

Timber Utility Pole Fracture Mechanics Due to Non-Deformable and Deformable Moving Barrier Impacts

2011-01-0288

Published
04/12/2011

Jeffrey Croteau, Benjamin Frank, Daniel Peterson and Cleve Bare
Exponent Inc.

George Kyanka
Syracuse University

Copyright © 2011 SAE International

doi:[10.4271/2011-01-0288](https://doi.org/10.4271/2011-01-0288)

ABSTRACT

The energy dissipated by the fracture of wooden utility poles during vehicle impacts is not currently well documented, is dependent upon non-homogenous timber characteristics, and can therefore be difficult to quantify. While there is significant literature regarding the static and quasi-static properties of wood as a building material, there is a narrow body of literature regarding the viscoelastic properties of timber used for utility poles. Although some theoretical and small-scale testing research has been published, full-scale testing has not been conducted for the purpose of studying the vehicle-pole interaction during impacts. The parameters that define the severity of the impact include the acceleration profile, vehicle velocity change, and energy dissipation. Seven full-scale crash tests were conducted at Exponent's Arizona test facility utilizing both moving deformable and non-deformable barriers into new wooden utility poles. The vehicle energy was dissipated in a bi-modal event for the non-deformable barrier tests and a tri-modal event for the deformable barrier tests. In the deformable tests, the three modes were identified as 1) deformation of the vehicle structure, 2) fracture and separation of the pole from its base, and 3) acceleration of the pole out of the vehicle path. The analysis associated with these test results provided a better understanding of pole fracture mechanics and corresponding vehicle kinematics as well as the energy dissipation during the full-scale dynamic events.

INTRODUCTION

Impacts with fixed roadside objects comprise a small number of fatalities as compared to the overall annual number of fatal injuries in motor vehicle crashes. A significant portion of the fatal crashes with fixed roadside objects involve potentially frangible narrow objects such as trees and utility poles. Recent data from the National Highway Transportation Safety Administration (NHTSA) indicates that between 2004 and 2008, 60% of the fatalities with fixed roadside objects resulted from impacts with trees and utility poles, accounting for 5,655 fatalities per year ([Figure 1](#)).

In the reconstruction of motor vehicle accidents involving frangible poles and trees, the vehicle speed analysis is often complicated by the uncertainty in estimating the energy required to fracture and/or separate the tree/pole during the impact. A better understanding of the deceleration profile, velocity change (ΔV), and fracture mechanism would improve the analyst's ability to quantify the energy dissipation for impacts where complete fracture occurs.

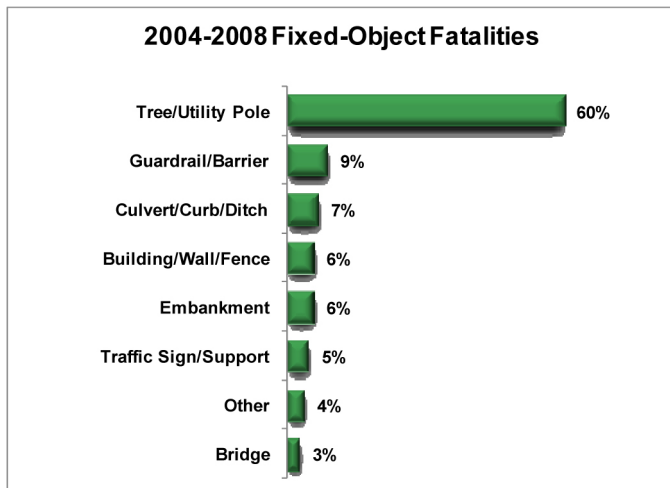


Figure 1. Distribution of motor vehicle crash fatalities during 2004-2008 with fixed roadside objects. The impacts with trees and utility poles resulted in an average of 5,665 lives lost per year.

In 1974, Southwest Research Institute published results from testing utilizing full-size poles that were modified to reduce ultimate strength with holes and grooves. Several research papers have since been published based upon the data from this test series, and they have provided tools such as the Mak [1] formula for estimating pole fracture energy and Owing's [2] accident reconstruction technique. The Owing technique divides impact events into three theoretical stages (vehicle deformation, pole fracture, and pole acceleration). Also, Morgan [3] devised a 2-dimensional analysis based on a single full-scale pole impact. In 1998, Kent et al [4] predicted lower pole fracture energies than previous authors based on equations derived from both static and dynamic software based models; they also conducted 1/8 scale non-deformable pendulum impact tests that partially validated the models' predicted fracture energies.

To the authors' knowledge, Exponent's pole test series represents the first full-scale crash test project to study wooden utility pole fracture mechanics. The study emphasizes a comprehensive analysis of the deceleration pulse of the moving barriers and the energy required to initiate fracture, then separate and accelerate the utility pole.

The behavior of wood under impact loading is a complex process due to the orthotropic and viscoelastic nature of the material. Theoretical analysis of the deformation process requires consideration of three elastic moduli, six Poisson's Ratios, and the time-dependency of these material properties. The elastic-plastic viscous deformations can lead to fracture and the fracture process itself is governed by six fracture toughness coefficients. For many wood species, all of these material parameters are not known under general conditions and, even if known, they vary with moisture content.

Predicting the behavior of timber fracture is a multivariate problem and it is consequently very difficult. Fracture testing of wood is rare and standards such as ASTM D-143 [5], which is based on a drop height to failure on a simple beam sample, are not representative of the impact dynamics in a vehicle-pole collision. The fractures obtained during the ASTM procedures are categorized as either high-energy or brash. Brash fracture, also referred to as brittle fracture, leads to very low energy absorption in relation to the initial amount of contact energy. A common example of a brash fracture is a broken bat in a baseball game or a board broken in a karate chop demonstration.

It is not surprising to find brash fractures in vehicle-pole collisions given the right impact speed and properties of timber under a dynamic impact. Physical properties of the wood, including its specific gravity (proportional to strength), the presence of knot clusters, and the variability of moisture content, can affect the nature of the timber fracture. The photographs in Figure 2 show the anchored end of the impacted utility poles in our first three tests and are representative of brash fractures.



Figure 2. Brash fractures from 30 mph impact tests with a non-deformable moving barrier.

POLE TESTING SETUP

Southern yellow pine class 4 utility poles coated with Pentachlorophenol preservative were mounted in hard packed desert soil. The utility poles were 35 feet (10.7 m) tall with a nominal 10 inch (25 cm) diameter at ground level and weighed approximately 950 lbs (431 kg). Their measured moisture content ranged between 10-17%. The poles were placed in six foot deep, 18 inch (46 cm) diameter holes and the holes were back-filled with native desert soil. A four inch thick reinforced concrete pad was constructed to replicate a typical sidewalk at the base of each utility pole. A 400 lb (181 kg) spherical mass, fully supported by a 50 ton (45.4 metric ton) crane, was attached to the struck side of each pole

approximately 8 feet (2.4 m) from the top. This constraint was installed to simulate conductor and other in-service loads (Figure 3). This constraint can alter the manner in which stress waves are reflected during an impact potentially augmenting the stresses created at the compression zone in a wooden pole. From a pragmatic perspective, the crane also provided a means to constrain the motion of the pole after it fractured to prevent damage to adjacent test equipment.



Figure 3. 400 lb spherical mass attached to pole to simulate conductor and other in-service loads.

Both non-deformable and deformable bumpers were fabricated and mounted to the front of a moving barrier, as shown in Figure 4. The deformable barrier bumper was constructed using the frame and bumper reinforcements from a mid-size sport utility vehicle. The non-deformable bumper was constructed to represent the same contact patch to the poles as the deformable face. All barrier faces were rigidly mounted to the moving barrier to achieve a 26 inch (66 cm) bumper height. Honeycomb was mounted behind the deformable faces to simulate the increased stiffness of the radiator support, A/C condenser, and fan components that are located between the bumper and the engine. The honeycomb

stiffness was the same as that used for the FMVSS 214 dolly face, which is representative of the frontal stiffness of a passenger car. In both configurations, the barrier was ballasted to simulate the inertial properties of a mid-size sport utility vehicle. It had a wheelbase of 119 inches (302 cm), a track width of 62.5 inches (159 cm), a front overhang of 45 inches (114 cm), and a test weight of 4,500 lbs (2,041 kg) with a 54% front / 46% rear weight distribution.



Figure 4. Non-deformable moving barrier (top) and deformable moving barrier (bottom).

For each test, the barrier was first placed in contact with the pole and the impact configuration was documented with still photographs. The barrier was then pulled back and accelerated to impact speed using a wire rope tow system (Figure 5). The first three tests were conducted at an impact speed of approximately 30 mph (48 kph) with non-deformable bumpers to evaluate the fracture mechanisms of the poles and explore variability of impact dynamics with three distinct wooden poles under the same impact conditions. Two additional tests were conducted at 20/40 mph (32/64 kph) with non-deformable bumpers, and two tests were conducted at 33/15 mph (53/24 kph) with deformable bumpers.



Figure 5. Non-deformable barrier positioned at the impact configuration (top) and in the pulled back condition (bottom) for 30.5 mph NDMB test.

After the test series was complete, the moisture content and specific gravity were measured for each tested pole. This data, along with the impact speed, is listed in [Table 1](#). The samples collected from the poles for the moisture content and specific gravity measurements were taken above the impacted area. Notable outliers in the data are the specific gravity measured in the pole from Test #2 and the moisture content of the poles from Test #4 and Test #7. Photographs of the fracture zone and a cut section from each tested pole can be found in [Appendix A](#).

Table 1. Summary of pole test series

	Test Number	Impact Speed (mph)	Pole Moisture Content (%)	Pole Specific Gravity
NDMB	1	30.5	12	0.46
	2	31.2	12	0.58
	3	30.2	12	0.49
	5	40.9	10	0.47
	7	20.2	17	0.48
DMB	4	33.2	17	0.49
	6	14.8	13	0.44

The moving barrier was instrumented with accelerometers to record the impact profile and allow the calculation of barrier velocity and energy dissipation. The accelerometers were mounted on the moving barrier's centerline 19 inches (48 cm) forward of its center of gravity. The accelerometers included two triaxial sets rated for 100g and 500g full-scale (MSI 1201F-0100-10-12X, ICSensors 3035-500) and a third longitudinal accelerometer rated for 250g full-scale (Entran EGAXT-250). All data was acquired at 10 kHz and anti-aliased filtered at 500 Hz, in accordance with the SAE J211 recommended practice. Processed data from the 100g longitudinal accelerometer was integrated to calculate the barrier speed as a function of time, which allowed the calculation of energy dissipation. The barrier energy was analyzed as a function of time and barrier displacement.

Quadrant targets were attached to the poles, the ground, and the barrier for post-test motion analysis and comparison. The video camera setup included one panning real-time camera, one stationary real-time camera, and six high-speed cameras operating at 1000 frames per second. The high-speed perspectives included a wide lateral view to study pole translation and rotation, and close-up lateral views to analyze the behavior of the wood in the fracture zone. High-speed video was captured from several angles, and synchronized data and high-speed video compilations were generated post-test. The synchronized video and data provide an effective analysis tool for studying the pole fracture in each test.

POLE TESTING RESULTS

ACCELERATION PULSE

In each of the tests conducted with the non-deformable moving barrier (NDMB), the pole fractured early in the collision and the impact was separated into two distinct regions. These two regions are depicted in the blue and green shaded regions in [Figure 6](#) for the 30.5 mph (49.1 kph) test. In this test, the barrier experienced a peak deceleration of 16 g, which corresponds to the initiation of fracture. Fracture of the pole was complete at 9.7 milliseconds, corresponding with the right edge of the blue shaded region. Once the pole had fractured (after 10 ms), the non-grounded (upper) portion was accelerated by the barrier and separated from the

anchored end. Video footage of the overall interaction between the NDMB and the pole clearly shows local deformation to the pole in the contact zone (Figure 7). In this figure, the image on the left is at first contact (time zero) and the image on the right is at 10 ms. The pole center of mass has not moved during the first 10 ms of the impact, yet the pole has clearly fractured, as shown in the close-up frame captures from the high-speed video in Figure 8 and Figure 9. The apparent movement of the bottom portion of the pole is actually localized deformation caused by the barrier at the compression zone, and is associated with the strain energy required to cause the pole to fracture. The authors have defined this first region of the barrier deceleration as the “pole fracture” phase based on our analysis of the deceleration profile and confirmation from the high-speed video, which illustrates the local deformation to the pole and the clear fracture of the wood fibers on the non-struck side of the pole.

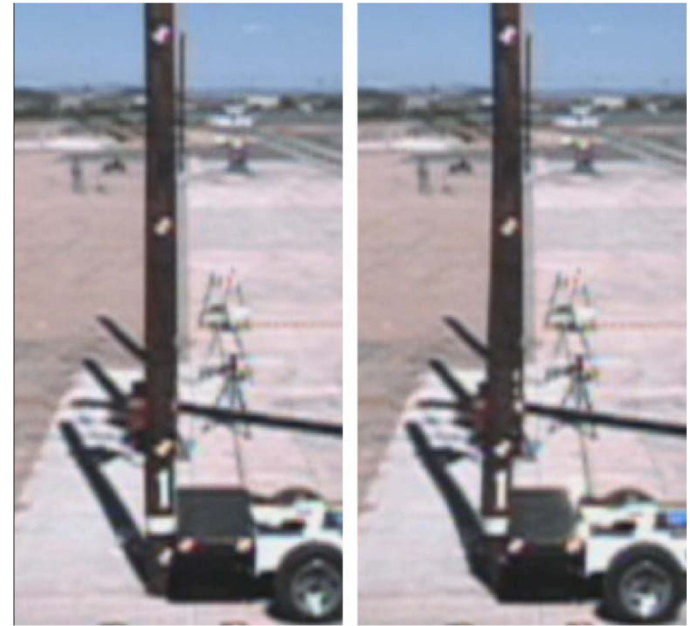


Figure 7. Test photos from the 30.5 mph NDMB at time zero (left) and 10 ms (right) that shows local deformation of the pole in the contact zone and no movement of the pole center of mass.

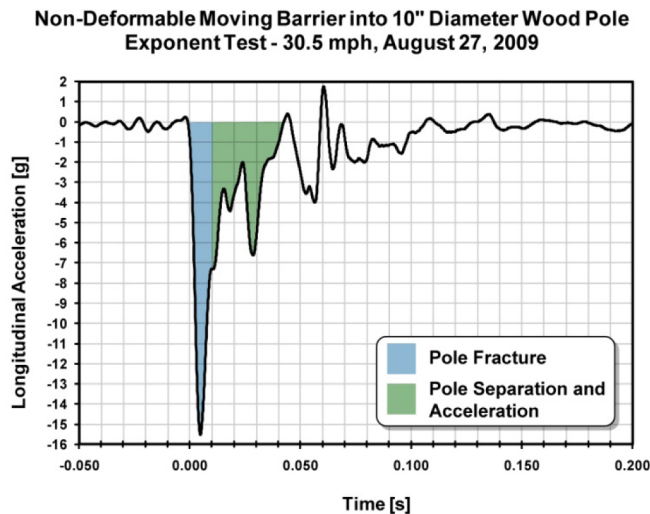


Figure 6. Longitudinal acceleration time history for the 30.5 mph NDMB test, annotated with two distinct regions of pole fracture and separation/acceleration.

The second (green) shaded region in Figure 6 represents what we have termed the “Pole Separation and Acceleration” phase of the upper portion of the pole; in this test, this phase occurred from 10-44 ms. After pole fracture, the intruding barrier tore the wood fibers in the pole and accelerated the pole, transferring kinetic energy to the pole. As a result of this energy dissipation and transfer, the barrier continued to decelerate with a corresponding reduction in barrier energy. The lower structure of the barrier passed over the anchored end after the pole separated and the effect of this interaction can be observed later in the acceleration profile (beyond 44 ms).

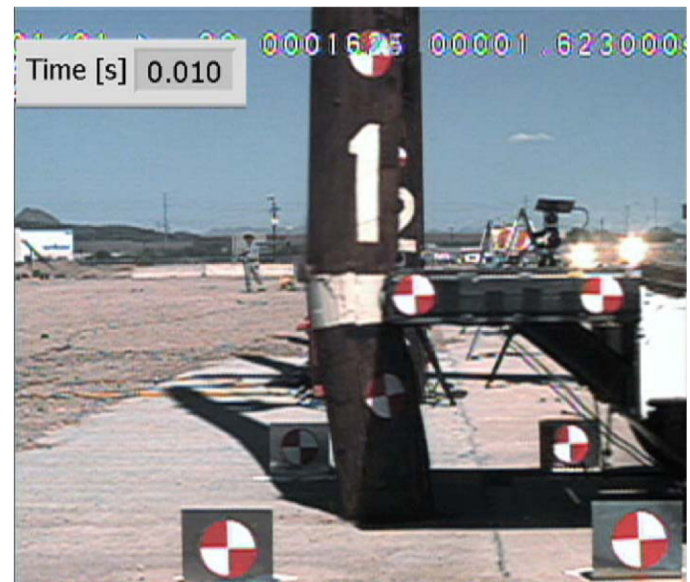


Figure 8. Frame capture from the 30.5 mph NDMB test video, showing the left side of the pole at 10 ms from contact.