LOW-IMPACT, HIGH TOUGHNESS TRANSPORTATION BARRIERS

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ABSTRACT

Alternatives to existing transportation truck escape ramps and crash barriers are examined using arrays of wood, bamboo, and fiberglass structural elements that act as energy absorbers as they deform. The behaviors of each material type are analyzed to determine if they have the necessary potential for extensive use in such applications.Calculations based upon static and dynamic testing are made to predict the type of system required to bring vehicles to a stop. The findings are discussed and guidelines for future applications are suggested.

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EXECUTIVE SUMMARY

Low-impact, high-toughness transportation barriers are explored that use materials with relatively low modulus but strong materials to absorb the kinetic energy of impacting vehicles. The intent of this work was to test the validity of systems that do not require long distances or gravity to balance or resist the motion of vehicles.

Several test configurations were explored and tested both in component form and as a system using the experimental ramp system at Colorado State University. The primary system is composed of a system of vertical fiberglass rods placed in sequence. Here the bending action of the beam is the primary method of energy absorption. Additionally, a bamboo fibrous mat was tested to determine its ability to perform a similar capability.

Although both materials proved to be extremely tough, at least relatively, the bamboo mat would only stop a cart weight 475 pounds (i.e., our test cart) moving at about 5 mph and is destroyed during testing. The rod array system is far more durable, can be re-used, and, for an equivalent amount of funding (i.e., $100 to purchase fiberglass rods), can stop the same cart moving at 25 mph in less than 20 feet.

1. INTRODUCTION

There are several methods and systems for either slowing or stopping vehicle motion, depending on the application. These can include everything from concrete barriers to cable lines across interstate medians. Of significant interest, especially to drivers of freight vehicles on steep roads, are the runaway truck ramps that are easily recognized by drivers in mountainous regions of the United States (Figure 1.1). These ramps are designed to gradually slow rapidly moving vehicles that have lost control of their breaking systems without causing harm to the driver or excessive harm to the vehicle. In 1990, there were 170 ramps located in 27 states. According to somewhat dated data (1981 NHTSA), there are roughly 2,500 runaways per year in the U.S. Although AASHTO noted in 1994 that “specific guidelines for the design of ramps are lacking at this time,” there are local guidelines and design practices used by most engineers to determine the necessary requirements for safe use.

By far, arrestor beds have been the most widely used of all possible alternatives. This is primarily because they are simple and very effective. Gravel arrestor beds work by dissipating the kinetic energy of a moving vehicle through increasing the magnitude of rolling resistance between the tire and the gravel surface. Arrestor beds are often upwards of several hundred feet long and are graded to an incline if possible. Geographic location and topography often determine whether this is a viable option or not. The deceleration and stopping distances of gravel arrestor beds depend upon vehicle parameters such as truck size and speed as well as the inclination angle of the ramp and the gravel type and size. Maximum average decelerations of beds have been observed in one study to be approximately 0.5 g. Nearly every transportation organization has standard design methods that can be used to determine the size, length, and nature of arrestor bed ramps depending on the application.

Figure 1.1 An example of a gravitational runaway truck ramp in Arizona.

Existing gravel arrestor beds require a certain level of maintenance, and this is an expected cost to entities responsible for maintaining and repairing such systems. Studies have determined that a well “fluffed” bed yields shorter stopping distances compared to an arrestor bed that has slowly compacted itself over time. Studies have also shown that a bed requires fluffing approximately twice a year and after each use [1]. Depending on use, this can be a significant cost, and it also depends on weather conditions (e.g., snow coverage) and the amount of access for the equipment necessary to complete this task. There are few studies that have been completed on these influences.

Figure 1.2 A gravitational ramp with sand piles in Virginia.

Planing effects have also been observed on some escape ramps. This effect occurs when trucks skim across the surface of the gravel at high speeds rather than gripping into the gravel. For some designs, this behavior can be minimized depending on the size of the aggregate, but it is difficult to eliminate entirely. In the pursuit of shorter stopping distances, the use of structural mounds (see Figure 1.2) in combination with planing vehicles has been shown to cause detrimental effects. In fact, it has been observed that at speeds over 25 mph, mounds may send planing vehicles airborne. The difficulty is that ramps, though designed for vehicles with a relatively large gross vehicle weight, they can possibly be used by smaller vehicles. Since the gravitational force is much lower for smaller vehicles, the vertical lift from mounds can overcome this restraint and lift the vehicle before it has a chance to slow.

Figure 1.3 Perhaps the most-used runaway ramp in Colorado: the western side of the Eisenhower tunnel on I-70 just east of Silverthorne, showing a maintenance crew after an event. This ramp has over 20 reported events per year, with 106 reported 2001-2004.

Figure 1.4 The same ramp as that of Figure 1.3 during the winter, with snow coverage.

Other solutions to emergency off ramps include gravity and sand pile escape ramps. Gravity escape ramps (Figures 1.3 and 1.4) utilize long roadways inclining upward that run parallel to the road. The concept behind the design is that gravitational potential energy will balance the kinetic energy. In fact, gravity ramps are often combined with arrestor beds to provide two means for slowing down vehicles. Complications with gravity escape ramps include a large distance required for the vehicle to reach a stop. Additionally, drivers have been observed to have a problem maintaining control of the vehicle on the ramp, often resulting in overturning of the vehicle and significant damage to the ramp along with a loss of property. Finally, rollback once the truck has stopped can be an issue unless the ramp design specifically accounts for this possibility.

2. PROJECT PURPOSE AND OBJECTIVE

There are several alternatives to common arrestor beds that possess some positive features that directly target the weaknesses of arrestor beds. One alternative to the existing types of escape ramps that are explored in this study uses an array of cylindrical rods oriented vertically in a network to absorb the energy of the vehicle passing over. When the rods are struck by the vehicle, deformation will occur, which acts to balance the kinetic energy associated with the vehicle slowing down its velocity. The rods would then recover (in reality, they are likely to vibrate as the load is removed and eventually stop moving from internal friction) as the truck passes over, resulting in minimal damage to the underbody and engine.

This idea stems from the principle of a lawn mower blade cutting through thick grass. When enough blades of grass are gathered together, they can stop a sharp, motor driven blade. In a similar manner, it is anticipated that a given number of rods will be able to stop a moving vehicle. Although the single blade of grass has only a small amount of structural capacity, there are so many of them that together they can stop a blade. The same is theoretically possible for an array of thin rods. The challenge is determining if this is a practical, economical alternative to existing methods and in determining how many, of what size, and what material is best.

The proposed method would require targeting a deceleration that is appropriate to the truck dynamics of a hard breaking stop. A force exceeding that of a hard breaking stop may cause undesirable stresses on the vehicle and could shift the contents being transported. The barrier would also need to slow the moving vehicle while minimizing the chances of injury to the driver and damage to the vehicle. Additionally, parameters such as vehicle retrieval and rehabilitation cost of the escape ramp would have bearing on the feasibility of the design. Although these secondary considerations are important, they were not considered in this study. Instead, the basic mechanics of use are examined to determine if such a system was possible and what scale of a rod system is necessary.

In the present study, vertical cylindrical rods are grouped a small distance apart, and are anchored to the floor/ground. Rods made of wood, bamboo, and fiberglass were examined to determine their structural capacity. Rods of varying diameter were tested to determine the optimal amount of energy absorption while still preventing permanent damage. Material properties such as the modulus of elasticity, deflection, and durability were also examined. All of these traits were studied, since these materials are the key component in these “soft barriers” that do not depend on gravitational change or arrestor bed behavior. Instead, they are meant to be a completely new alternative to these traditional tools. Their primary advantages are that 1) they do not require fluffing or any maintenance after use, 2) their performance is independent of the weather, 3) they do not depend on topography of the road and can be used even in relatively tight spaces, and 4) they can be specifically located to direct the path of a vehicle so that there is no loss of control.

3. TECHNICAL APPROACH

3.1 Material Selection

The use of wood and bamboo material for energy absorption is stimulated by the renewable nature of each product. Wood and bamboo are both low cost and readily available materials. Each would also act as a good material choice for sustainable and eco-friendly design. Fiberglass is a synthetic, lightweight composite material consisting of long glass fibers embedded in polyester. This allows the composite to draw flexibility from the polyester reinforcing agent as well as rigidity and strength from the embedded glass fibers that run longitudinally in the material. Fiberglass is an ideal material for this application due to its flexibility, resistance to weathering, and structural stiffness. The primary difference between the wood/bamboo versus fiberglass approaches are the far higher elastic modulus and durability of the latter but with a cost that is significantly higher than the wood materials. We do not include economic factors in this study, but instead focus on the basis mechanics to determine which of the materials has the better properties.

3.2 Static Deflection Test

A static bending test was designed to determine the amount of energy that would be absorbed by a single rod or a series of rods in bending when the base is fixed and the load is applied in a direction transverse to the axis of the rod. Physical tests were necessary because of the changes in the load position and the nonlinear geometric response of the rod with the applied displacement. The test would also determine the adequacy of each material in regard to flexibility and durability. Multiple tests were conducted by bending rods to incremental displacements and recording the necessary force required to achieve the particular displacement. A picture of a static displacement test on a 1/4 in. fiberglass rod can be seen in Figure 3.1. The force was then plotted against displacement and the total energy absorption was calculated by integration of a fifth order trend line. Plots of the curves for the various rods tested can be seen in Figure 3.2 (series 5=14 inch rod). For each material candidate, at least a dozen different tests were completed so that average values could be obtained for each material.

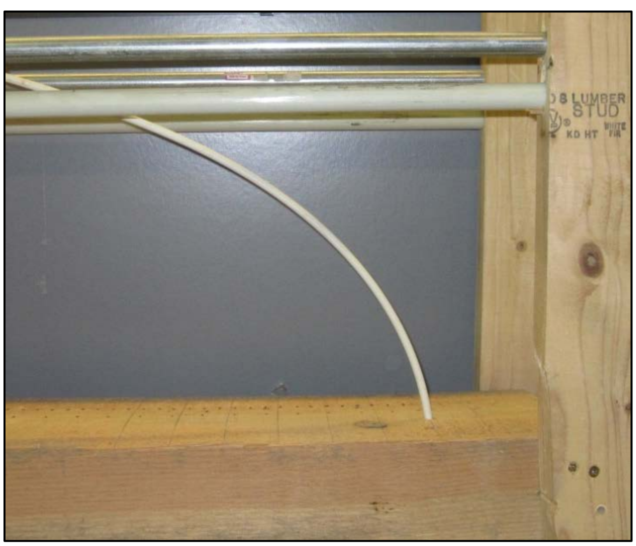

Figure 3.1 Static Deflection Test 1/4 in. Fiberglass Rod.

It is important to recognize that usual formulas for force-displacement (and therefore energy storage) response would not be useful in this case, since the problem is geometrically nonlinear and the displacements are large. Hence, physical experiments are extremely useful in calculating the overall structural response for these structural elements.

The deformation pattern in Figure 3.1 clearly shows the type of energy storage that is relied upon for the use of this sort of transportation barrier. All structures deform when they are loaded, but most structures have infinitesimal displacements that cannot be seen by the human eye. They are relatively stiff, and hence any loading will result in a shock to the system that is loading it. In this case, the rods are relatively soft. They immediately give way under loading but absorb energy as they do so. When they are linked together into an array of individual rods, the forces that slow down a vehicle are applied sequentially, resulting in a gradual slowing of the vehicle. If, for example, the rods were bonded into an individual unit with the same amount of material (but with inter-rod connectivity), the resultant moment of inertia would skyrocket and the impact would be similar to a car running into a pole. The rods would deform much less, but the damage to the vehicle and its occupants would be far more severe.

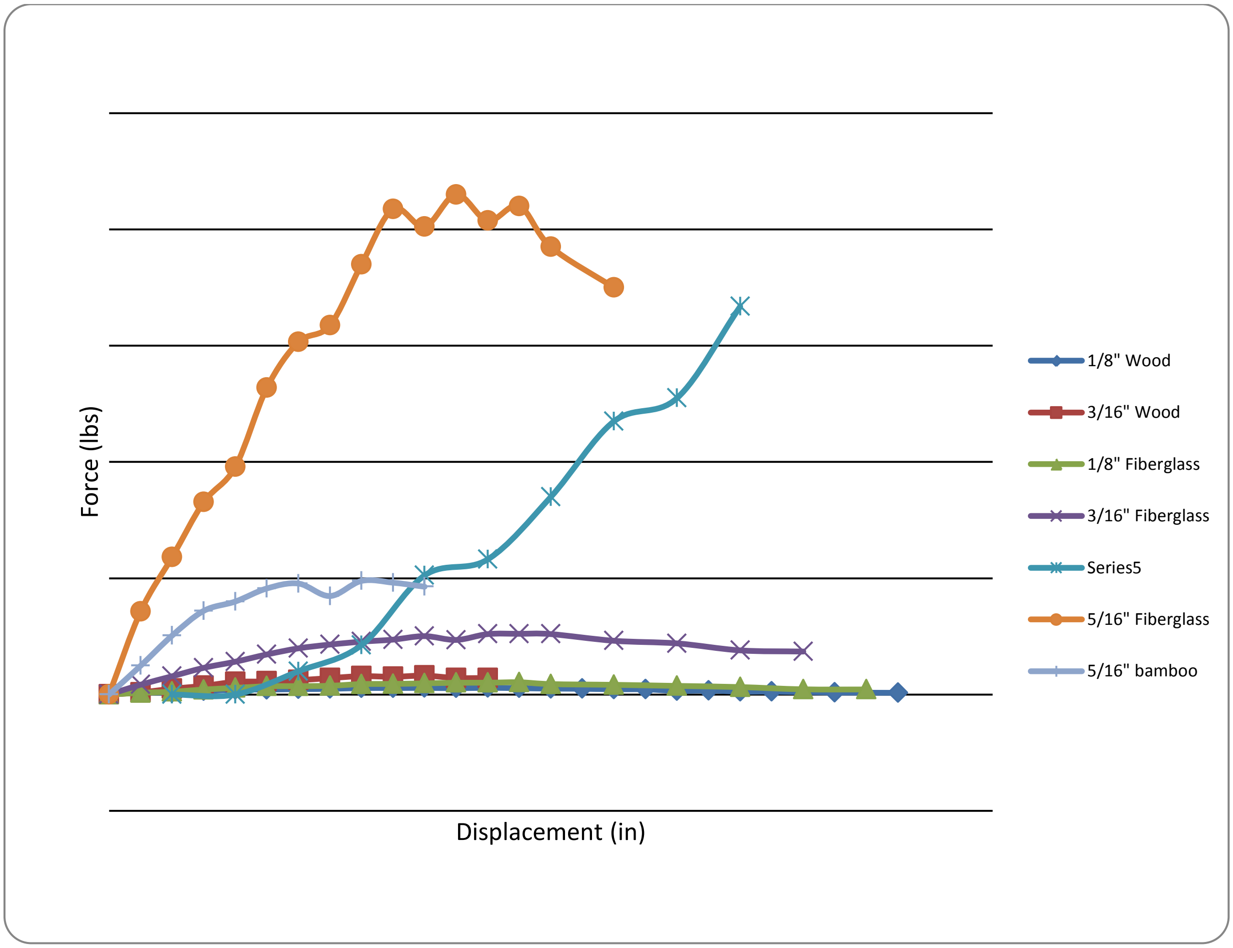

Figure 3.2 Static bending test data for various materials.

A height of 9 in. was used for the point at which rods would make contact with the axle. The rods were cut to a length of 20 in. and embedded into a wooden beam at a depth of approximately 1in. exposing about 19 in. above the timber base. Ideally, the rods would need to perform within their elastic range with no permanent deformation, but this issue was of secondary concern in the initial round of testing.

The resulting force required for an incremental amount of deflection was recorded for bending both two and five rods simultaneously, with multiple rods being used to maintain a consistent deformation pattern for the entire duration of the loading. The force required for each respective displacement was divided by the number of rods in bending to achieve the final average. The results confirmed that the force required to bend the rods was directly proportional to the number of rods in bending.

3.3 Wood and Bamboo Rods

Wooden dowels of 1/8 in. and 3/16 in. diameter were tested. The wooden rods displayed no plasticity or temporary deformations, but they did generally display brittle failure. Bamboo rods of approximately 5/16 in. diameter failed with a brittle rupture after deflection of just three to five inches. Most of the wooden dowels were able to deflect up to approximately 12 in. elastically (this is in the horizontal direction). The bamboo rods were able to resist relatively large forces before they ruptured.

The exploration of wood and bamboo was inspired by the materials being economically feasible, of renewable resources, and readily available. However, the high degree of variability and heterogeneity in the material properties detract from their eligibility of candidacy for this application. The brittle failures of both of these materials deem them unreasonable choices for this application. The durability of wood and the susceptibility of its material properties to the elements also make these materials questionable. Finally, no effort was made to model the environmental degradation that would occur during normal changes in weather.

3.4 Fiberglass Rods

Fiberglass rods of diameters 1/8, 3/16, 1/4, and 5/16 in. were tested and evaluated. All of the fiberglass rods performed in their elastic range. However, the 5/16 in. diameter rods often ruptured during the bending at deflections ranging from four to seven inches. The larger diameter of rod used, the greater the capacity for energy absorption, but the larger strains occur during the normal deformation process. As a result, the ideal size of rod for future tests was chosen to be 1/4 in. diameter. This maximized the energy absorption while maintaining an elastic range of full deformation without any damage evident in the vast majority of experiments.

The results from the static deflection test showed the 1/4 in. diameter fiberglass rod was the optimal material for further testing. This is obvious from the results in Figure 3.2, with the level of energy absorbed for the same amount of displacement being dramatically larger for the fiberglass than the wood materials. Additionally, fiberglass is an economically feasible material and it proved to have superior performance in bending to that of wood and bamboo. The material is more uniform and was shown to have relatively small variability between specimens, creating an ideal candidate for this application. Fiberglass also has a significantly higher energy absorption envelope to minimize the number of rods necessary for energy absorption. A modulus of elasticity of between 2,800,000-5,500,000 psi was provided for the specimens by the manufacturer, McMasters. The force-deflection curve for the 1/4 in. fiberglass rods can be seen in Figure 3.3.

3.5 Rods in Bending

A theoretical prediction of the number of rods needed to stop a moving vehicle was found using Equation 1 below, which represents a simple statement of work-energy:

$$\frac{1}{2}mv^2 = \int f\,dx$$

Eq. 1

In this equation, m represents the mass of the vehicle, v represents the velocity, f represents the force exerted by each individual rod onto the vehicle, and dx represents the deflection of the rods as they are bent. The right-hand side is also equal to the internal strain energy stored in the rod as it deforms, which is the total work done by the Cauchy stress as it moves through the strain imposed during the rod bending. The mass of the vehicle is known, the velocity can be measured, and the force applied by each rod and the deflection from the vertical can be measured. By dividing the kinetic energy, represented by the left-hand side of Equation 1, by the energy envelope for a single rod, represented by the right-hand side of Equation 1, a required number of rods can be calculated to determine how many rods are necessary to stop a vehicle with a given mass moving at a given speed. The number of rods predicted to bring a test vehicle that weights 475 lb. to a stop for various speeds can be found in Table 3.1.

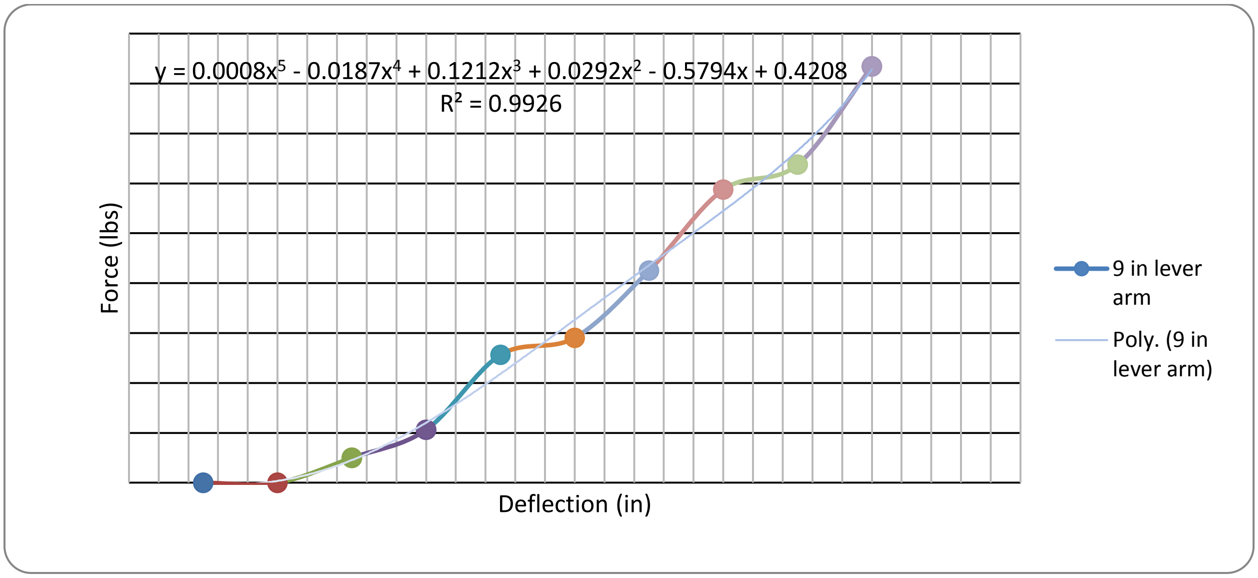

Figure 3.3 Bending test 1/4 in. fiberglass rod. The area under the curve is the energy stored during the deformation.

Table 3.1 Calculated Number of Rods (475 lb cart)

Speed (mph)	Speed (m/s)	Kinetic Energy (J)	Predicted # Rods
1.0	0.4	23.3	2
2.0	0.9	93.1	7
3.0	1.3	209.5	17
4.0	1.8	372.5	30
5.0	2.2	582.0	47
6.0	2.7	838.1	67
7.0	3.1	1140.8	91
8.0	3.6	1490.0	119
9.0	4.0	1885.8	151
10.0	4.5	2328.2	187
11.0	4.9	2817.1	226
12.0	5.4	3352.6	269
13.0	5.8	3934.6	315
14.0	6.3	4563.3	366
15.0	6.7	5238.4	420

3.6 Ramp Test

In order to simulate a truck on an escape ramp, a scaled experiment was performed on the CSU vehicle testing ramp. A cart was released from various points on the ramp to generate different test speeds. The 475 lb. cart was attached with a guidance system to ensure that it traveled straight down the testing ramp with a very small amount of frictional force. The setup of rods was located at the bottom of the ramp, where the cart was traveling its fastest. Plywood sandwiched between two sheets of plastic was mounted on the ground to hold the rods. Holes were drilled through each layer to give the rods an adequate hold, while still allowing for freedom to bend. Pictures of the testing facility can be seen in Figures 3.4 through 3.6. A high-speed camera oriented perpendicular to the ramp was used to record the footage of each test and to measure the final velocity of the cart just before it made contact with the rods.

The intent of this sequence of tests was to 1) determine the matching between predicted numbers for rods needed and those needed in the physical experiments to bring the vehicle to a stop, 2) asses any additional mechanical effects that might arise in the actual use of this sort of barrier system, and 3) physically demonstrate how this system can be used to stop a vehicle moving at a reasonable speed.

Figure 3.4 CSU vehicle testing ramp. The change in elevation allows a vehicle speed of up to 25 mph to be achieved with little effort, providing a reasonable amount of kinetic energy that needs to be absorbed by the flexible ramp system. The two white blocks at the bottom of the ramp (after the center rail, which guides the vehicle, ends) are in fact the array of fiberglass rods.

Figure 3.5 Rod and mount setup.

Figure 3.6 CSU vehicle test ramp from below.

A number of tests were performed, with varying speeds and numbers of rods. Based on the theoretical calculations and static deformation tests, a predicted number of rods were tested for each speed. The results of the testing can be seen below in Table 3.2. The entire point of this test was to use just enough rods from theoretical predictions so that the vehicle would stop at the end of its run through the rod bed. The velocities were determined from a combination of a radar gun and also theoretical calculations from a simple physics prediction.

Table 3.2 Final Results for the Ramp Test

	# of Placed Rods	**Speed at Impact (mph)**	**Stopped**
Test 1	40	5.2	Y
Test 2	40	5.0	Y
Test 3	47	5.4	Y
Test 4	80	7.6	Y
Test 5	88	8.1	Y
Test 6	119	8.1	Y
Test 7	160	10.1	Y
Test 8	400	14.2	Y
Test 9	420	14.7	Y
Test 10	363	15.1	N
Test 11	366	15.1	N
Test 12	420	15.2	Y

4. RESULTS AND DISCUSSION

4.1 Ramp Results

The results of the dynamic testing on the vehicle testing ramp demonstrated an excellent correlation between the experimental data and the predicted number of rods required to bring the vehicle to a full stop. Tests were conducted at varying speeds and rod counts. Tests 1, 2, and 3 ranged between speeds of 5.0 and 5.2 mph with a total number of rods on each test ranging from 40 to 47. Based on our calculations, it would require 47 rods to stop the cart moving at 5.0 mph. Our experimental results were even better than predicted as the 47 rods stopped the cart traveling 5.4 mph and just 40 rods stopped the cart at 5.0 mph.

Our calculations also predicted 91 rods would stop the cart traveling at 7.0 mph, but in Test 4 the cart was traveling even faster at 7.6 mph, and just 80 rods were able to stop the cart. At a speed of 8.0 mph, 119 rods should have been necessary to stop the cart, yet at 8.1 mph as little as 96 rods were able to stop the cart. Test 5 used 80 rods placed vertically, with 16 more rods oriented horizontally (two per row of 10 rods) and performed very well. In Test 6, the predicted 119 rods (all vertical) stopped the rods as well. A picture of the horizontally oriented rods can be seen in Figure 4.1.

Figure 4.1 Horizontal bracing.

At a speed of 10.0 mph, it was predicted that 187 rods would need to be in place to stop the cart. However, our experimental results showed that just 160 rods were able to stop the cart at 10.1 mph. Test 8 through Test 11 were somewhat inconclusive. Given the nature of our testing ramp, it proved very difficult to attain the precise speed that was required to verify our predicted calculations. For example, in Test 8 through Test 12, the cart was raised to the same level on the ramp for all five tests, yet the speed varied between 14.2 and 15.2 mph because of slight variations in the tracking mechanism and other influences that may slow the cart down from its predicted, frictionless path. Given this variability, it should not be misconstrued that our measuring system was inaccurate, but rather that variances with our cart and guidance system led to differing speeds for these tests. In fact, the high-speed camera and a radar gun used for confirmation provided very accurate measurements of speed. Test 8 and Test 9, using 400 and 420 rods respectively, were able to stop the cart traveling at over 14.0 mph; however, with those rod counts it should have been able to stop the cart at 15.0 mph. Therefore, these two tests don’t relay any valuable information about our predictions.

In Test 10 and Test 11, the cart was raised to the same level as the two preceding tests in order to verify our predictions at 14.0 mph with 366 rods; however, in each case the cart traveled 15.1 mph. In each of these two tests, the cart was not stopped by the rods. Because fewer rods were used that should have been necessary to stop the cart at that speed, the tests were again inconclusive. They are reported here for completeness.

Finally, in Test 12, the 420 rods correlating with a speed of 15.0 mph was attained. The cart traveled at 15.2 mph and the 420 rods stopped the cart.

In every case where the number of rods was equal to or less than the predicted amount for a certain speed, the predictions held true. There were no cases in which the predicted number of rods for a given speed failed to stop the cart. The experimental results on the vehicle testing ramp proved even better than our calculations had anticipated, demonstrating that it is possible to predict the number of rods used in any barrier bed for a specific design speed and vehicle mass.

It should be noted that the number of rods used in testing doesn't provide the entire picture or completely represent the challenges associated with regular use. The layout and spacing of the rods have a signficant impact on the performance of the barrier. The high-speed camera footage revealed that the cart would lift off the ground due to the vertical force exerted upon it by the rods. When the cart lifted, it would often jump over a number of rods as can be seen in Figure 4.2. As shown in Figure 4.3, the use of clusters spaced apart was effective and kept the cart low to the ground. Consequentially, the spacing of the rods was altered so as to prevent any rods from being jumped. Our high-speed footage also revealed that grouping the rods into clusters had a positive impact on the performance of the barrier. One preliminary test was performed in which individual rows of rods spaced 14 inches apart was compared with rows of rods spaced just two inches apart. Each layout used 40 rods. The test with the rods bunched together was able to stop the cart, while the test with the rods spread out at 14-inch intervals failed miserably at the same speed. When the rods are closer together, they interact with one another and act as a more rigid unit while still maintaining their flexibility.

Figure 4.2 Cart lift due to tightly spaced clusters.

Figure 4.3 Clusters spaced apart with no lift.

A similar result can be seen from Test 5 in which two rods were woven in between every row of ten rods. With the horizontally woven rods acting to band the ten rods in each row together, the barrier exhibited a more rigid behavior while still remaining flexible.

One problem noticed during testing was the dislodging of the rods upon impact. On average, 31% of the rods were displaced on each test. This was due in large part to the hole diameter of the mounting system being slightly larger than the diameter of the rods. It was discovered during the static testing that if the hole diameter was exactly the same as the diameter of the rod, the rod was very difficult to remove upon completion of the test. Also, if the rod was deflected beyond its elastic limit, it would fracture when fixed tightly into the mount. As a result, the holes were widened just enough to allow the rod to fly out if necessary so as to limit the number of damaged rods. Hence this is a pragmatic concern for the current round of tests but does not appear to influence any of the results of this work.

After several rounds of preliminary and final tests on the ramp, the rods began to split vertically along the length of the rod. With this, the rods lost some of their capability to store elastic energy as an entire solid. However, despite lacking complete strength from the rods, Test 12 was a success even though it used almost exclusively broken rods.

4.1 Improvements

While the results of this experiment demonstrated the extraordinary ability of fiberglass rods to balance kinetic energy, there is room for improvement. It has already been discussed how the layout of the rods has an influence on their stopping ability, but the orientation of the rods can also be changed. When the rods were oriented vertically, the cart was often lifted off the ground. To eliminate this lift, the rods could be oriented horizontally. The rods would be cantilevered out from walls on both sides of the vehicle. The farther the walls are spaced apart, the longer the rods could be made, which would allow for more bending and ultimately more energy absorption capacity. A larger diameter rod could be used with the longer lever arm, because the possibility of brittle failure is significantly diminished. The results of the static testing showed the larger diameter rods had a much greater energy absorption envelope as well.

Other materials, besides the likes of wood, bamboo, and fiberglass, should be explored as well. For example, carbon-fiber reinforced polymer can have a modulus of elasticity of up to 116,000,000 psi (800 GPa) [2]. This would provide over 21 times the allowable stress when compared with fiberglass. A significant decrease in the number of rods could be seen from implementation of such a material.
The use of a network of rods has many other practical applications beyond truck escape ramps. A similar system could be implemented as a defense mechanism against a terrorist attack around government properties. In such an instance, the rods could be made stronger as the damage to the vehicle would not

be of concern. It would have a great appeal to airports where planes need to make emergency landings with a short stopping distance. Current systems utilizing concrete blocks require demolition and reconstruction after each use and can be very expensive. For example, a system used at Teterboro Airport in New York and New Jersey cost $20 million for installation on just two runways [3]. If the rod network was implemented, longer and larger diameter rods could be used.

4.2 Other Designs

One of the driving forces behind this work was the observation that current designs for emergency ramps contained significant room for improvement. Many existing ramps rely on gravitational loss to offset energy and/or arrestor beds that can often result in a loss of vehicle control. One of the more innovative designs that has successfully been used by other researchers in a very unusual circumstance is the emergency ramp on Highway 14 between Buffalo and Ten Sleep, Wyoming. This novel approach uses a sequence of wire meshes along with breakaways that absorb the energy for a ramp that is in the downhill direction.

This design is unique in that it replaced an existing gravity ramp that required the driver to cross over the highway, crossing oncoming traffic, to access the ramp. The current design is a cleverly positioned ramp, with side barriers, and cable nets. It has seen little use, but one spectacular success as highlighted in the press announcement below (courtesy of Entwistle, the manufacturer and designer of this system, located in Hudson, Massachusetts):

Runaway Truck Ramp / Buffalo, Wyoming

Today we had the first truck utilize the new runaway truck ramp west of Buffalo, Wyoming. The driver, Mike Stewart said his brakes got hot and he was about to lose his air, so he decided to take the ramp. He said was traveling about 40 mph when he entered the ramp. He was hauling an 80,000 lb tanker load of sulfuric acid. He traveled approximately 330' into the ramp and went through 5 sets of nets. As you can see from the photos, damage to the truck was limited to the front bumper and cab. The driver actually backed the truck up after getting stopped. As a matter of fact, the driver was going to drive the truck out of the ramp and down the mountain, no wrecker service needed. The driver stated that he was very thankful that the ramp was there - "Thank God it was here; go ahead and build more of them". He said he would hate to think what would have happened if he took the old ramp especially with the type of load he was hauling (sulfuric acid). With the old ramp, there is potential for the truck to jackknife, and turnover and potentially cause a spill. The driver stated that when he hit the first net, there was only a slight jolt (just enough to slide his dog out of the passenger seat). After that, it was a very gradual and smooth slow down. He did state that the signs prior to the ramp were a little confusing, but that they did point him towards the ramp. The driver said the trucking company is **Groendyke Transport, Inc**., 620 Railroad Ave., P.O. Box 606, Riverton, WY 82501; Phone: 307-857-5881.

Runaway Truck Ramp – Buffalo, WY

Figure 4.4 The novel ramp design on Wyoming Highway 14, in the eastbound lane just outside of Buffalo. The older ramp was on the other side of the highway, requiring the driver to cross oncoming traffic. The metal mesh webs are designed to absorb energy to a point and then break away.

The ramp design is shown in Figure 4.4, and pictures of the ramp and the vehicle after an actual incident are shown in Figures 4.5 and 4.6. By far the most significant advantage is its lack of reliance on an uphill grade. This system can be placed anywhere. It also has the advantage of allowing a gradual slowing of the vehicle. It works extremely well. The downside of this system is the replacement cost after use. Although no figures exist in the public domain, they are expected to be significant.

Figure 4.5 The crumbled wire gates following a successful ramp event.

Figure 4.6 The front of the truck after stopping, showing the relatively minimal damage to the vehicle.

As an alternative to the types of metal meshes used in the Wyoming ramp design, we also considered alternative testing materials during the preliminary phases of this study that had the key features of being widely available and low cost. After preliminary testing of several other materials, the main material candidate chosen for secondary testing was a woven bamboo mat. This type of material is shown in Figure 4.7.

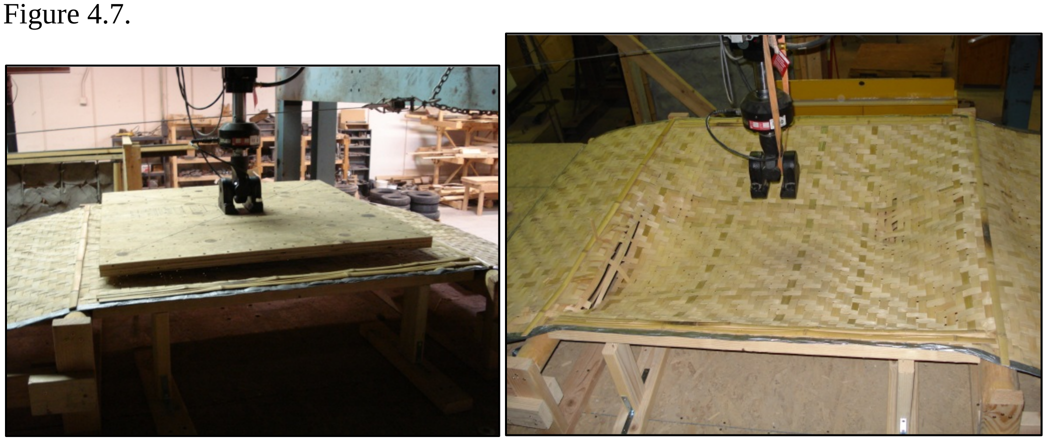

Figure 4.7 The puncture shear testing of a woven bamboo mat.

The advantages of using this material is that it is extremely inexpensive (a roll of several dozen feet was purchased for testing for less than $100) and widely available through southeast Asian sources. Preliminary testing was completed to derive initial estimates for the amount of energy absorbed during static loading. A sample of the results is shown in Figure 4.8.

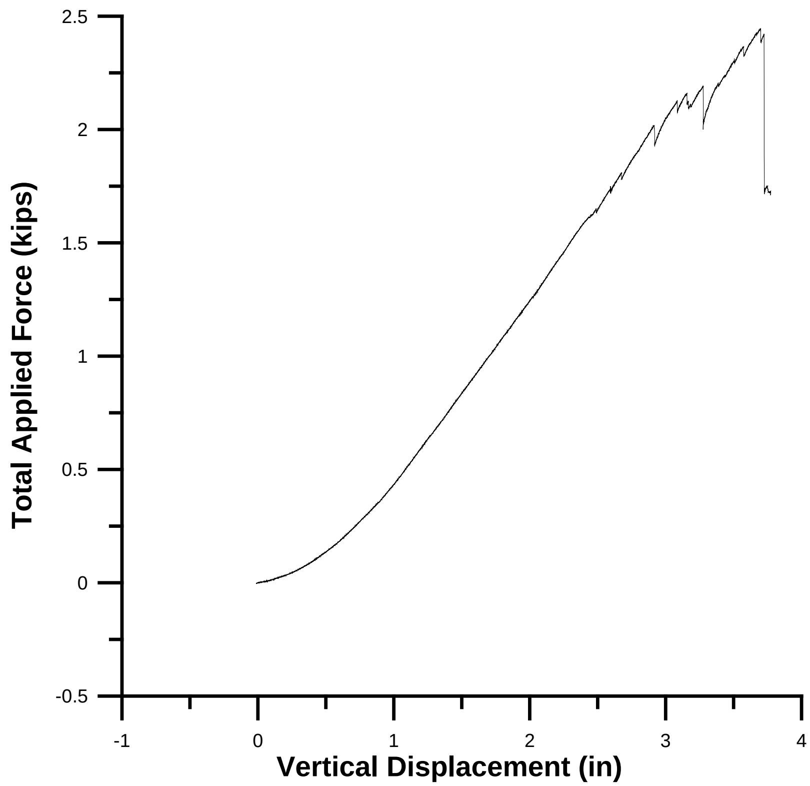

Figure 4.8 The static deflection test for the bamboo mat.

The results of this testing are mixed. Although the material is extremely tough, at least relatively, this mat would only stop a cart weighing 475 pounds (i.e., our test cart) moving at about 5 mph and is destroyed during testing. The rod array system is far more durable, can be re-used, and for an equivalent amount of funding (i.e., $100 to purchase fiberglass rods) can stop the same cart moving at 25 mph. Although these tests were very preliminary and somewhat limited, these results directed our efforts in the direction of the rod array, and further testing of the web-mesh system was not explored.

5. CONCLUSIONS AND RECOMMENDATIONS

The bottom line for the proposed barrier system can be summarized in two words: it works. The use of fiberglass rod barriers as an alternative to truck escape ramps shows great promise. Although the wood and bamboo proved to have difficulties in implementation, the fiberglass performed even better than the theoretical calculations predicted it should. A system using a number of rods to dissipate the kinetic energy of a vehicle has many benefits. When compared with existing truck escape ramps, the maintenance requirements would likely be lower than those with gravel beds that must be fluffed on a regular basis. Perhaps more importantly, the rods can be confined to a small area, as opposed to some escape ramps that are hundreds of feet long. If longer rods were used, larger diameter rods could be explored, and the absorption capability would improve even more. The applications for a rod barrier system extend beyond the scope of escape ramps as well. Uses in the field of defense as well as other areas of transportation could benefit from such a system. The results from this research clearly show that a network of rods can successfully be used in many applications.

The next phase of this work would obviously involve a larger prototype system acting on vehicles with much greater weights moving at much higher speeds. But the principles are the same, and these applications would only be a matter of scale. Although there are a number of challenges to consider, this method is worthy of additional exploration and a larger scale of testing.

REFERENCES

[1] Wambold, J. "Field Study to Establish Truck Escape Ramp Design Methodology." *Transportation Research Record*, Issue: 1233, 1989. 93-103

[2] (n.d.) Fiber Reinforced Polymer. The Constructor. Retrieved August 3, 2011. http://theconstructor.org/concrete/fibre-reinforced-polymer/1583/

[3] (August 2006). In the wake of the Teterboro Challenger overrun, the FAA intensifies industry oversight Aviation International News. Retrieved August 4, 2011. http://www.ainonline.com/ain-and-ainalerts/aviation-international-news/single-publication-story/browse/0/article/charter-under-the-microscope 244/?no_cache=1&tx_ttnews[story_pointer]=5&tx_ttnews[mode]=1

APPENDIX A. IMPACT TEST OBSERVATIONS

	Impact Observations	**Speed Before Impact (mph)**
Test 1	40 Rods No Impact 2nd Axle	5.0
Test 2	40 Rods Mild Impact 2nd Axle	5.2
Test 3	Back Axle Not Impacted	5.4
Test 4	Both Axels Contacted All Rods	7.6
Test 5	Back Axle Impacted Bent Up 80	8.1
Test 6	Back Axle Stopped By First 80	8.1
Test 7	Back Axle Passed 80, Impacted 80	10.1
Test 8	Back Axle Impacted 4th Row of 80	14.2
Test 9	Stopped on Rear Axle Last Row of 80	14.7
Test 10	Not Stopped, Cart Lifted Over Middle Section of Rods	15.1
Test 11	Not Stopped	15.1
Test 12	Rear Axle Made Impact on Last Row of 21	15.20