKN LRD	5	5	5	5	5	5	5	5	5	5	5	5	60
SKN HRD	5	5	5	5	5	5	5	5	5	5	5	5	60
Population	45		45		45		45		45		45		270
Total tests	60	15	60	15	60	15	60	15	60	15	60	15	450

[a] Static tests were conducted at FPL, dynamic tests at MwRSF.

[b] BKN, big knot; SKN, small knot; LRD, ≤4 rpi); HRD, ≥6 rpi; population, random mixture of posts.

Timber Product Inspection grading supervisors assisted in identifying posts with the required diameter knot and rpi categories.

For each round of testing, 10 posts for each species and knot–ring category were identified to have the appropriate knot–ring combinations. An additional 45 posts were collected from the larger population of posts for static testing. Each post was weighed, knot mapped, and measured. Longitudinal stress wave modulus of elasticity (SWMOE) was determined. The posts for static and dynamic testing were sorted by SWMOE and then randomly assigned to either dynamic or static testing.

The Phase III dynamic soil embedment tests were conducted to determine how round posts behave in soil. A schematic of the soil embedment test setup is shown in Figure 2. A rigid-frame bogie vehicle was used to strike the posts at 40 km/h. This velocity was chosen so that the kinetic energy of the bogie exceeded the energy absorbed in the previous post–soil tests, which were used to determine the approximate peak load.

Two different soil depths and post diameters were investigated for each species in the soil embedment testing. A complete description of the testing methods has been published [3,4].

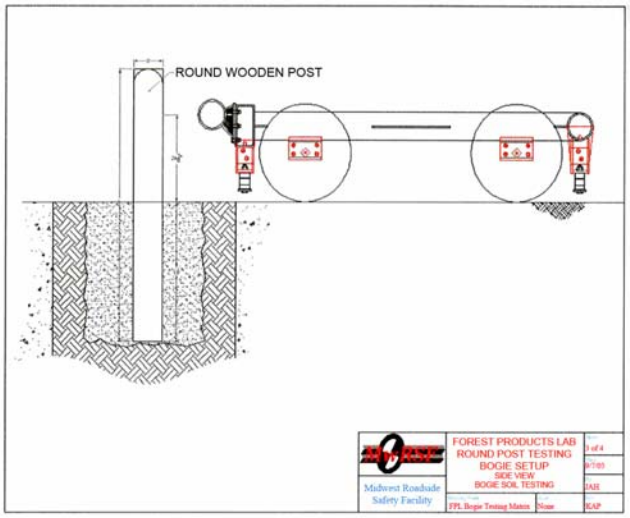

Fig 2 Dynamic soil embedment test configuration

Table 2. MOE, MOR, and peak load average values for Phase II testing[a]

		Round 1						Round 2					
		DF 184 m		PP 216 mm		SYP 190 mm		DF 178 mm		PP 184 mm		SYP 171 mm	
Test mode[b]	Property	ST	DY	ST	DY	ST	DY	ST	DY	ST	DY	ST	DY
BKN LRD	SWMOE (GPa)	9.9	9.6	6.8	6.9	7.6	7.0	9.2	10.1	4.5	4.3	7.4	6.3
	MOR (MPa)	42.4	60.9	26.9	44.8	34.5	48.3	39.9	49.8	35.0	45.9	35.1	38.5
	Peak load (kN)	41.8	59.6	45.4	73.4	32.0	48.5	28.5	40.9	33.8	39.1	32.0	33.8
SKN LRD	SWMOE (GPa)	9.7	9.5	5.4	5.4	6.5	4.0	10.5	10.1	4.3	4.6	4.2	4.4
	MOR (MPa)	48.5	51.7	32.4	39.0	54.1	50.6	41.7	52.5	35.0	50.5	38.8	44.3
	Peak load (kN)	44.0	52.0	50.3	64.5	51.6	53.8	34.3	45.8	33.8	36.9	35.1	41.8
SKN HRD	SWMOE (GPa)	10.5	10.1	9.6	9.4	13.7	13.7	14.3	10.1	7.8	8.1	11.0	12.0
	MOR (MPa)	50.3	65.5	45.9	63.3	75.3	84.4	62.8	69.2	45.6	52.1	70.8	61.6
	Peak load (kN)	48.9	64.5	78.7	113.0	68.1	82.3	50.7	59.2	44.0	54.7	65.4	57.4
Pop.	SWMOE (GPa)	10.3	—	8.5	—	8.9	—	12.8	—	7.0	—	9.9	—
	MOR (MPa)	52.5	—	37.5	—	51.9	—	56.3	—	41.0	—	59.1	—
	Peak load (kN)	48.5	—	63.2	—	48.9	—	45.4	—	40.0	—	53.4	—

[a] DF is Douglas-fir; PP, ponderosa pine; SYP, southern yellow pine.

[b] BKN LRD, big knots and ≤4 rpi; SKN LRD, small knots and ≤4 rpi; SKN HRD, small knots and ≥6 rpi; population (pop.), random mixture of posts.

5. Results

5.1 Static and Dynamic Tests

Table 1 summarizes the static and dynamic test program for Phase II. Results for SWMOE, MOR, and peak load are presented Table 2. See Hascall and Kretschmann [3,4] for a complete description of test results.

5.1.1 Round 1 Testing

After round 1 tests were completed, peak force, MOR, and material dimensions were studied to determine if any changes were required. Peak load capacity is a principal parameter for guardrail post design. Based on previous MGS post testing, a peak load of 44.5 kN was selected as the target for the round post tests. Box plots of round 1 test results for dynamic and static peak loads are shown in Figure 3a. The peak load level of the ponderosa pine, given its size (215.9-mm-diameter top end) compared to that of Douglas-fir and southern yellow pine (190 and 184 mm, respectively), was considerably higher than the desired value. After analyzing the data, the research team decided that the southern yellow pine and Douglas-fir posts could be reduced slightly in diameter and still perform adequately in the MGS. The results also suggested that a larger reduction in the ponderosa pine cross section may be possible for the post to carry loads similar to those of southern yellow pine, and a slightly smaller post size for southern yellow pine should be investigated. The new sizes for round 2 were a top-end diameter of 190.5 mm for ponderosa pine, 171 mm for Douglas-fir, and 177.8 mm for southern yellow pine.

After the first test round, significant flaws were found in the standard methods used in cantilever bogie tests. Post strength may have been overestimated by as much as 50% because of the effects of inertia, leading to inaccurate and misleading diameter calculations. An alternative procedure was investigated in a series of three additional cantilever bogie tests. These tests confirmed the problem and showed that a reduction in bogie impact speed would

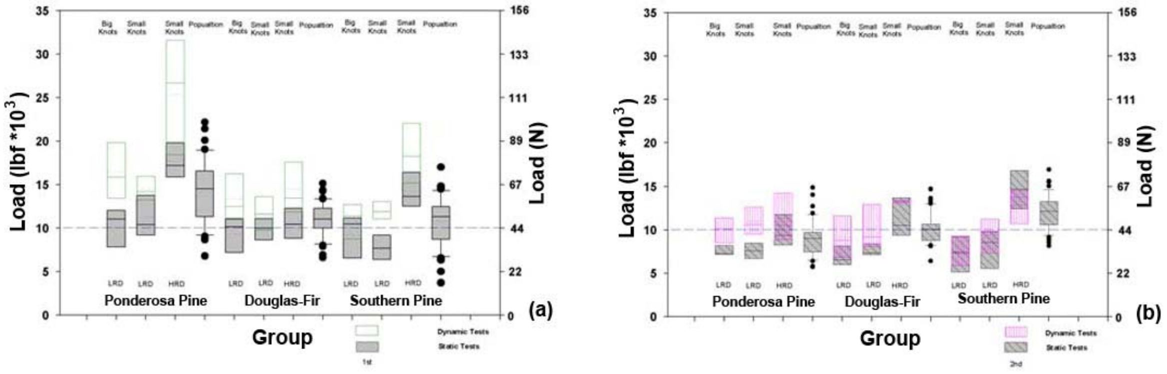

Fig 3 Box plots for peak load for round 1 (a) and round 2 (b) dynamic and static tests. Where appropriate, box plots show 5th, 25th, 50th, 75th, and 95th percentiles and extreme points. Dashed lines represent mean.

significantly reduce the effects of inertia, leading to a more accurate prediction of ultimate fiber stress. Unfortunately, the flaws were not identified in time to modify the original diameter calculations since the posts had already been ordered; however, the adjustments were utilized in the second round of tests.

5.1.2 Round 2 Testing

The results of round 2 test peak loads are shown in Figure 3b. The population results suggest that the diameters of Douglas-fir and southern yellow pine were close to the desired 44.5-kN level. The size of the ponderosa pine material, however, needed to be increased. In addition, comparison of the results from rounds 1 and 2 suggested a dynamic magnification factor of 20% to 30%.

A 3% failure rate was established as an acceptable level or risk for the system to fail; system failure was defined as the failure of four consecutive posts when the system was subjected to NCHRP Report No. 350 test level-3 (TL-3) criteria. The proper minimum size was determined using elastic bending equations and estimated MOR. Sixty percent of the posts needed to withstand an impact force of 42.3 kN at a height of 632 mm or a bending moment of 26.7 kN-m. The resulting target sizes were 165 mm for Douglas-fir, 184 mm for ponderosa pine, and 177.8 mm for southern yellow pine. These sizes were investigated in the Phase III soil embedment testing.

5.2 Soil Embedment Tests

Two separate sets of embedment tests were conducted. Initially, a total of six soil tests were completed for Douglas-fir and ponderosa pine, three for each species. An embedment depth of 1016-mm, the standard for MGS posts, was used as a starting point for the tests. The tests were conducted at approximately 37 km/h. This velocity was chosen so that the kinetic energy of the bogie vehicle exceeded the energy absorbed in previous MGS post–soil tests. Initial dynamic soil tests showed that the estimated soil resistance force was 20% lower than the actual force determined from the testing. These results indicated an increase in diameter for both the Douglas-fir and southern yellow pine posts.

A second set of embedment tests was conducted to evaluate the larger posts. The anticipated peak force was increased to 53.4 kN for Douglas-fir and 57.8 kN for ponderosa pine. The anticipated force level was higher for ponderosa pine to account for the larger diameter because the post would have to move more soil and have a flatter cross section, which would increase resistance to soil rotation. Based on these adjustments, the target nominal diameter was increased to 184 mm for Douglas-fir and 203 mm for ponderosa pine. The embedment depth was also reduced to 940 mm in an effort to lower the peak values. An acceptable number of the resized posts passed the second round of soil testing.

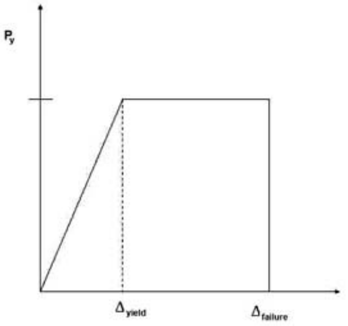

Fig 4 Approximated post soil rotation behavior

5.3 Barrier VII Modeling

Prior to full-scale vehicle crash testing, the final analytical step included the use of BARRIER VII [5] to predict the behavior of the MGS system constructed with round wooden posts. In the BARRIER VII model, post load curves were approximated using a perfectly plastic model, as shown in Figure 4. To define the curve, the stiffness, yield force, yield moment, and maximum deflection were defined. Although the model was not a perfect representation of the test results, it did offer a very simple and somewhat accurate representation of a post rotating through soil. In the initial portion of the curve, the force resistance increases as the post begins to move and compress the soil. Eventually, the force reaches its yield point, P_y, and the stress on the soil is great enough that the soil fails and allows the post to rotate through with a constant force. At some point, the post reaches a maximum deflection, Δ_{fail}, at which it separates from the rail, making it ineffective (no resistive capacity). The average energy and average stiffness of the tested posts were used to determine the average yield force (28.9 kN). The yield displacement, Δ_y, was equal to 24 mm.

BARRIER VII simulations were completed for a baseline model and for models with one to four consecutive weak posts. The results did not show a distinct point at which one additional failed post would cause the system to drastically fail. However, failure of four consecutive posts matched the previous limit—that a maximum deflection in excess of 1321 mm was too large. Therefore, the definition of system failure was maintained as the fracture or failure of four consecutive posts.

5.4 Grading Criteria

The size and grading criteria were developed after reviewing the static and dynamic test data and the population distribution of knots and ring density. The criteria were chosen to be tight enough to reduce the diameter of the posts as much as possible, but relaxed enough to allow a high percentage of the posts to qualify. The grading criteria that were developed for the full-size MGS crash test systems are given in Table 3. For the grading criteria, the diameter at ground line (0.914 m from base) rather than the top-end diameter was specified.

Table 3. Criteria for MGS posts

Species	Diameter at ground line (mm)	Knot size (mm)	rpi	Slope of grain
Douglas-fir	184	≤38	≥6	1:10
Ponderosa pine	203	≤89	≥6	1:10
Southern yellow pine	190	≤64	≥4	1:10

5.5 Guardrail Systems

Using the information from the Barrier VII simulations, guardrail system designs were developed for the three test species; the design for Douglas-fir is shown in Figure 5. Full-scale crash tests, complying with NCHRP standards, will be conducted on ponderosa pine and Douglas-fir systems.

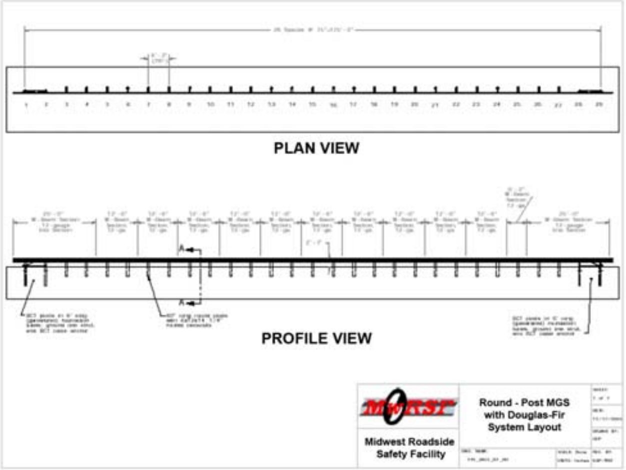

Fig 5 Proposed guardrail system design for Douglas-fir

6 Discussion

The results and computer simulations indicated that 184-mm-diameter Douglas-fir posts with ≤38-mm knots and ≥6 rpi, 203-mm-diameter ponderosa pine posts with ≤89-mm knots and ≥6 rpi, and 190-mm-diameter southern yellow pine posts with ≤64-mm knots and ≥4 rpi, with a 1:10 slope of grain, should perform successfully in the Midwest guardrail system design.

Acknowledgments

Many thanks to our industrial cooperators, without whose assistance and guidance this project would not have been possible: Timber Products Inspection, Hills Products Group, JH Baxter, All Weather Wood Products, Rogue Valley Fuels, Burke–Parsons-Bowlby, Arnold Forest Products Corp., Interstate Timber Products, and Goshen Forest Products.

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