Flexible Highway Barriers

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Disclaimer

ABSTRACT

Highway barriers exist in part to protect life and property from excessive danger as part of normal road usage. Typically, these barriers can be characterized as stiff and passive. In this study, we report on the potential use of highly flexible materials that maintain the effective resistance to load of passive structures, but do so in a much more flexible manner. In this regard, these flexible barriers are softer, and have the potential to limit damage. The initial focus of this work is on inexpensive one-dimensional networks of biological or metallic elements that can undergo large deformations but still remain as viable barrier candidates. The intent is to explore the levels of energy absorption and global strength, with eventual barrier prototypes constructed and tested.

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TESTING

The energy per unit length of dowel to yield and rupture (total energy) of dowels-based models was sought. This analysis may be used to generate the number of dowels and length, or dowel density, for railing structures that would be required to absorb the energy of a moving vehicle upon impact. Compressive load tests were conducted on multiple test specimens with various materials, diameters, quantities of dowels, lengths, and angles. A test specimen consisted of a sandwich type structure with 2x6 platforms for the top and bottom with the dowels in between as shown in Figure 1.

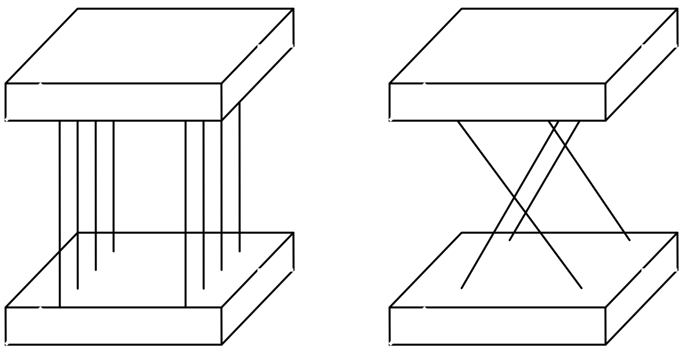


Figure 1 Example test specimens – 8 vertical dowels, 4 angled dowels (opposing direction)

General procedures and a basic description of the tests conducted by date are shown in the following:

General Procedure:

1. Platforms for the structure were cut and made from wooden beams with dimensions of 1.5" thick by 5.5" wide.

2. 1" deep holes for the dowel connections were drilled and spaced evenly on the platforms.

3. Dowels with various lengths were cut with an additional 2" for the end connections in the platforms.

4. Dowels were attached to platforms with glue to create a sandwich type structure or test specimen with rigid planks and a flexible interior.

5. Each test specimen was then loaded to the Instron testing machine for analysis.

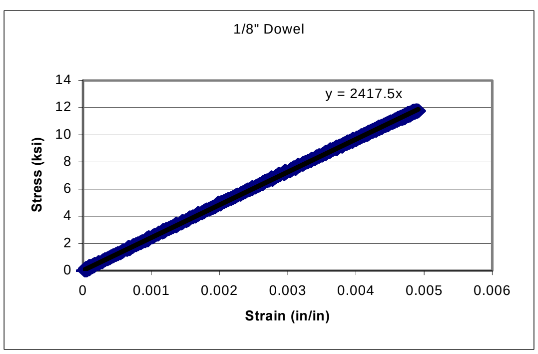
6. Once load and displacement data was retrieved, the displacement was plotted versus the load applied. From the information and plots, the maximum force, maximum compression, energy to yield and rupture, and energy per inch to yield and rupture were calculated for each test. The energies were calculated by using area approximations to find the area under the curve. The average load between two points was multiplied by the change in displacement to find the energy between those two points. They were then summed to find the energy to yield and the total energy.

TENSILE TESTS

Tensile pull tests were conducted on 1/8" diameter wooden dowels, 3/16" diameter wooden dowels, bamboo, and a plastic material using the Instron testing machine. These materials were examined to investigate the modulus of elasticity and ultimate strength values. Stress-strain curves were plotted and the modulus of elasticity values was determined. Ultimate strengths were also determined from the strength at which the material failed. The wooden dowel materials tested demonstrated failures of brittle material. The bamboo material demonstrated brittle failure in the matrix (the center material), but also demonstrated some ductile material behavior because the fibers would remain intact even during large deformations. The following table shows the modulus of elasticity and ultimate strengths for each test. The next eight graphs show the stress versus strain and load versus extension for each of the four materials.

Table 1 Physical and mechanical properties of various materials

Material	Modulus of Elasticity (ksi)	Ultimate Strength (lbf)
1/8" Dowel	2418	150.3
3/16" Dowel	2964	507.9
Bamboo1	4737	843.0
Bamboo2	2329	347.1
Plastic	665	229.4



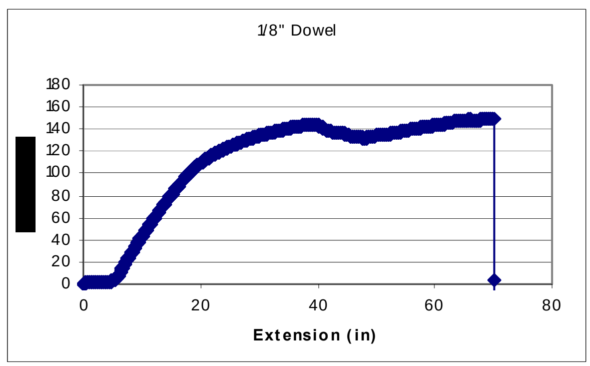


Figure 2 Stress versus strain and load versus displacement graphs for wood used for 1/8" wooden dowels

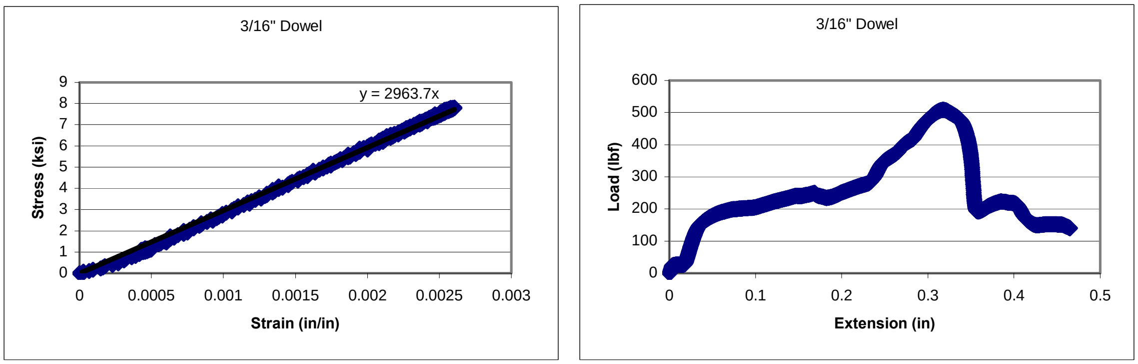


Figure 3 Stress versus strain and load versus displacement graphs for wood used for 3/16" dowels

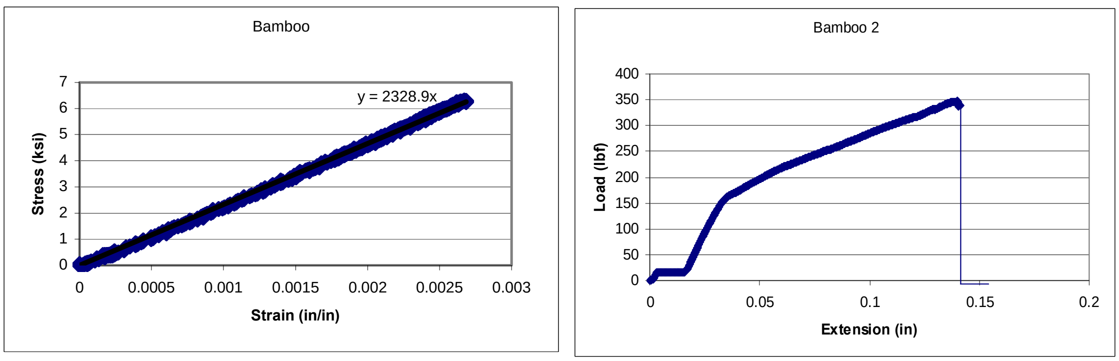


Figure 4 Stress versus strain and load versus displacement graphs for bamboo

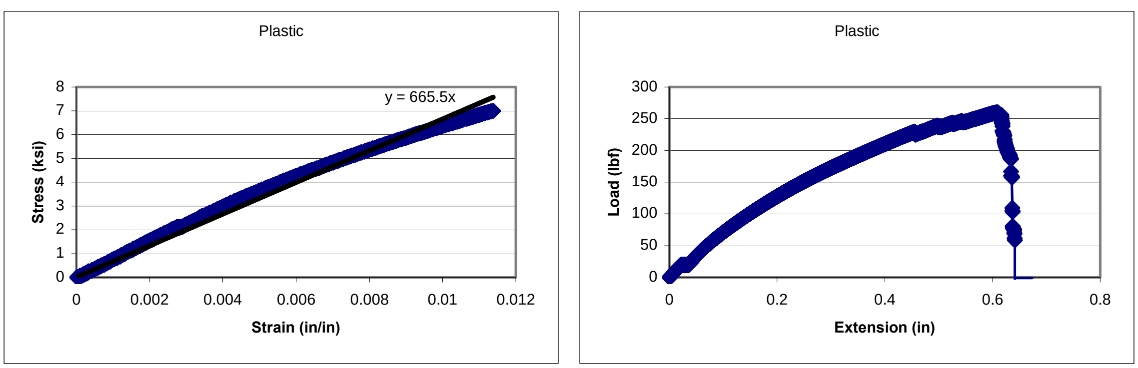


Figure 5 Stress versus strain and load versus displacement graphs for plastic material

VERTICAL 1/8″ WOODEN DOWELS

Tests were performed on wooden vertical dowels on two separate days thus far: February 1, 2007, and February 15, 2007. One-eighth inch wooden dowels were placed vertically into 6" square wooden platforms via 1" drilled holes.

On the first trial day, 02/01/07, five vertical tests were run: 6" dowels with 4 and 8 dowels, 12" dowels with 4 and 8 dowels, and 18" dowels with 4, 8, and 12 dowels. These lengths are the visible lengths and do not include the length of the dowels in the bases. The problem encountered on this first day was that the holes were re-drilled so that the bases could be re-used. After successive tests, the holes were irregular, and the dowels would receive the loading at different times. Since the 8 and 12 dowel tests were done last, they had the most irregular holes, with different depths and width. This seemed to cause a yield point at a later displacement, but sooner rupture than that found with glued dowels.

On the second day of testing, glue was used to keep the dowels firmly in place. The prototypes were made and glued two days before the testing to allow time to dry. This ensured more uniformity in the placement of the dowels. The holes were the same size and depth, and the dowels were unable to move in the connection. Nine vertical trials were performed: 6", 12", and 18" dowels, each with 4, 8, or 12 dowels.

The team was able to draw basic conclusions from these tests. In all the tests, the more dowels used in a test, the more load and deformation could be taken. Increasing the number of dowels per area increases the capacity of the prototype. For the 6" and 12" models, this increase in capacity was fairly linear, but the 18" model seemed to increase in capacity exponentially.

The short dowels were able to take large loads and more energy per inch, but gave very small deformations. The loads taken by the 6" dowels ranged from approximately 100 to 350 lbf, and the deformations went from half an inch to an inch. The latter number in each range was the trial with the larger number of dowels. This gave an average energy per inch of 0.6 lbf-in./in. The common method of failure of the shorter tests was localized crushing, both at the connection and in the dowels.

The longer dowels gave large deformation, but could take less force and less energy per inch. The 18" dowels took loads from about 20 to 40 lbf, but sustained deformations from around an inch to almost 6 inches. Again, the latter number in each range was the trial with the larger number of dowels. These models gave any average energy per inch of 0.25 lbf-in./in. The common method of failure for the longer dowels was buckling of the dowels with some localized crushing at the connection.

Many attachments are included for these series of tests. Two pages of tables are included, one for each day. These summarize the energy to yield, the energy to rupture, the maximum force and maximum deformation sustained, and the energies per inch of dowel. Five graphs are also included: one for all the tests for each day, and one for all the tests for each dowel length.

The following pictures of the vertical prototypes were taken during the testing on the second day.

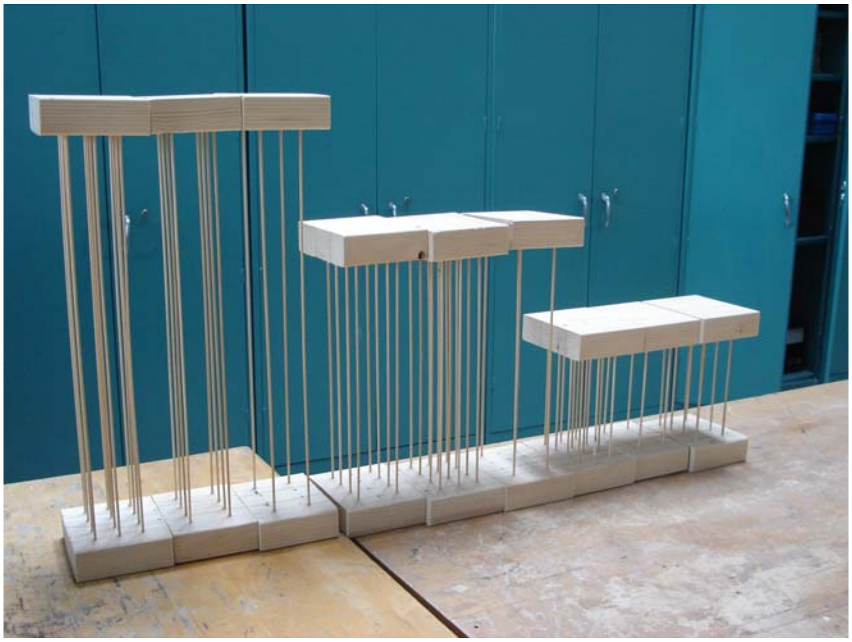


Figure 6 The nine prototypes before testing

Figure 7 The 6", 12-dowel model during testing

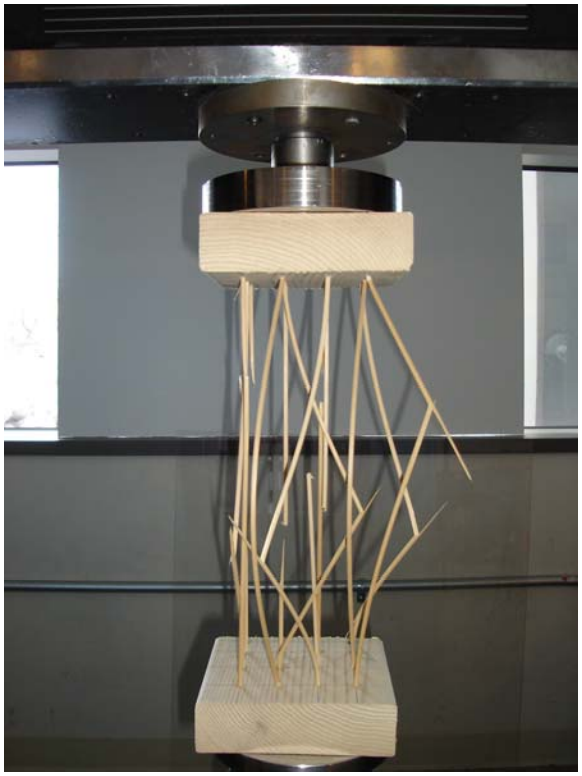


Figure 8 The 12", 12-dowel model during testing

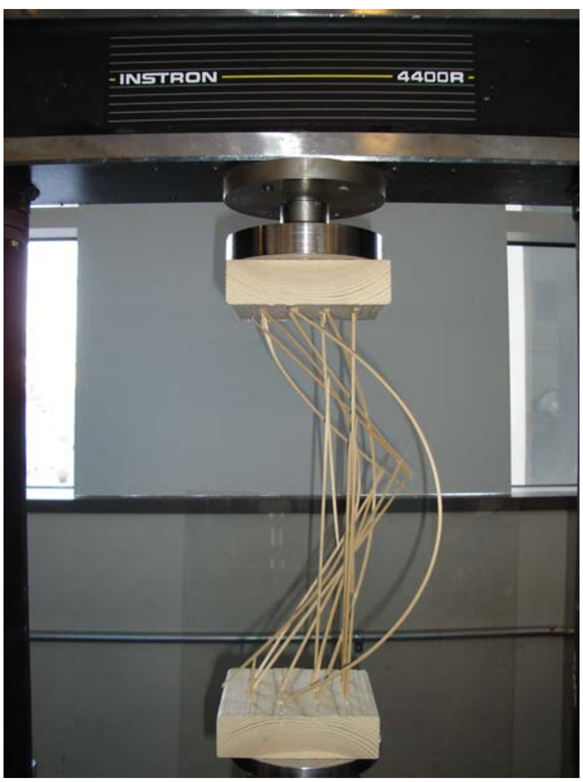


Figure 9 The 18", 12-dowel model during testing

ANGLED WOODEN DOWELS (OPPOSING DIRECTION)

In the initial set of tests on February 1, 2007, angled dowel structures were included in the investigation. The dowels were angled by 25° and 45° at various lengths of 6", 12", and 18". Four dowels were used for each test specimen. Data from the results were analyzed and the energy per unit length for yield and rupture were determined.

For the 25° angled dowels, the energy per unit length to yield ranged from 0.0244 to 0.233 lbf-in./in. and the total energy per unit length ranged from 0.168 to 0.609 lbf-in./in. For the 45° angled dowels, the energy per unit length to yield ranged from 0.0067 to 0.167 lbf-in./in. and the total energy per unit length ranged from 0.035 to 0.288 lbf-in./in. When compared to the vertical dowel analysis, the 6" angled dowels were similar and did not show much improvement. For the 12" and 18" dowels, the energy per unit length values were lower than for the angled dowels.

The energy to yield, the energy to rupture, the maximum force maximum deformation, and the energies per inch of dowel for each test are shown in summary Table 2. There were no significant improvements in the results by angling the dowels (opposing direction). It was also observed that the construction of the angled dowels was more complex, increasing the inconsistencies experienced in the analysis. Hence, angled dowels were dropped from the analysis in trial 2.

Table 2 Results for February 1, 2007, Testing

6-inch dowels				
	Energy to yield (lbf - in)	Energy to Rupture (lbf-in)	Max Force (lbf)	Max Deformation (in)
Vertical - 4 dowels	5.6797	5.6797	61.8522	0.36934
Vertical - 8 dowels	14.51546	14.51546	93.4494	0.76796
25 degrees	5.5866	5.5866	51.2482	1.23801
45 degrees	4.017445	4.017445	42.2021	0.5096

12-inch dowels				
	Energy to yield (lbf - in)	Energy to Rupture (lbf-in)	Max Force (lbf)	Max Deformation (in)
Vertical - 4 dowels	5.019177	5.019177	24.2147	1.427
Vertical - 8 dowels	10.29796	10.29796	24.0268	1.4796
25 degrees	1.172771	1.172771	19.3557	1.01293
45 degrees	2.875892	2.875892	12.349	1.02124

18-inch dowels				
	Energy to yield (lbf - in)	Energy to Rupture (lbf-in)	Max Force (lbf)	Max Deformation (in)
Vertical - 4 dowels	0.900207	0.900207	10.604	1.4796
Vertical - 8 dowels	8.62934	8.62934	46.2281	1.23126
Vertical - 12 dowels	25.92885	25.92885	52.4294	1.4796
25 degrees	2.414838	2.414838	10.8725	1.31633
45 degrees	0.482434	0.482434	5.15435	0.61956

6-inch dowels		
	Energy to yield (lbf-in/in)	Total Energy (lbf-in/in)
Vertical - 4 dowels	0.236654167	0.236654167
Vertical - 8 dowels	0.302405417	0.302405417
25 degrees	0.232775	0.232775
45 degrees	0.167393542	0.167393542

12-inch dowels		
	Energy to yield (lbf-in/in)	Total Energy (lbf-in/in)
Vertical - 4 dowels	0.104566188	0.104566188
Vertical - 8 dowels	0.107270417	0.107270417
25 degrees	0.024432729	0.024432729
45 degrees	0.059914417	0.059914417

18-inch dowels		
	Energy to yield (lbf-in/in)	Total Energy (lbf-in)
Vertical - 4 dowels	0.012502875	0.012502875
Vertical - 8 dowels	0.059925972	0.059925972
Vertical - 12 dowels	0.120040972	0.120040972
25 degrees	0.033539417	0.033539417
45 degrees	0.006700472	0.006700472

Table 3 Results for February 15, 2007, Testing

6-inch dowels				
	Energy to yield (lbf-in)	Energy to Rupture (lbf-in)	Max Force (lbf)	Max Deformation (in)
4 dowels	4.677875667	15.56289274	114.63058	0.80382
8 dowels	8.765989439	27.80956182	196.50958	0.4105
12 dowels	10.72565224	42.08501495	328.85821	1.12633

12-inch dowels				
	Energy to yield (lbf-in)	Energy to Rupture (lbf-in)	Max Force (lbf)	Max Deformation (in)
4 dowels	5.982569775	22.61752395	38.71132	1.36961
8 dowels	4.718954339	34.75951408	65.79849	1.2272
12 dowels	9.08347053	53.07484974	110.06684	1.59716

18-inch dowels				
	Energy to yield (lbf-in)	Energy to Rupture (lbf-in)	Max Force (lbf)	Max Deformation (in)
4 dowels	0.993041373	10.67995105	16.02681	0.7872
8 dowels	4.440022936	32.83324182	30.41603	1.29375
12 dowels	11.68151926	83.36644434	41.87909	5.71864

6-inch dowels		
	Energy to yield (lbf-in/in)	Energy to Rupture (lbf-in/in)
4 dowels	0.194911486	0.648453864
8 dowels	0.18262478	0.579365871
12 dowels	0.148967392	0.584514097

12-inch dowels		
	Energy to yield (lbf-in/in)	Energy to Rupture (lbf-in/in)
4 dowels	0.12463687	0.471198416
8 dowels	0.049155774	0.362078272
12 dowels	0.063079656	0.368575345

18-inch dowels		
	Energy to yield (lbf-in/in)	Energy to Rupture (lbf-in/in)
4 dowels	0.013792241	0.148332654
8 dowels	0.030833493	0.228008624
12 dowels	0.054081108	0.385955761

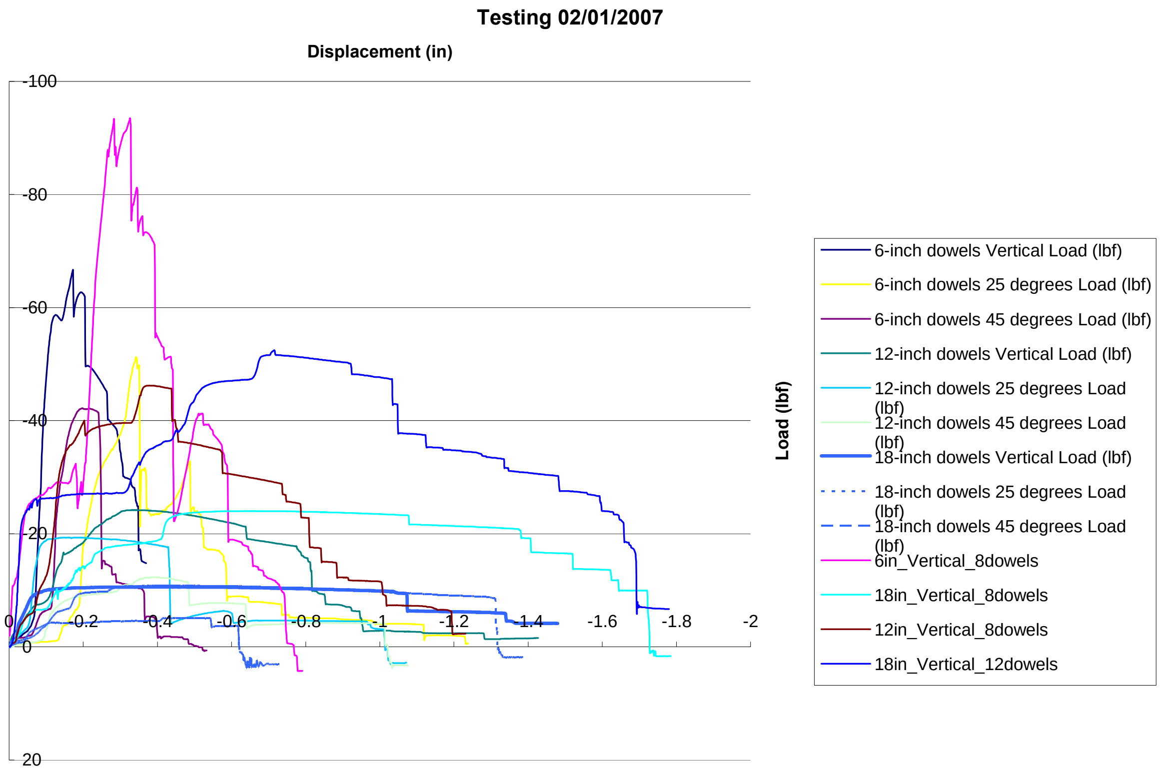


Figure 10 Load versus displacement graph for February 1, 2007, testing

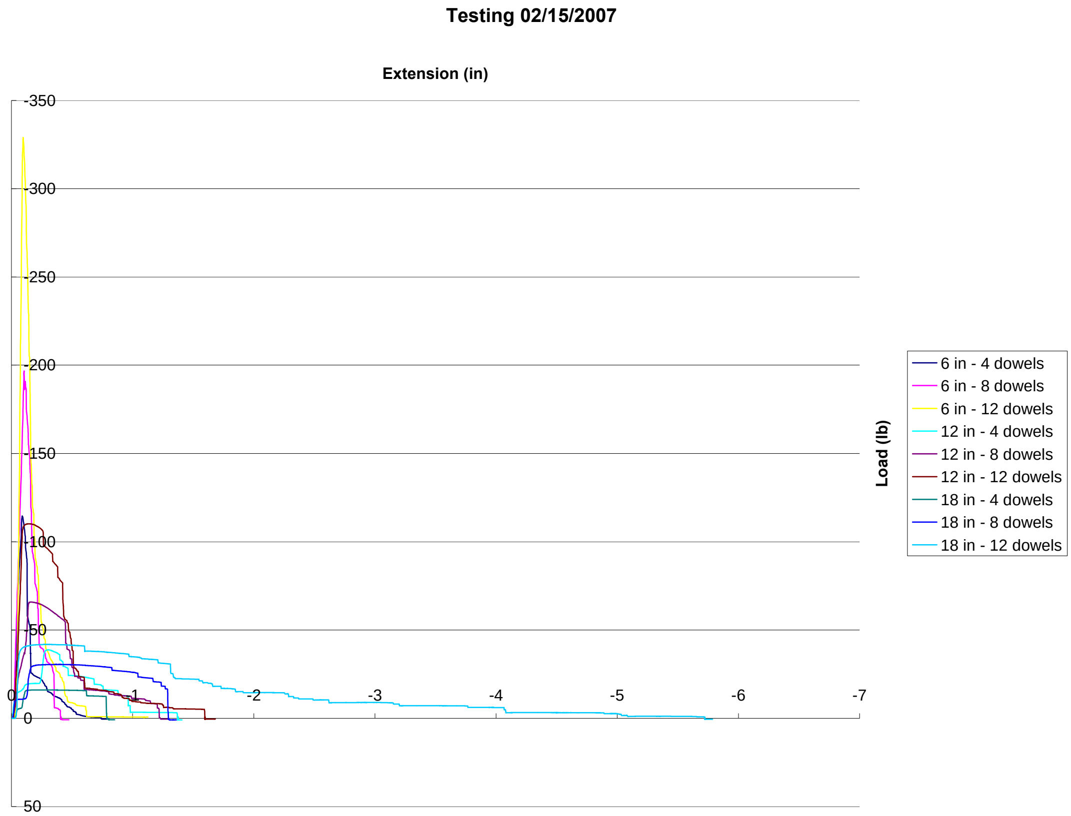


Figure 11 Load versus displacement graph for February 15, 2007, testing

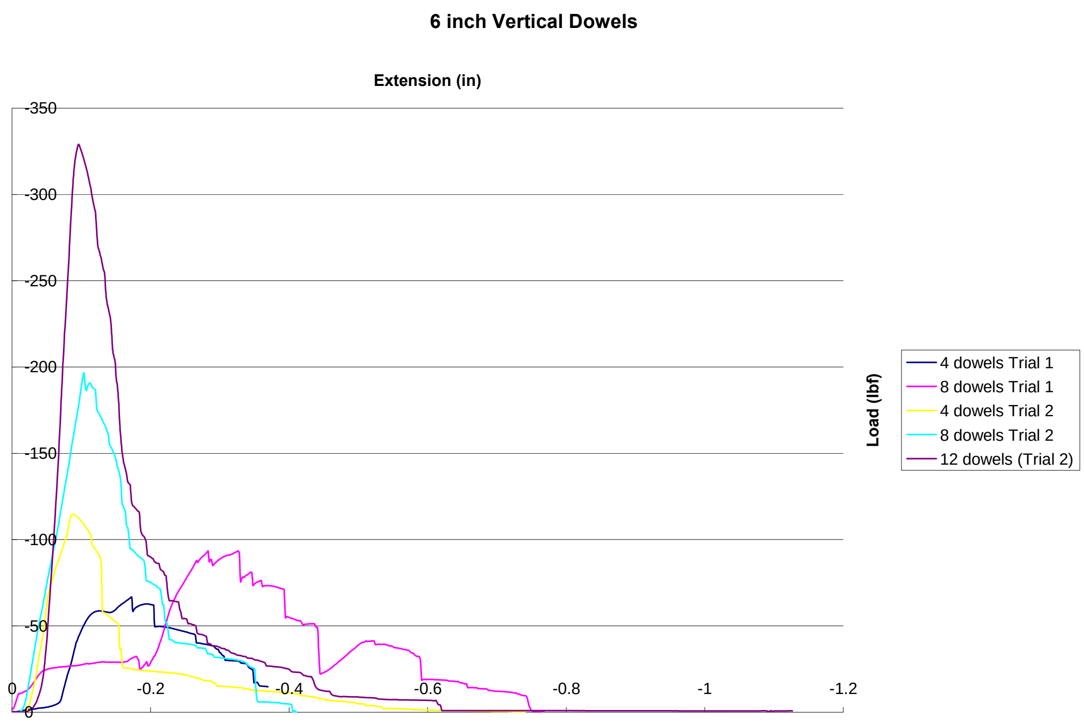


Figure 12 Load versus displacement graph for 6" vertical wooden dowels

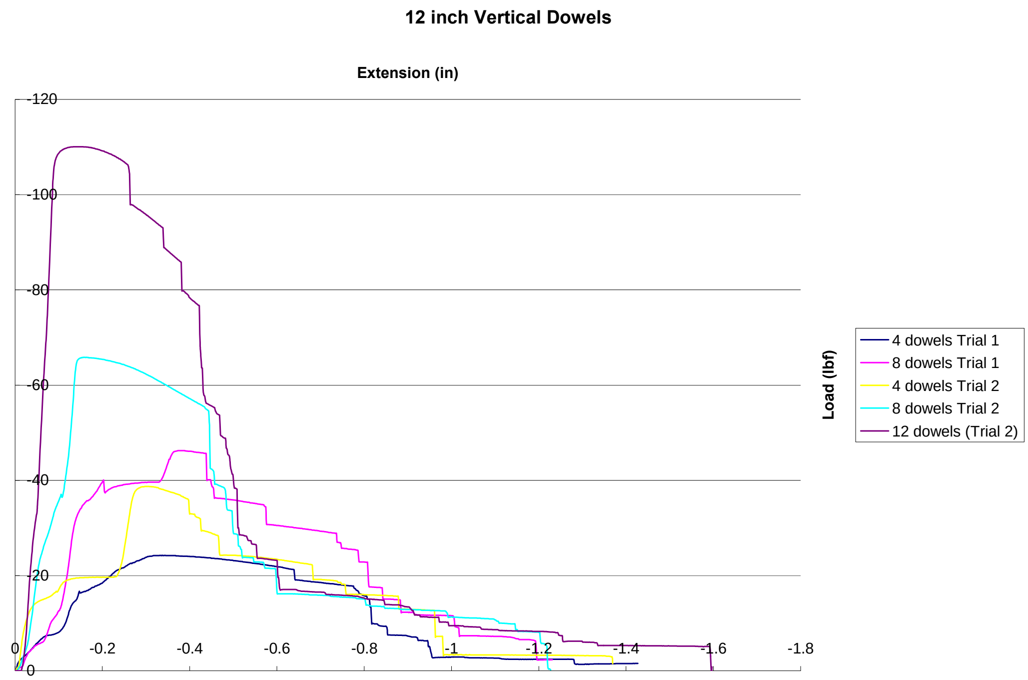


Figure 13 Load versus displacement graph for 12" vertical wooden dowels

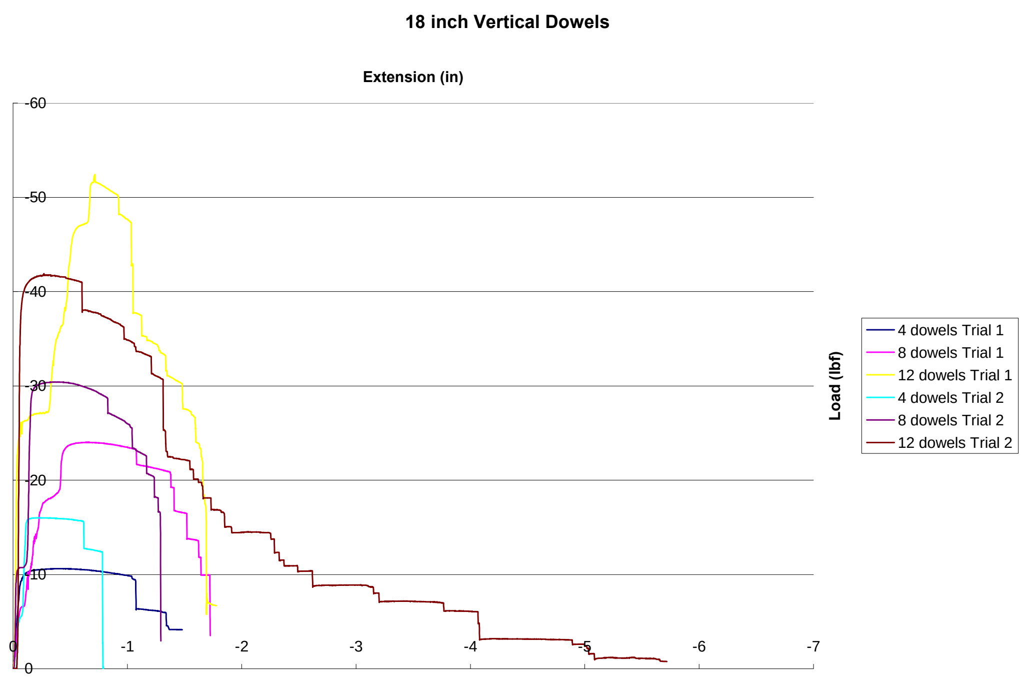


Figure 14 Load versus displacement graph for 18" vertical wooden dowels

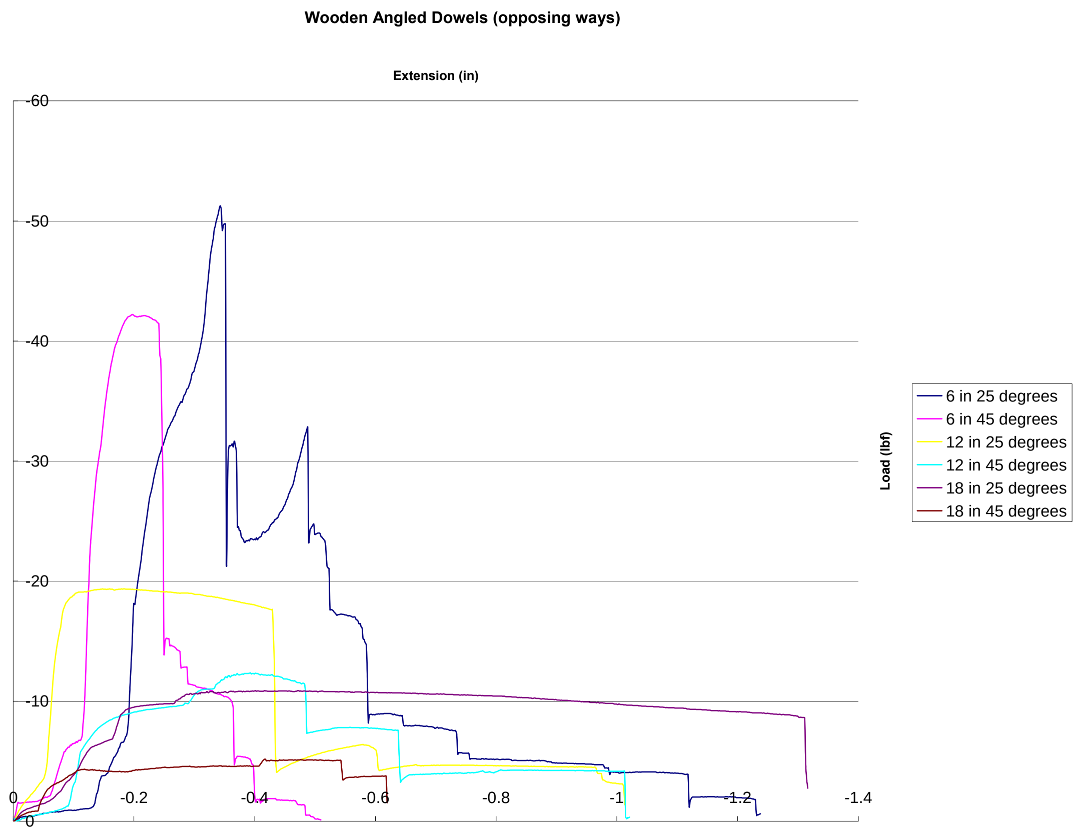


Figure 15 Load versus displacement graph for angled wooden dowels (in opposing directions)

VERTICAL STEEL SPOKES

An 8 1/2" prototype was made of four steel spokes from a bicycle tire on March 1, 2007, and the model was loaded twice. The load peaked at 80 pounds after about 0.15 inches. After this, the load decreased exponentially towards what seemed to be a limiting value of about 30 pounds. The steel stayed deformed, but did show elastic behavior when the load was removed. It was loaded again, and the load increased exponentially to, again, what seemed to be a limiting value of approximately 30 pounds. After being loaded once, the prototype basically acts as a spring that can hold up to 30 pounds. This behavior could be exploited in a railing application as an initial impact that severely deforms the railing would still be capable of resisting smaller impacts until repairs are made. The next pages contain the graphs of the load versus the displacement for each loading.

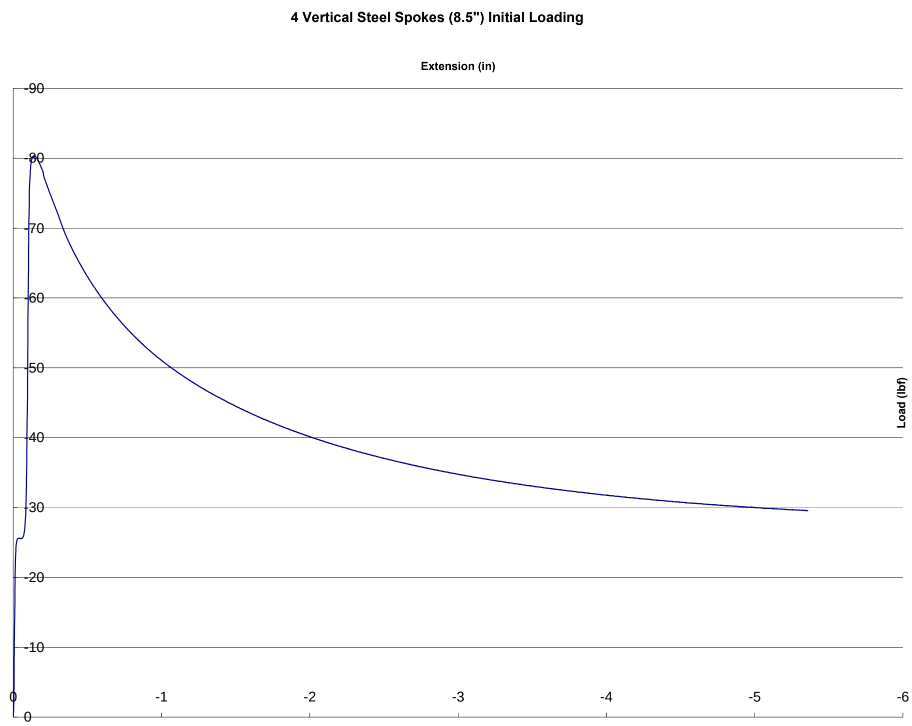


Figure 16 Load versus displacement graph for initial loading for vertical steel spokes

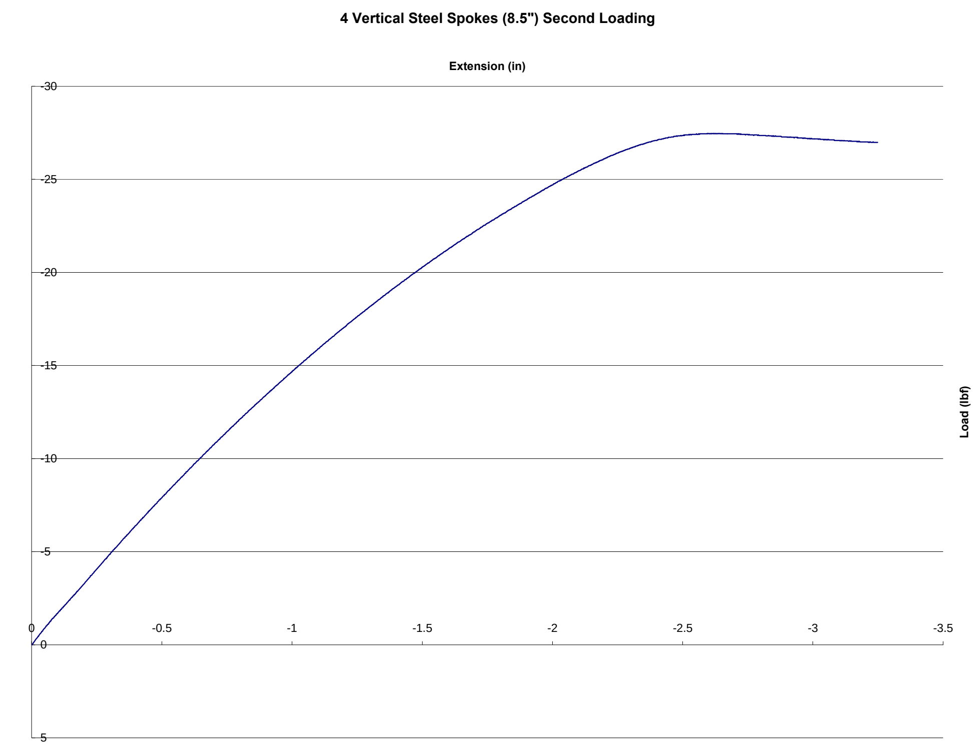


Figure 17 Load versus displacement graph for second loading for vertical steel spokes

VERTICAL 3/16″ WOODEN DOWELS

On March 1, 2007, two tests were performed that would be classified under this prototype. The first test was 4 – 18" dowels, and the second test was 12 – 18" dowels. Both tests had similar energy to yield (6.565 and 6.946 lb.-in., respectively) and displacements (1.44 and 1.69 inches, respectively), but the test with four dowels took a much higher force. The maximum force for the 12 dowels was 155.65 pounds, while the maximum force for the 4 dowels was 80.21 pounds, which is expected as more dowels are added. When compared to the same test with 1/8" diameter dowels, the maximum displacement stays similar while the maximum force is around four times greater. Figures 18 and 19 show the graphs produced by these two tests.

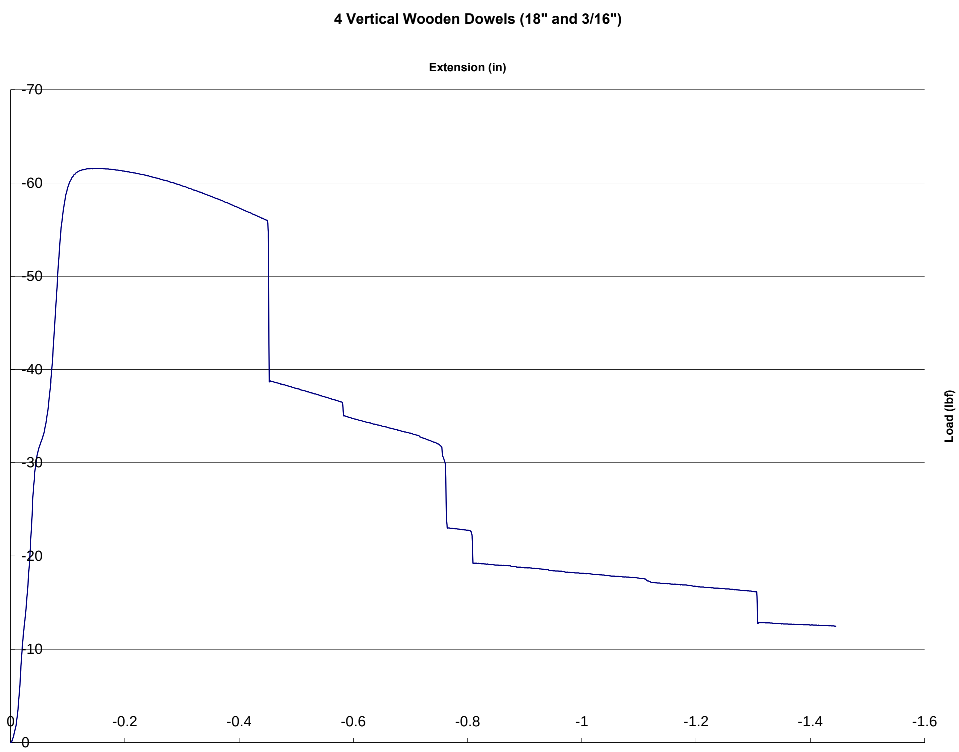


Figure 18 Load versus displacement graph for four vertical 18" dowels (3/16" diameter)

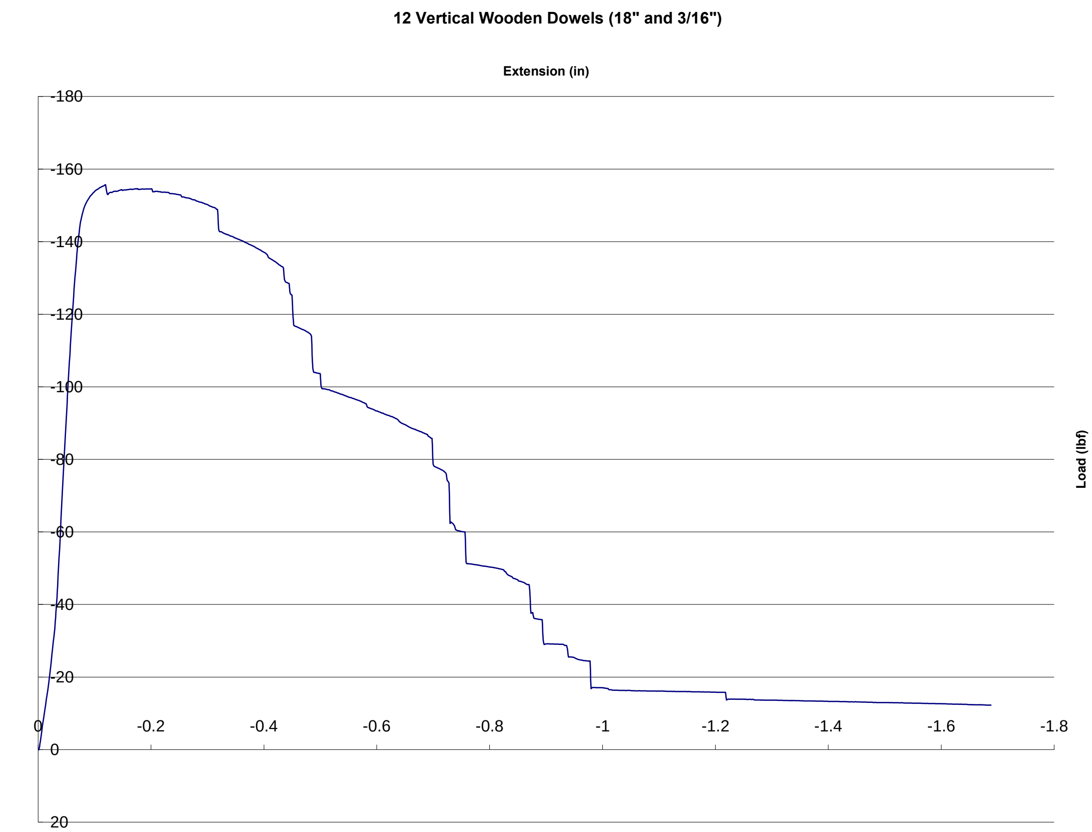


Figure 19 Load versus displacement graph for twelve vertical 18" dowels (3/16" diameter)

VERTICAL BAMBOO DOWELS

On April 26, 2007, an eight-dowel model was tested with 8" bamboo dowels. These dowels had an average diameter of 0.2 inches. This test was able to take 387 pounds of force, and deformed by 1.791 inches. This deformation was approximately 50% greater than the comparable wooden vertical dowels test, and took well over twice as much load. Although some of the dowels fractured completely, others broke by the fibers splitting. This model retained its shape better than any of the comparable wooden models. A picture of the failed model and a graph of the results are shown in Figures 20 and 21.

Figure 20 Vertical bamboo model after testing

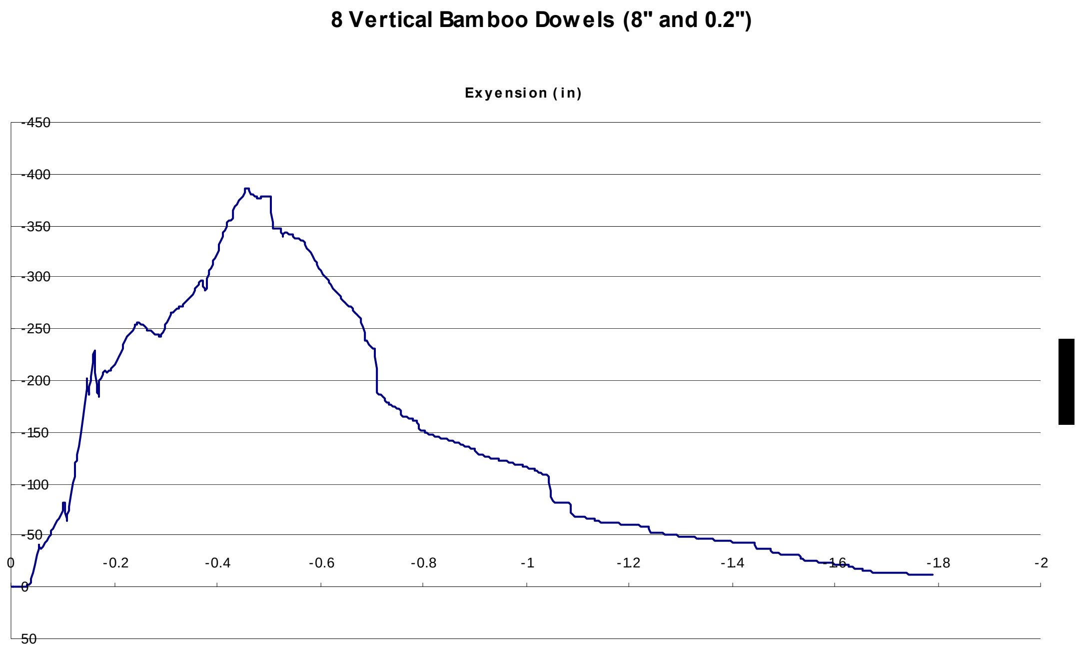


Figure 21 Load versus displacement graph for the vertical bamboo test

DOWELS ANGLED IN THE SAME DIRECTION

On March 1, 2007, two models with dowels angled in the same direction were tested. Each had 16, 4" dowels with a diameter of 1/8 inch, and one had an angle of 25 degrees while the other had an angle of 45°. Both angles yield close to 12 pounds, but the model with 45 degrees took nearly twice as much total load, while the model with 25 degrees took almost twice as much deformation. When compared to the vertical tests, these angled prototypes contain more energy per inch, and their deformation shape is predictable, while the vertical models deform randomly. These models would fail at a mixture of local cracking and after buckling.

On March 7, 2007, three more models were tested that were angled the same way. All three models had 45° angles and 8" long dowels. The difference in this test was different materials. The first model had dowel diameters of 3/16 inches. This model yielded at 11.72 pounds-feet, ruptured at 48.03 pounds-feet, withstood 85.2 pounds, and had 1.85 inches of deformation. These models also contained about twice as much energy per inch as the 1/8" dowels. Figure 22 shows this wooden test.

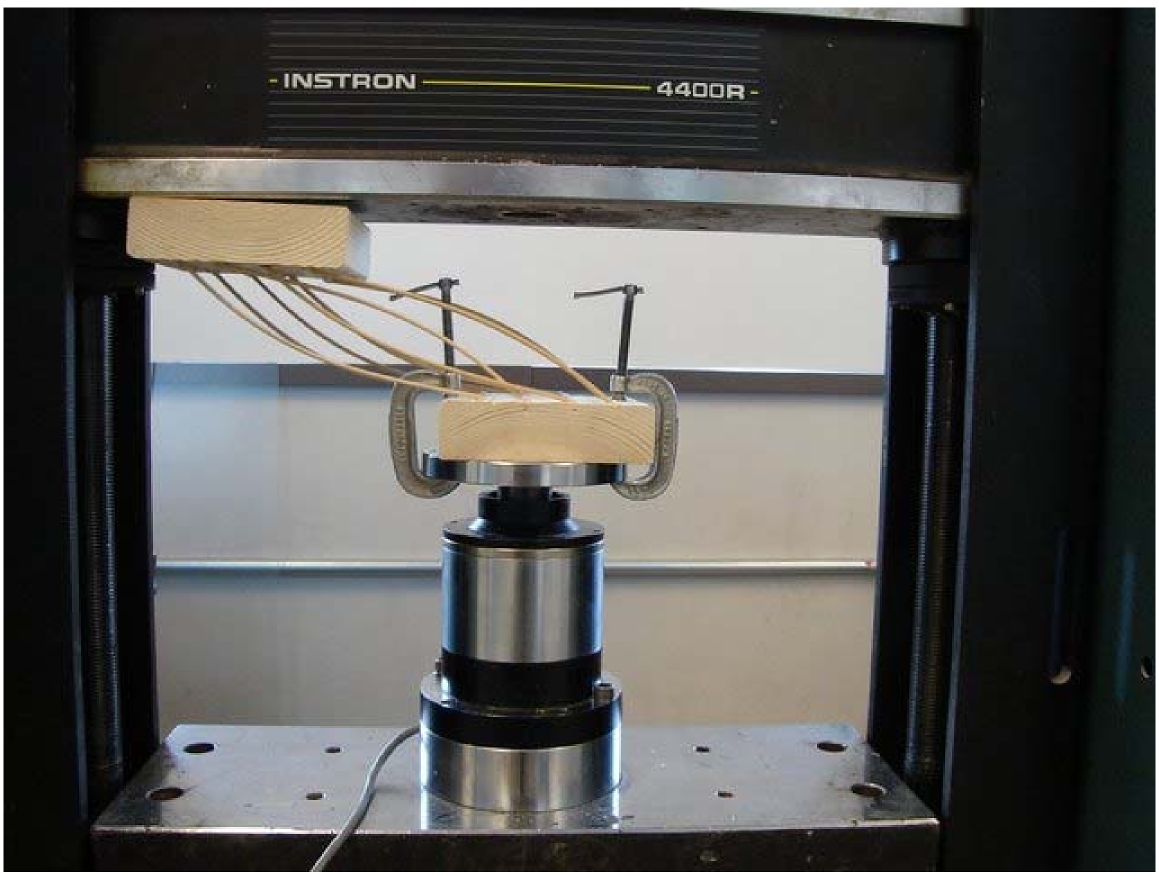


Figure 22 The wooden model during testing

The second test was eight steel bicycle spokes, which yielded at 39.37 pound-inches and reached maximum energy at 90.06 pound-inches. Compared to the previous test, this model took more deformation (6.47 inches) but less load (20.13 pounds). However, both tests had nearly the same energy per inch (1.49 lb.-in./in.). The model never failed, and when the load was removed, it recovered about half of its original height. Figure 23 shows the maximum deflection of the steel test.

Figure 23 The steel model during testing

The final test that day used a plastic dowel, which is normally used in street sweeping. This test used 24 dowels: 8 bundles of 3 dowels. This test yielded at 1.732 pound-inches, reached its maximum deformation of 6.31 inches at 9.578 pound-inches, and took a maximum load of 6.31 pounds. The energy per inch was, on average, 30 times less than the other two materials, and it took much less load. However, the deformation for this material was as large as it could physically be in the model, and the loading did not phase it. It returned to its original shape after loading, and as it was loaded a second time, it reached the same maximum load and deformation, indicating that it is highly elastic even under very large deformations. Figure 24 shows the maximum deflection of the plastic test.

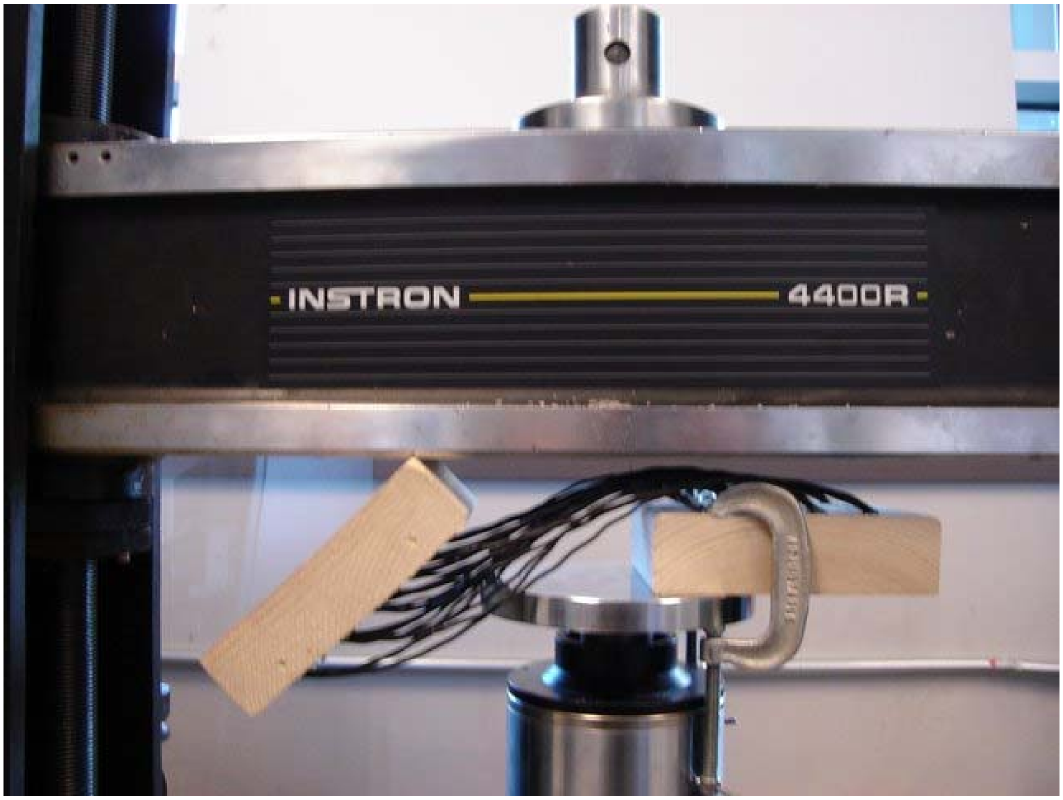


Figure 24 The plastic model during testing

On March 27, 2007, additional models of wooden dowels of 3/16" diameter all angled in the same direction (45 degrees) were tested. The number of dowels was increased to 8, 16, 32, and 64 dowels to investigate results at higher yield strengths. For the 16-dowel model, there was an increase in deformation but a slight decrease in energy to yield when compared with the 8-dowel model. Also, deformation and energy to yield per inch decreased when the number of dowels was increased to 32 and 64. This may be due to the limited spacing that was available for the dowels.

Even though the total load increased as dowels increased, the load per dowel decreased as the number of dowels increased. In the 8-dowel test, each dowel took about 5 pounds of force, while in the 64-dowel test, each dowel took 3.7 pounds of force. This shows that the force per dowel as dowels are added is not a linear relationship.

On April 10, 2007, and April 26, 2007, bamboo dowels were tested in the same configuration. Eight 8" bamboo dowels were tested on April 10, and 16 8" dowels were tested on April 26. Both of these models were angled at 45°, but the diameters did differ. The 8-dowel model had an average of 0.211" in diameter, while the 16-dowel model had an average diameter of 0.28". The 8-dowel model resisted almost 60 pounds of force and deformed nearly 6.5 inches. The 16-dowel model allowed almost 230 pounds of force and 6.44 inches of deformation. When compared to the wooden tests, the graph of load versus displacement from the 16-dowel test is similar to that of the 64-dowel wooden test, which can be seen in Figure 26. So far, these tests have taken the most total energy per inch with a value of 3.83 and 6.44 inch-pounds, respectively. The second test required six times the energy than the same test using wooden dowels. Also, the model did not completely fail like the wooden models. Even where major local deformation occurred, the bamboo fibers remained intact and the model rebounded to at least half the original height. If the nodes of the bamboo were placed near the ends, it would completely fracture there.

However, if they were placed in the center, they would not break. And the member would still retain some capacity after loading. Figure 25 shows the 8-dowel model during testing.

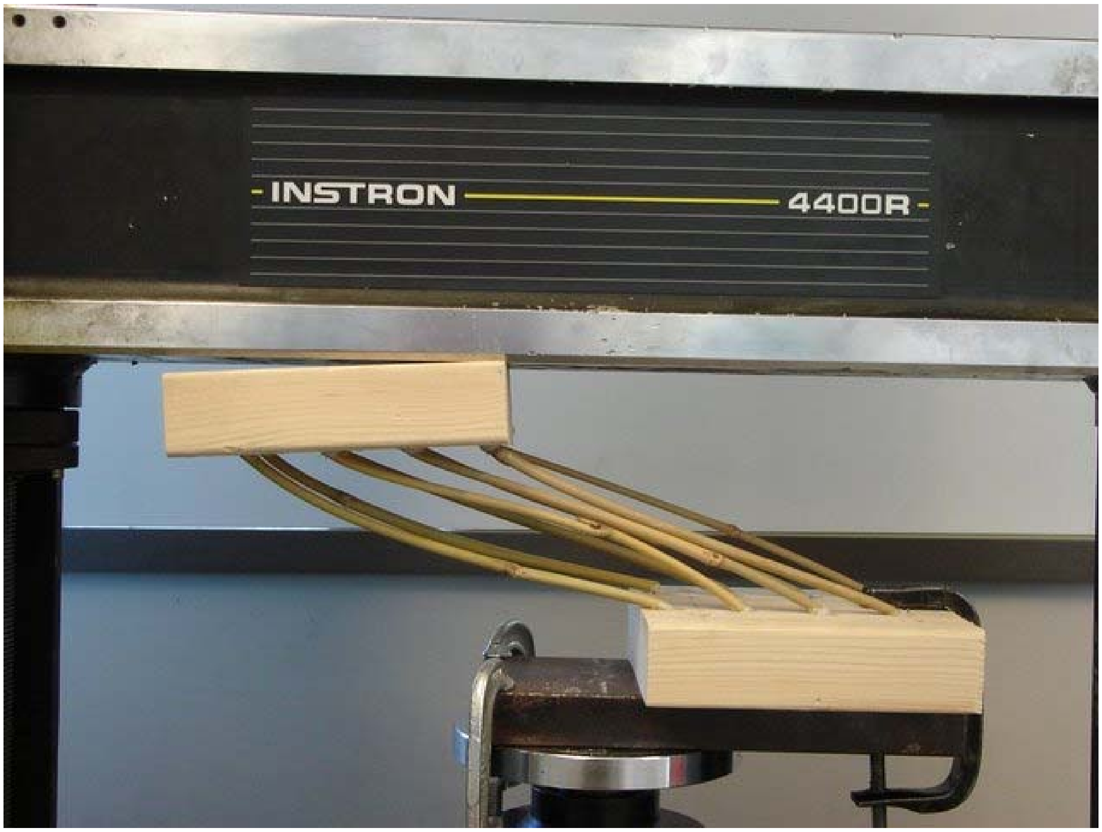


Figure 25 The bamboo model during testing

Table 4 shows the prominent information for dowels angled in the same direction. Figure 26 contains a graph of all the tests.

Table 4 Results for Dowels Angled the Same Direction

	Energy to yield (lbf-in)	Energy to Rupture (lbf-in)	Max Force (lbf)	Max Deformation (in)
16-4" Wooden Dowels 25º (1/8")	11.71	48.03	85.20784	1.85304
16-4" Wooden Dowels 45º (1/8")	12.11	33.99	47.91935	2.758
8-8" Wooden Dowels 45º (3/16")	38.46524	88.4525	37.4764	4.2688
8-8" Steel Dowels 45º	39.367	90.063	20.1342	6.4771
24-8" Plastic Dowels 45º	1.732564	9.578	3.51677	6.31253
8-8" Wooden Dowels 45º (1/8")	6.6059	33.9439	12.993	4.8759
8-8" Wooden Dowels 45º (3/16")	42.8824	78.2068	38.6033	4.2342
16-8" Wooden Dowels 45º (3/16")	84.218	260.87	77.2871	6.55
32-8" Wooden Dowels 45º (3/16")	127.841	343.202	109.637	6.0843
64-8" Wooden Dowels 45º (3/16")	270.954	665.424	234.094	4.99525
8-8” Bamboo Dowels 45 º (0.211”)	69.964	244.63	59.5166	6.3442
16-8” Bamboo Dowels 45 º (0.28”)	331.877	824.848	229.664	6.44075

	Energy to yield (lbf-in/in)	Energy to Rupture (lbf-in/in)
16-4" Wooden Dowels 25º (1/8")	0.18296875	0.75046875
16-4" Wooden Dowels 45º (1/8")	0.18921875	0.53109375
8-8" Wooden Dowels 45º (3/16")	0.601019375	1.382070313
8-8" Steel Dowels 45º	0.615109375	1.407234375
24-8" Plastic Dowels 45º	0.009023771	0.049885417
8-8" Wooden Dowels 45º (1/8")	0.103217188	0.530373438
8-8" Wooden Dowels 45º (3/16")	0.6700375	1.22198125
16-8" Wooden Dowels 45º (3/16")	0.657953125	2.038046875
32-8" Wooden Dowels 45º (3/16")	0.499378906	1.340632813
64-8" Wooden Dowels 45º (3/16")	0.529207031	1.29965625
8-8” Bamboo Dowels 45 º (0.211”)	1.09290625	3.822265625
16-8” Bamboo Dowels 45 º (0.28”)	2.592789063	6.444125

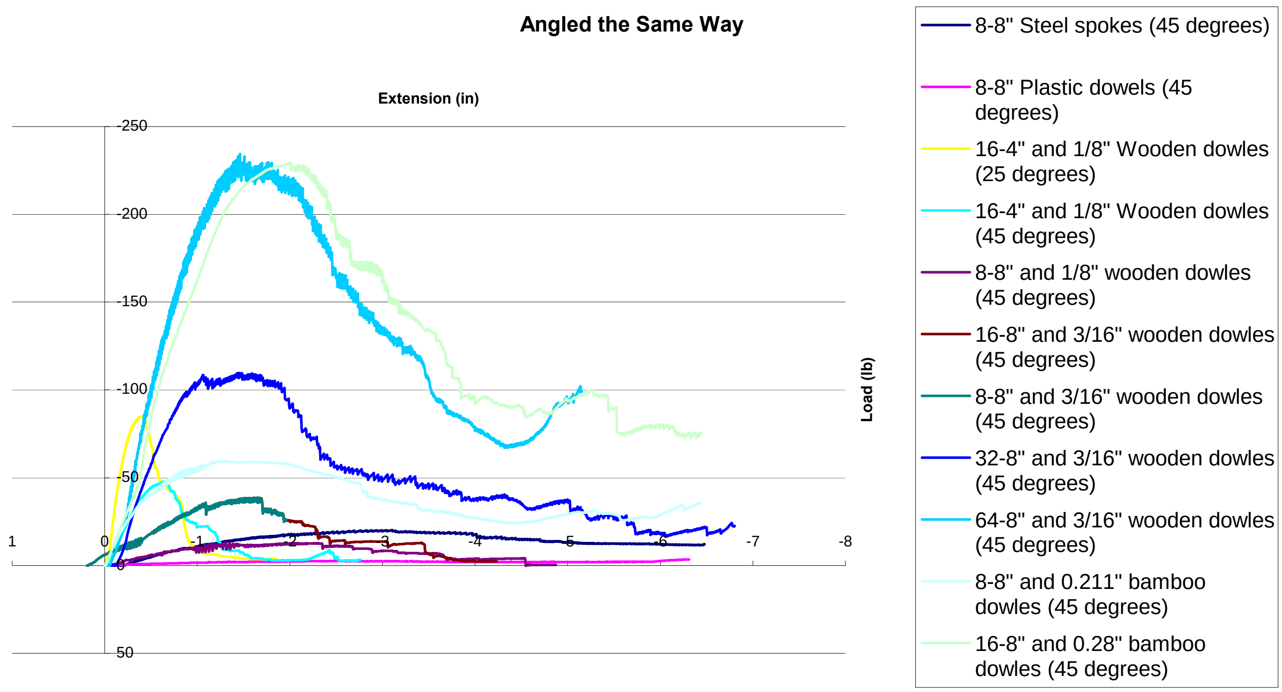


Figure 26 Load versus displacement graph for dowels angled the same way

BRUSH TEST

On March 8, 2007, an 18" cubed box was filled with random brush and sticks. The brush was loaded until the lid on the box began to break. The brush took 880 pounds of load, 4075 pound-inches of energy, and 8.698 inches of deformation. The energy per inch during this test ended up being 12.58 lb.-in./in. These numbers are smaller than they could have been because the test had to be stopped when the lid began breaking. Figures 27-29 show the brush before, during, and after the test. The graphs (Figures 30 and 31) for this test follow. Because the test lasted so long the data had to be split between two graphs.

Figure 27 The brush before testing

Figure 28 The brush during testing

Figure 29 The brush after testing

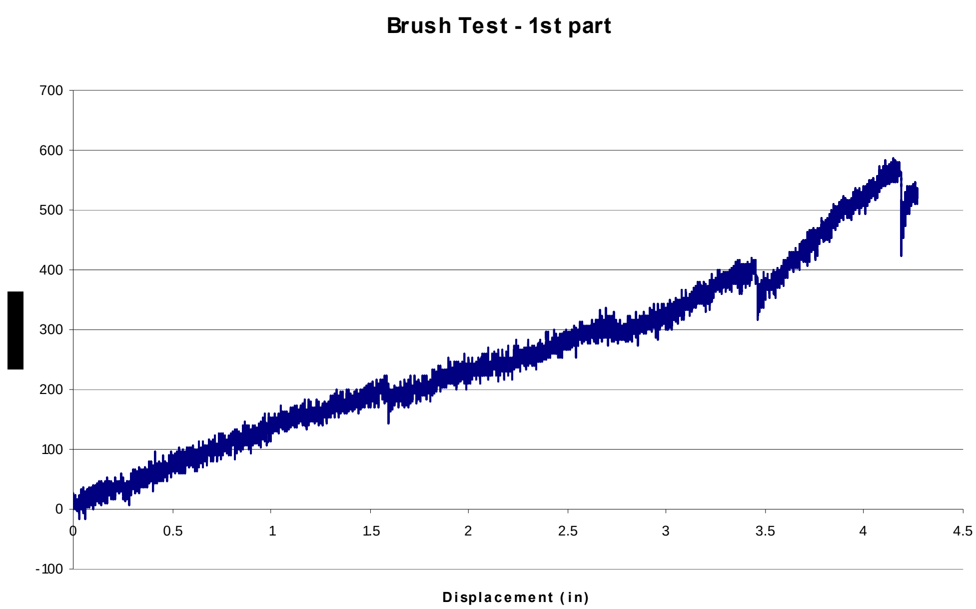


Figure 30 Load versus displacement graph for the first portion of the brush test

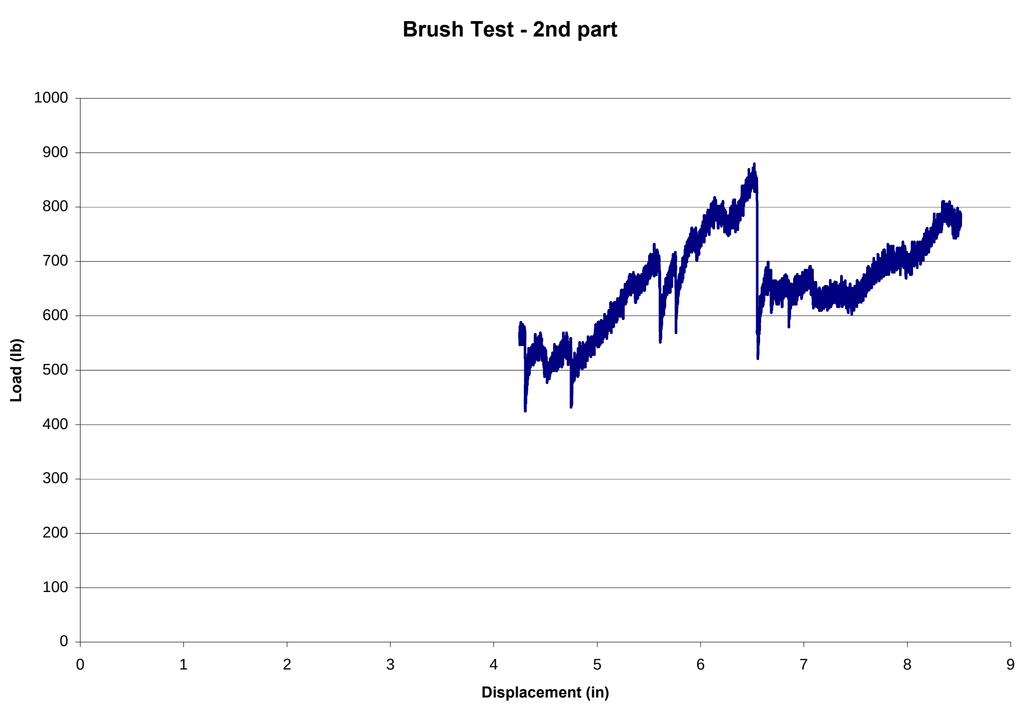


Figure 31. Load versus displacement graph for the final portion of the brush test

CYCLICAL TESTING

On March 27, 2007, a cyclical test was conducted on a wooden model of 8 dowels of 3/16" diameter angled in the same direction (45 degrees). The Instron testing machine was set to compress the model by one inch and then return to origin for each cycle. A test of 10 cycles was conducted. The load and extension were nearly the same for every cycle. The extension did not change, and the load only dropped from 32 to 27 pounds. A plot of the deformation versus load is provided from the test. In the plot, a kink or a drop in the load is present. This kink is due to the friction between the model and testing machine.

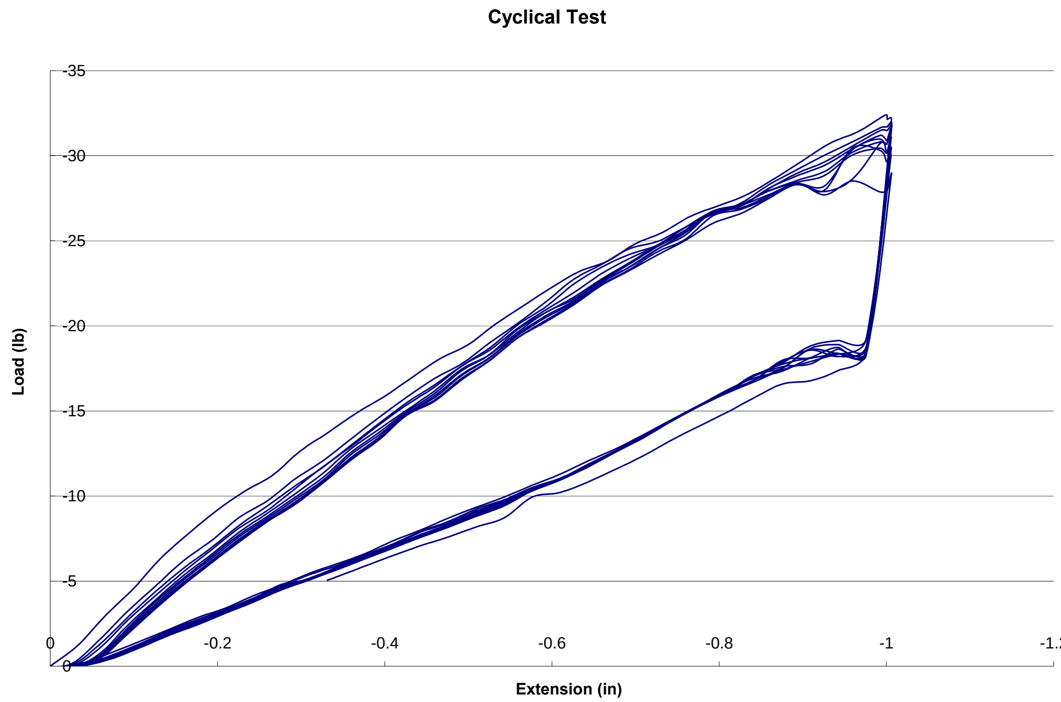


Figure 32 Load versus displacement graph for the wooden cyclical testing

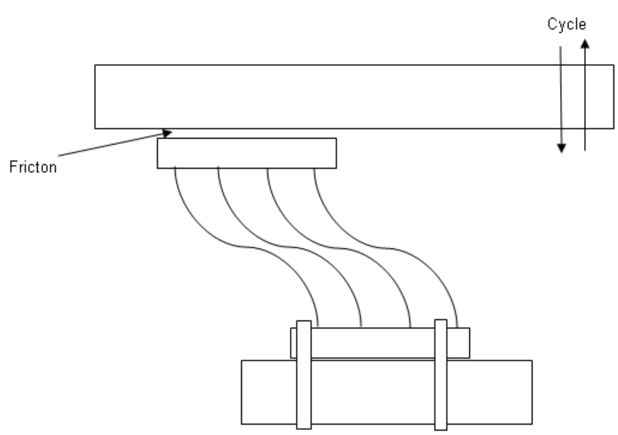


Figure 33 The friction between model and Instron testing machine

On April 26, 2007, the same cyclical test was performed on an 8-dowel bamboo model. This test also contained 8” long dowels angled at 45 degrees. In this test, there was a permanent deformation of approximately 0.3 inches after the first loading. This was due to cracking in the fibers from the initial load and rounding of the supports in the 2x6. However, after the first cycle, the degradation settles down. During the first loading, the load went to 140 pounds; on the second loading, the maximum load was 125 pounds. By the end of the tenth cycle, the maximum load was about 110 pounds. Although there was this initial deformation, the bamboo was able to take much more load than the wooden model. The results of this cyclical test are shown in Figure 34.

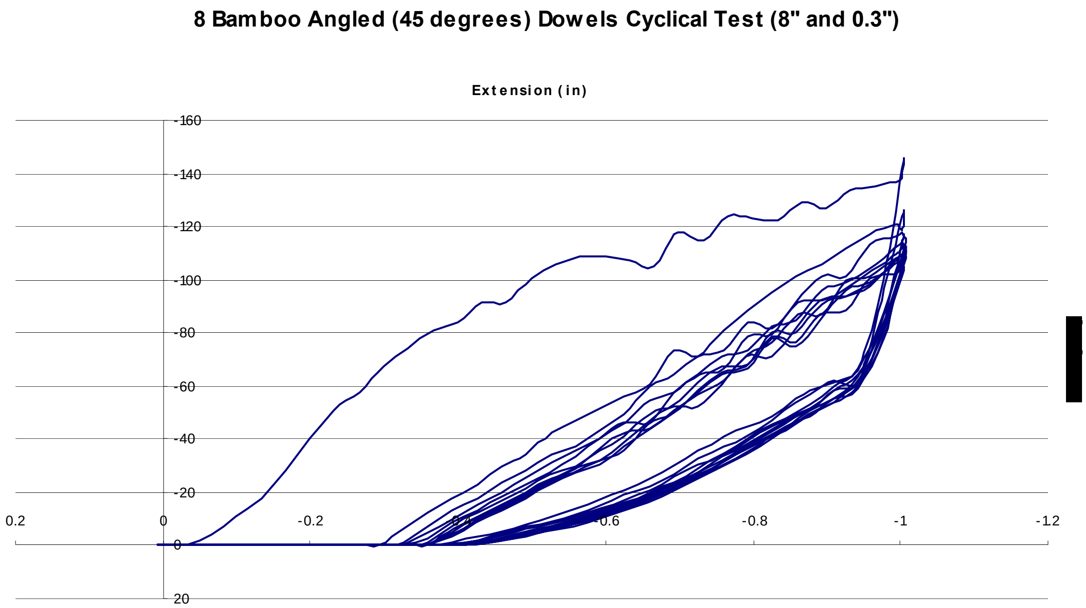


Figure 34 Load versus displacement graph of the bamboo cyclical test

DROP TEST

Once the cyclical testing was done, an impact test was performed on the wooden model. A 10 lb. weight was dropped from 6 inches above onto the surface. Unfortunately, the model failed as soon as the weight hit it. In a slow loaded test, the model was able to take over 30 pounds, but under impact, it was not able to even take 10. Data collection was not fast enough to capture the load deflection data with enough accuracy to properly analyze this test.

PLATES ANGLED IN THE SAME DIRECTION

On April 10, 2007, a model was tested using wooden plates instead of wooden dowels. Four plates were used, each 8" long, 6" wide, and 1/8" thick. During testing, the plates ended up cracking the 2x6 piece at the top and bottom before the plates failed. Also, there weren't many individual members to fail, and the plates cracked in places but never fractured entirely so the model remained relatively intact. The model took 521 pounds of force and deformed by 4.5 inches. The plates were able to hold a total energy per inch of 13.65 pound-inches, which is 12 times the value of the 64 wooden dowels model and triple the value from the bamboo testing. Because the support failed before the model, the plates could potentially hold more energy if they were anchored in a more secure base. Figure 35 shows a picture of the model at the end of testing and Figure 36 shows a graph of the results from the test.

Figure 35 The plate model at the end of testing

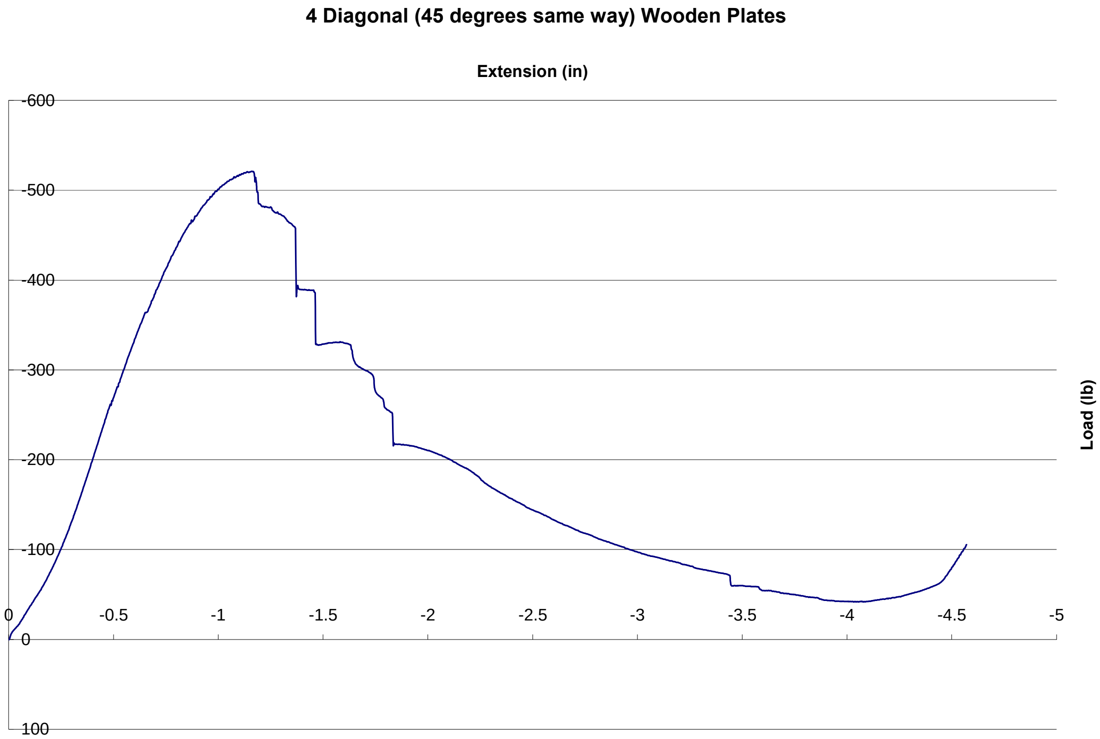


Figure 36 Load versus displacement graph for the wooden plate testing

TESTING SUMMARY

After all the testing performed over the past months, there were a few tests that stood out as superior. First, the prototypes that were angled 45 degrees seemed to be the best orientation. When compared to the vertical tests and the prototypes angled opposing ways, these prototypes contain more energy per inch, and their deformation shape is predictable, while the other models deform randomly**.** They would be easier to design a computer model for**,** and they can take more loads and deflections. The bamboo models did not fail completely and were able to partially rebound.

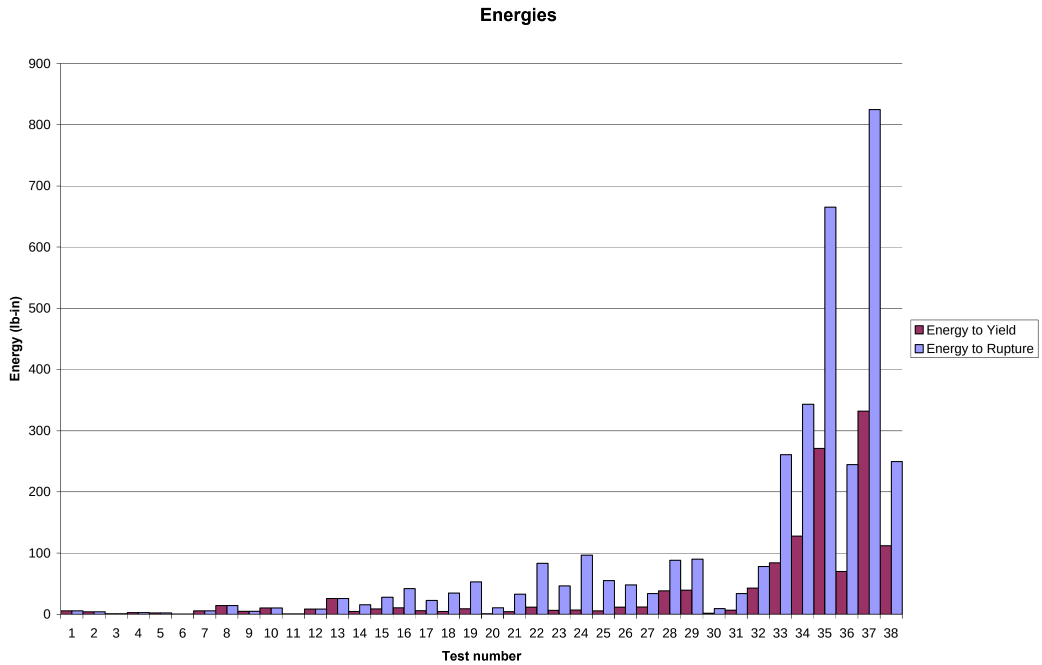
The bamboo seemed to be the superior material of all the ones considered in this report. The bamboo, on average, held 110 in.-lb./in.^{3}, while the wood that was angled 45 degrees held around 60 in.-lb./in.^{3}. This calculation of the energy per volume for bamboo was even conservative, because it assumed the bamboo is solid material, which is not true. The only other material that had more energy per volume was the steel which had on average 1000 in.-lb./in.^{3}. However, the steel does not match with the environmental concerns of this research. Wood and bamboo would not pose environmental problems if left broken, but the steel would.

Costs can also be taken into consideration to promote bamboo. The wooded dowels cost 10.5 to 12.25 cents per foot, while the bamboo only costs 7.5 cents per foot. The only disadvantage of bamboo is that it is not as straight as the wooden dowels, therefore, is not as assembled as easily. However, if mass production of these models is made, this concern will probably be eliminated. The one thing to be aware of in the assembly of bamboo models is to make sure the nodes are placed towards the center, not the ends; this will increase the model's load capacity.

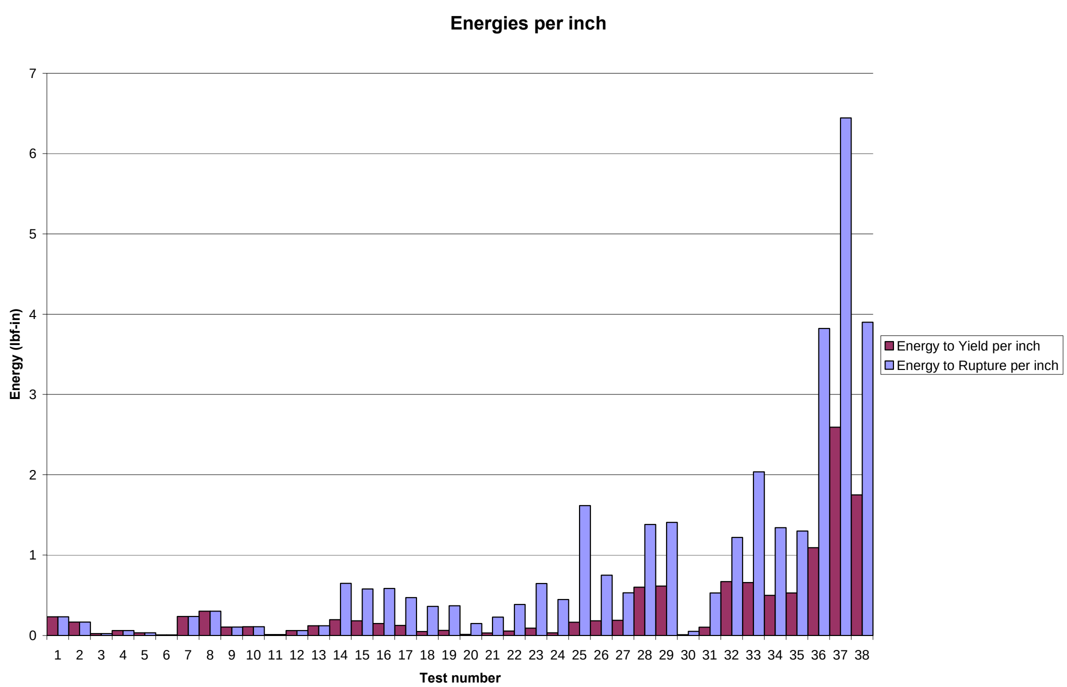
In conclusion, bamboo models angled at 45 degrees seemed to be the best solution found from this testing and analysis. The can take large deflections, can partially rebound, contain more energy per volume than wooden dowels, are environmental friendly, and are the cheapest material investigated. Appendix E contains the research performed on the properties, possibilities, and availabilities of bamboo. While steel did have many ideal properties, it does not fit in well with the environmental issues trying to be addressed, while bamboo does.

For future testing involving the use of bamboo in highway barriers, a statistical distribution of the physical properties of bamboo should be investigated. The American Bamboo Society (USDA) can be inquired for funding for this investigation. Due to the nature of car crashes, impact tests should be performed on similar models to represent a more realistic load rate that highway barriers would have to resist.

APPENDIX A: ENERGIES FOR ALL DOWEL TESTING

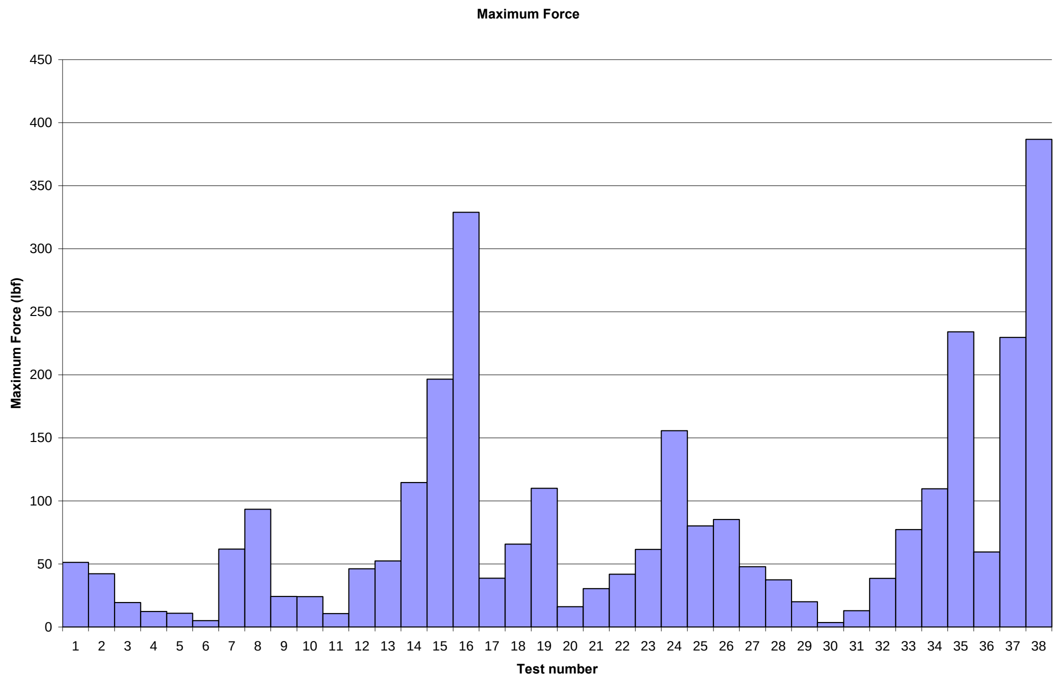


APPENDIX B: ENERGIES PER INCH FOR ALL DOWEL TESTING

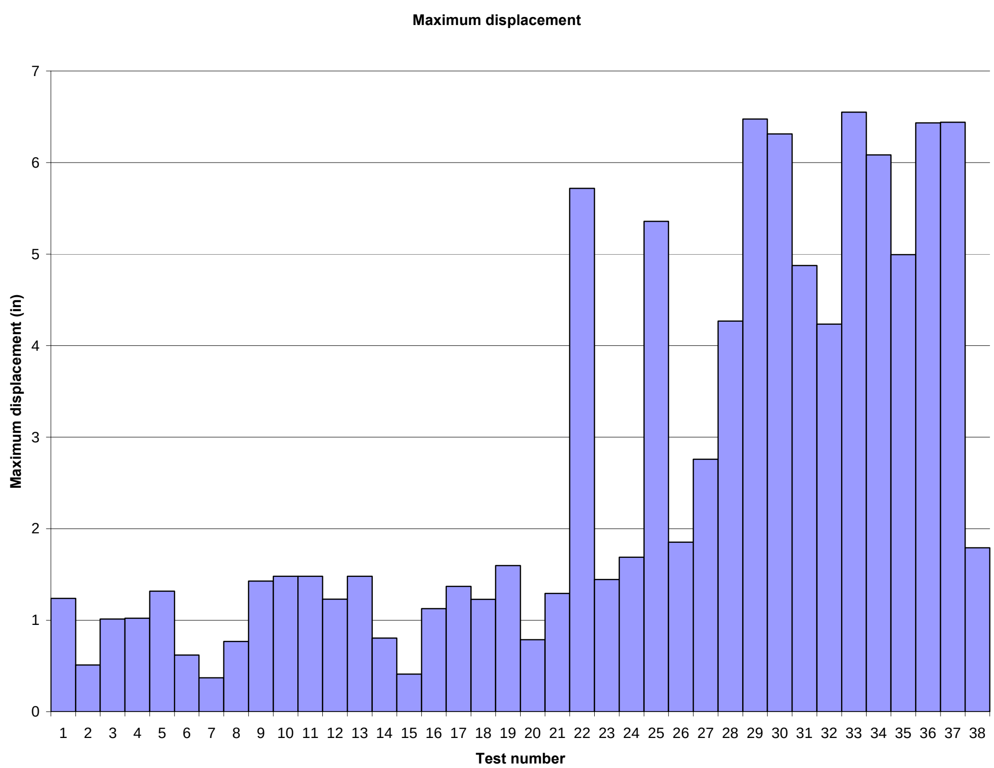


*Note: Appendix F contains a list of which tests correspond to these test numbers.

APPENDIX C: MAXIMUM LOADS FOR ALL DOWEL TESTING



APPENDIX D: MAXIMUM DISPLACEMENTS FOR ALL DOWEL TESTING



*Note: Appendix F contains a list of which tests correspond to these test numbers.

APPENDIX E: BAMBOO RESEARCH

Bamboo is a grass that grows much quicker than trees and can grow up to 150 feet in a few months. This material is known for its high strength to weight ratio and its flexibility, making it a promising structural material. There are over 1000 species worldwide, which are grown in many parts of the world, including the United States. To begin a discussion on bamboo, the physical characteristics need to be analyzed. The branches are known as culms and are attached with nodes. The fiber strength is significantly greater away from the nodes, and cracking is most likely to occur at the nodes.

The chemical components of the bamboo mainly include cellulose, hemicelluloses, and lignin. The lignin is the component that acts as glue for the fibers. This is the component that stores energy and responds to stresses. The fiber distribution in the bamboo is dense on the outer part of the bamboo and light in the center. This creates the mechanical properties of the bamboo, as the outer portion is much stronger, has a high Young's Modulus, and density greater than the inner portion. Because of this, the inner material will fail before the outer material, which was seen in this testing. This inner material is sometimes removed via chemical processing to hollow out the bamboo.

There is also a polylamellate wall structure that is not found in wooden dowels. The structure means that broad and narrow layers alternate and are located at different orientations. In the narrow portions, the orientation is mainly transverse, and it contains more of the lignin. Because of this intricate structure and its higher percentage of fibers and lignin than other materials, bamboo is known for its high tensile, flexural, and impact strengths along the fibers. In comparison, the material has minimum strength if loaded perpendicular to the fibers.

When compared to other building materials, its compressive strength is much higher than that of wood or concrete, but it falls second to the strength of steel. This material has a regeneration capacity per year of 80 to 300% and a time to maturity of 7 to 9 years. This is far superior when compared to wood, which has a regeneration capacity of 3 to 6% and a time of maturity of 60 to 80 years.

As for design codes, the ES Report done by ICC Evaluation Services states that the modulus of elasticity is 2,300 ksi, which is nearly identical to the value found in the tensile testing performed as part of this analysis. This report also states that the allowable bending strength is 2,940 psi, the allowable compressive strength is 1,140 psi, the allowable shear strength is 205 psi, and the allowable tensile strength is 2,170 psi.

However, the strength of the bamboo depends on many different aspects. These aspects include the species, age, speed of loads, humidity, position of the culms and nodes, size, and length of loading. In compressive testing recorded in *Bamboo Research in Asia*, the major factors affecting the strength are the moisture content and the position on the nodes. As moisture increased, the strength decreased, and the bamboo was stronger at the top of the culm. According to the same research, the length of the bamboo and the specifications of the node do not have any influence.

In the United States, the bamboo grown is much smaller than other parts of the world. It can grow up to 15 feet and one inch in diameter and has good availability. These varieties do not have common uses, and there is a need to find applications for this smaller diameter bamboo. These roadway barriers would be a perfect example of possible projects for this shorter, thinner bamboo. Currently, bamboo in the United States is being grown in Oregon, Washington, Louisiana, Alabama, and Georgia, although only a few thousand poles are currently being grown each year. Research is also being done in the San Francisco Bay area, as it contains a climate ideal for tropical and temperate species of bamboo.

Typical uses so far include larger scale housing, including walls and flooring, although it can be used in most aspects of a building. The majority of these large scale projects are seen in South America and Asia because the bamboo grown in the United States seems to be too small for such large projects.

The longevity of bamboo depends on many different aspects. Bamboo will disintegrate quicker in a humid climate, and can last approximately 5 years without treatments. However, in a dry climate, bamboo has been known to last almost 90 years. This bamboo was a matured, stronger species, so this time length could not be considered average. Smaller, less mature bamboo in a dry climate such as Colorado could probably last close to 20 or 30 years.

In conclusion, bamboo as a structural material is still a relatively un-researched and unregulated option when compared to other structural materials like steel, wood, or concrete. However, it does contain many ideal characteristics, including high strengths and flexibility, due to its unique physical characteristics. Plus, the market in the United States seems primarily filled with thinner bamboo that needs a practical application like highway barriers.

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