



Assessment of Fiber Reinforced Composite Wheels for the **MAGICWHEELS™ 2-Gear Manual Wheelchair Drive**



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FINDINGS

INTRODUCTION

- Up to 80% of today's manual wheelchair users suffer from shoulder pain (1,2)
- **MAGICWHEELS** 2-gear drive has been shown to reduced Shoulder Pain) by over 55% (3)
- 2-gear wheelchair necessitates a transmission hub
- Spoke wheels leave insufficient clearance for new hub
- New composite wheel built to allow space for hub
- New wheel design must be tested for equivalency with traditional spoke wheels
- The purpose of this study is to investigate the feasibility of a dish shaped composite wheel for the new **MAGICWHEELS** 2-gear manual wheelchair wheel (see Figure 1).

MAGICWHEELS Features

- 2:1 gearing for climbing
- Automatic hill-holding with override
- Assisted dynamic braking
- 1:1 gearing with no friction for flat terrain
- Easy to shift
- Quick release axle, easy upgrades
- Under 9.5 lb added weight to wheelchair
- Little to no added width



Figure 1: Subject using **MAGICWHEELS** 2-gear wheels

METHODS

- Test Stiffness and Strength of Composite Wheels vs. Standard Quickie® 24" Spoke Wheel
 - 4 loading conditions to represent stresses induced in wheelchair wheel with 2 gear drive
 - Axial, Radial, Bending and Torsional stresses applied with custom designed fixtures
 - Wheels tested to at least twice maximum design load
 - Additional testing for durability and reliability
- Protocol:
 - Load and displacement controlled with computerized Instron test frame
 - Wheels load and unloaded minimum of three cycles
 - In-situ visual inspection during testing
 - Tested both glass fiber and carbon fiber reinforced composite wheels

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MAGICWHEELS™ is a trademark of Magic Wheels, Inc., Seattle, WA for their 2-gear manual wheelchair wheel.

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- Axial Loading
 - Composite wheel more flexible than spoked
- Radial Loading
 - Composite wheel more rigid then spoked
- Bending Loading
 - Composite wheel too flexible
 - Redesigned wheel to double stiffness
- Torsional Loading
 - Composite wheels stiff
 - Spoke not designed for torsion

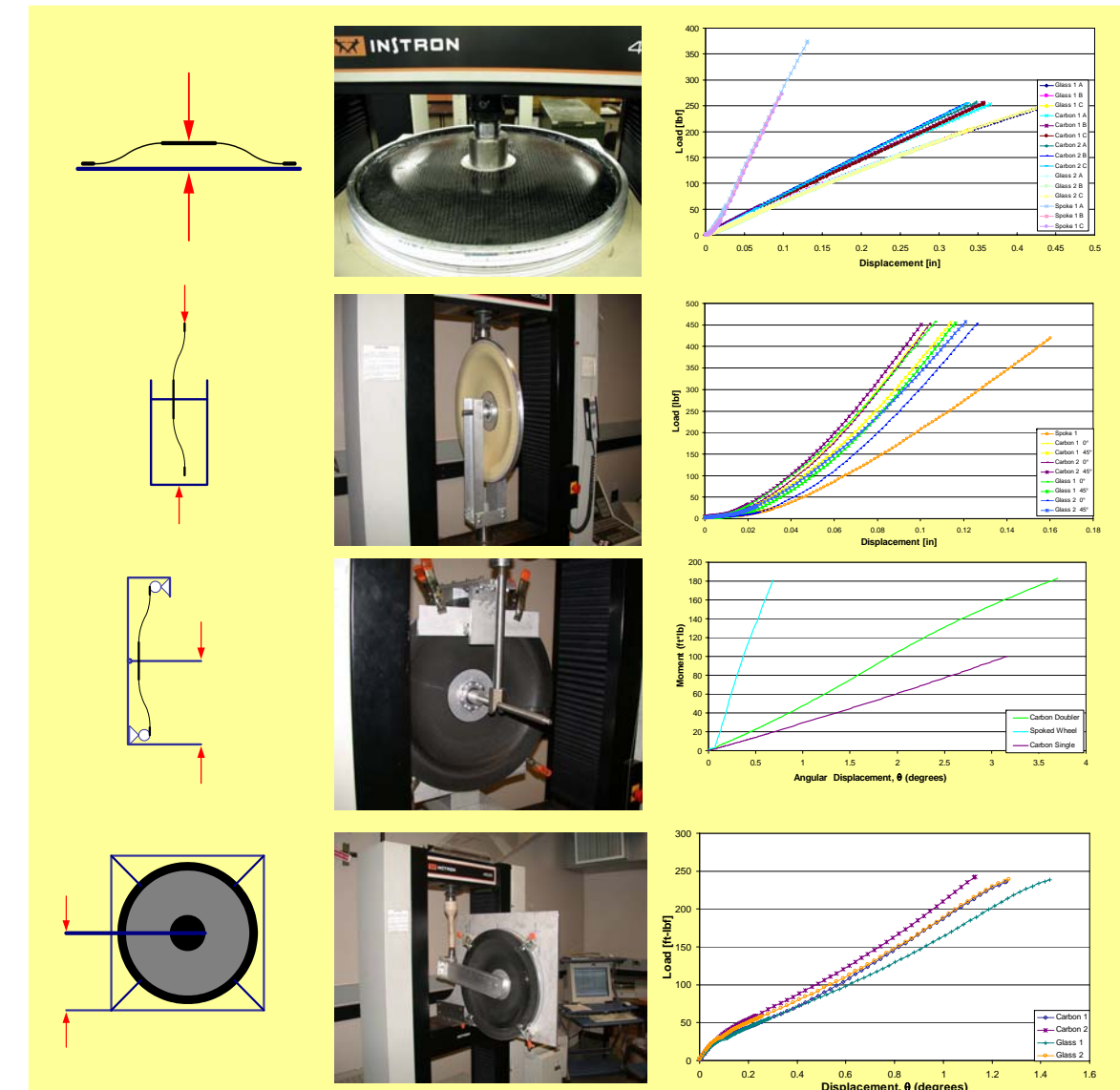
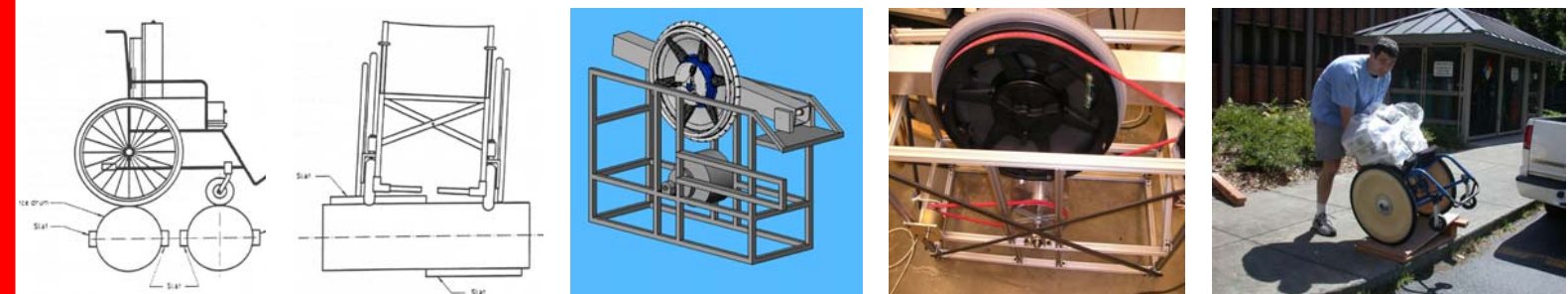


Figure 2: Mechanical testing of **MAGICWHEELS** dish shaped composite wheels

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ADDITIONAL TESTING for Durability and Reliability-Passed!



RESNA FATIGUE

MAGICWHEELS Hill-Hold Test, Shift Test, Inclined Curb Drop

➤ **These findings indicate composite wheels are suitable for use with **MAGICWHEELS** 2-gear drive.**

Assessment of fiber reinforced composite wheels for the MagicWheels™ 2 speed manual wheel chair,
Brian D. Flinn, PhD, PE

ABSTRACT

Most wheelchair users today have limited destinations because of the inability of manual wheelchairs to travel on both soft and rough surfaces adequately. Magic Wheels Inc. has designed a new 2 speed transmission that greatly increases the range of manual wheels chairs and reduces stress on the user. However this new transmission required the development of a concave shaped wheel to fit the transmission. The mechanical behavior of these new wheel designs were compared with a standard spoke wheel in loaded in axial, bending, radial and torsion. The dish shaped fiber reinforced composite wheels were as strong and more flexible than a “gold standard” spoke wheelchair wheel.

BACKGROUND

Wheelchair users have long sought to transport themselves more efficiently to increase their mobility and independence. Currently the over 3 million manual wheelchair users in developed countries (over 1.8 million in U.S.) suffer limited mobility on inclines (hills, sloping and uneven sidewalks, curb cuts and driveways) as well as uneven terrain such as grass, gravel, sand, and thick carpeting. Only brute force allows manual wheelchair users to overcome these obstacles, at significant cost to their bodies -- 20% to 80% experience shoulder pain and 30% to 70% wrist pain.

There have been many attempts to correct these limitations, but few have had mainstream success. Electric-powered wheelchairs are vastly too expensive for the average consumer, and other manual wheelchair designs have limitations on hill climbs, braking, and other problems. Magic Wheels Inc has developed a two-speed manual wheelchair that allows the user to freely access and navigate through areas that they could not previously. A patented two-speed gear drive delivers an elegant solution that doesn't depend on complex electronics, computers or cumbersome and expensive electric motors with heavy batteries. The second speed (2:1 gear ratio) helps reduce muscle stress and strain while doing hill climbs, and also assists in braking. A great asset of this new wheelchair design is that the new wheel fits and locks into a standard manual wheelchair using a quick-release mechanism that is compatible with industry standard axles and receiver bushing.

This new transmission had one major problem. The transmission for the Magic Wheels would increase the width of a standard wheelchair unless there are significant modifications made to the design. This problem was solved by developing a new type of wheel that is dish shaped and does not use spokes like standard wheelchair wheels. This new wheel is made of a foam core and fiber reinforced polymer composite skin to add additional strength to the wheel. This approach allows the wheel to be lightweight, strong, and be shaped in a design that will allow for the transmission to be mounted properly. The wheel also incorporates a new bearing system only ½” thick to accommodate the thin composite wheel. The new dish shaped composite wheel is a critical component of Magic Wheels' that allows the 2-speed transmission to be mounted deep inside the outboard wheel area and hence does not increase the width of the chair. In addition the composite wheel also provides a shiny smooth surface to prevent catching fingers between the push rim drive spokes and the outboard wheel surface

The Magic Wheels product was designed from the ground up expressly to meet the needs of long term wheelchair users. The innovative design not only meets most of the 10 design criteria for multi-speed manual wheelchair wheels identified by the US Ed. Dept. - National Institute of Disability and Rehabilitation Research (NIDRR), but also includes 2 important additional features not anticipated by them: 1) Hill holding with override feature to help climb steeper hills and 2) Push rim actuated assisted braking for reduced hand burning and added down hill control. Magic Wheels has also been designed to allow instant "snap-on" retrofitting in the field (using standard quick release axles in the wheelchair industry) to cater to the millions of people who already have wheelchairs. Magic Wheels incorporates an unusual hypocycloidal gear drive that has gear teeth passing through the center of wheel axle. This patented drive provides the lower 2:1 gear ratio and the unbalanced eccentric forces that produces the unique hill holding and assisted braking features noted above. This type of 2-speed transmission must be mounted at the outboard end of the axle, so a short axle length is critical in getting the transmission positioned deep inside the wheel so it (and the shift handle) do not protrude outboard of the push rim and hit objects during wheelchair operation.

The pictures of prototype wheels below show the effect of the thin dish shaped composite wheel. In the left picture the 2-speed transmission is mounted on a spoke wheel and the hub & shifters protrudes outboard of the push rim. The 2nd picture shows an early version of the thin dish shaped composite wheel, the transmission is about 1 3/4" further inboard (note bent push rim drive spokes) and in the 3rd generation (3rd picture) the shift handle could be mounted on the surface of the drum without extending outboard of the push rim. In the far right picture, three versions of the 4th generation of Magic Wheels are shown.



Figure 1: Four generations of MagicWheels. From left to right 1st, 2nd, 3rd and 4th generation

METHODOLOGY

Three generations of composite wheelchair wheels and one industry standard Quickie™ spoke wheel were received from Magic Wheels™ for mechanical evaluation. The objective of the wheel testing was to compare the stiffness and strength of the composite wheels with a standard spoke wheel. The first generation composite wheels were 2 carbon fiber composite wheels and 2 glass fiber composite wheels with a foam core mounted to a standard aluminum rim. Later generations were reinforced for additional bending stiffness with a composite “doubler”; a ring shaped extra layer of composite around the hub. Loads were applied using a computer controlled Instron™ 4500 load frame at a loading rate of 0.1 inches/minute using specially designed fixtures for each test, custom built by the University of Washington for this purpose. Load and displacement data were acquired by computer. Wheels were loaded and unloaded a minimum of three times to at least twice the design load.

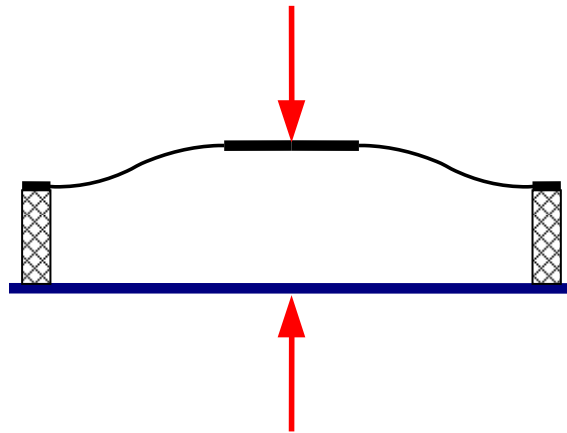
The composite and spoke wheels were subject to 4 different strength and stiffness tests:

- 1) Axial strength and stiffness
- 2) Bending (out of plane) strength and stiffness
- 3) Radial strength and stiffness
- 4) Torsional (in plane) strength and stiffness

Schematic illustrations and photos of the tests are shown in figures 2 thru 6.



Figure 6: Axial Test



The axial test was designed to test the wheels in the event that a load was placed against the midpoint of the wheel. Figure 2 describes this load, with the red arrows acting as the load and the specimen in the convex orientation. The actual testing setup required building a sample holder that was made of a wooden block, which had an exact replica of the aluminum rim that was used on the Magic Wheel. This rim was used to support wheel rim so that the hub would not hit the bottom of the fixture during the axial loading.

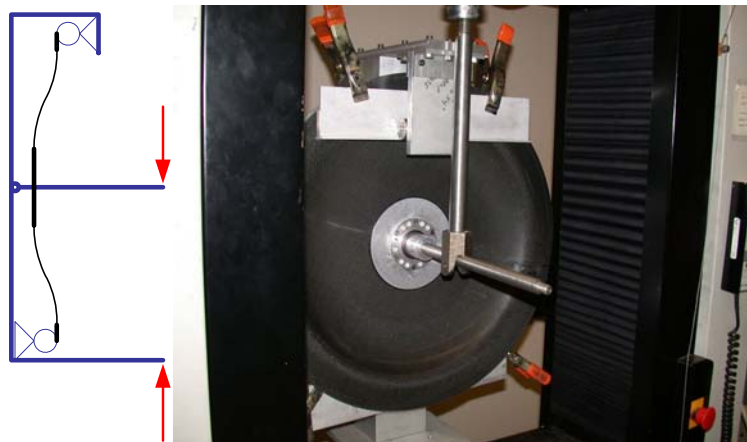


Figure 7: Bending test

The bend test also required a custom built fixture. The basic principle of this test was to create a moment on the wheel using a lever and a load placed at the end of the lever. This moment applied a force

on the wheel at the central location, which causes the wheel to bend. The rim of the wheel was supported with rollers to allow movement in the direction of loading to prevent radial loading of the wheel.

The radial test was designed to load the wheel without a tire to test the stiffness and strength of the hub and rim. The hub of wheel was supported by a fixture similar to a bicycle fork and a load was applied to the rim of the wheel.

The torsion test used the same fork fixture as the radial test, but it was rotated 90 degrees and fixed to the hub where the transmission is fastened. The outer rim of the wheel was clamped to prevent rotation and a load was applied to the fork to simulate the torque that would be applied to the wheel hub through the transmission.

RESULTS

Axial Loading

Representative load displacement data upon loading are presented in Figure 2. The load displacement curves were all linear, except for some nonlinearity at the toe of curve which is expected. There was no significant change in the load–displacement data between the five load-unload cycles. This linear elastic behavior is indicative of loading without any damage. Visual inspection of the wheels under load and after removal of load did not reveal any damage to the wheels. The spoke wheel was considerably stiffer than either the carbon fiber or glass fiber composite wheels. The carbon fiber composite wheels were slightly stiffer than the glass fiber composite wheels. None of the wheels failed during testing.

The second generation of composite wheels from magic wheels (#’s 4, 5 & 6) were three carbon fiber composite wheels with a thicker foam core and two wheels were selectively reinforced with an additional carbon fiber ply, coined “doublers”. Different adhesives were used in the two reinforced wheels. The objectives of the second generation testing were to determine the effect of: 1) using a thicker foam core, 2) adding additional carbon fiber reinforcement and 3) two different types of adhesives. The load displacement data for these three wheels is given in figure 3. The thicker foam core increased the axial stiffness compared to the first generation carbon fiber wheels. The additional carbon fiber doublers also increased the stiffness. There was a slight difference in the stiffness with the different adhesives. The wheel bonded with the film adhesive was slightly less stiff than the wheel bonded with paste adhesive. The stiffness of the best second generation wheel was approximately twice that of the first generation carbon wheel, however, it was still less stiff than a spoke wheel. None of the second generation wheels had any discernable damage after testing. Table I summarizes the second generation testing.

Table I: Axial Stiffness of Magic Wheels composite wheelchair wheels.

Wheel Type	Description	Stiffness (lb/in)
Carbon #4	Prepreg Adhesive w/o Doubler	1157.1
Carbon #5	Prepreg Adhesive w/ Doubler	1365.9
Carbon #6	2 Part Epoxy w/ Doubler	1533.5
Spoke	Original Spoked Wheel	2927.6
Carbon #1	1 st Generation Composite Wheel	716.87

The third generation of composite wheels (#'s 7-12) were first production prototypes with the thicker foam core, selective carbon reinforcement and film adhesive combination chosen from the second generation of wheels. The objective of the third generation testing was to determine product variability and to confirm second generation test results on multiple wheels. Six wheels nominally identical wheels were tested. The load displacement data is given in Figure 4. There were some minor variations in stiffness between the six wheels and the data confirmed the results of the second generation testing as shown in Table II. Wheels # 8, 9 and 10 contained some minor hub assembly errors as noted, but these did not effect the testing and were not detrimental to the wheels performance in these tests.

Table II: Axial Stiffness of Magic Wheels composite wheelchair wheels.

Wheel Type	Description	Stiffness (lb/in)
Carbon #4	Prepreg Adhesive w/o Doubler	1157.1
Carbon #5	Prepreg Adhesive w/ Doubler	1365.9
Carbon #6	2 Part Epoxy w/ Doubler	1533.5
Carbon #7	MW 0006	1439.8
Carbon #8	MW 0010 - Sleeve Misaligned	1391.5
Carbon #9	MW 0011 - Loose Bearing	1468.4
Carbon #10	MW 0012 - Sleeve Misaligned	1337.9
Carbon #11	MW 0013	1442.5
Carbon #12	MW 0014	1437.4
Spoke	Spoke wheel	2927.6



Figure 1: Photo and schematic of axial loading test

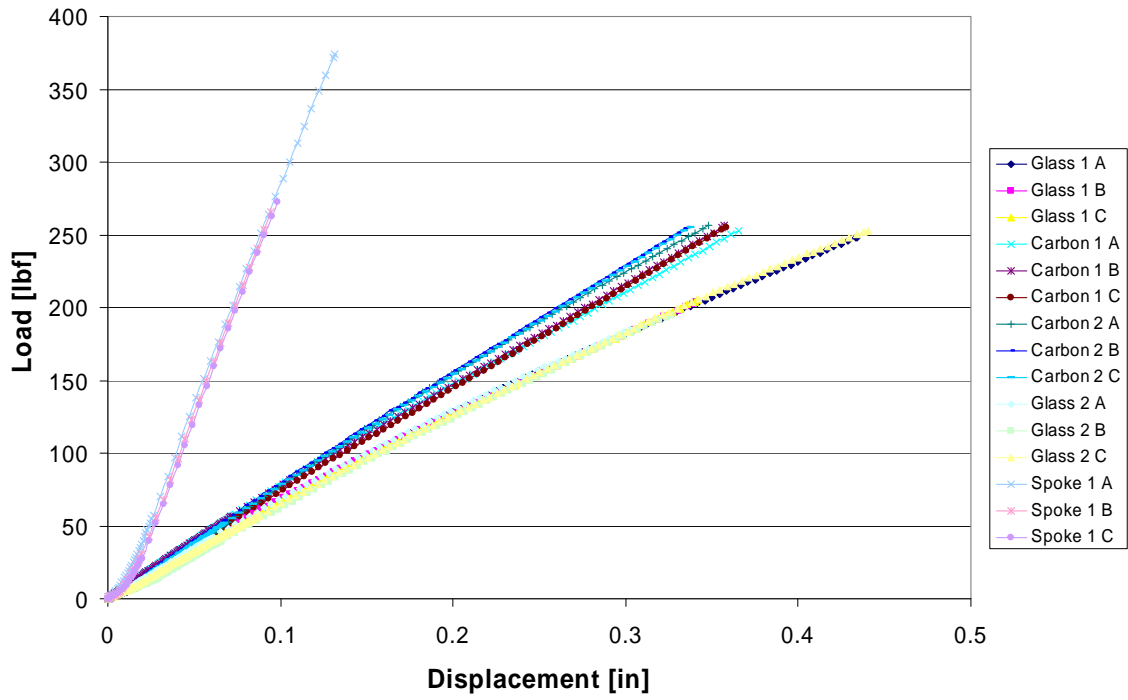


Figure 2. Axial load vs. displacement data for first generation wheel testing

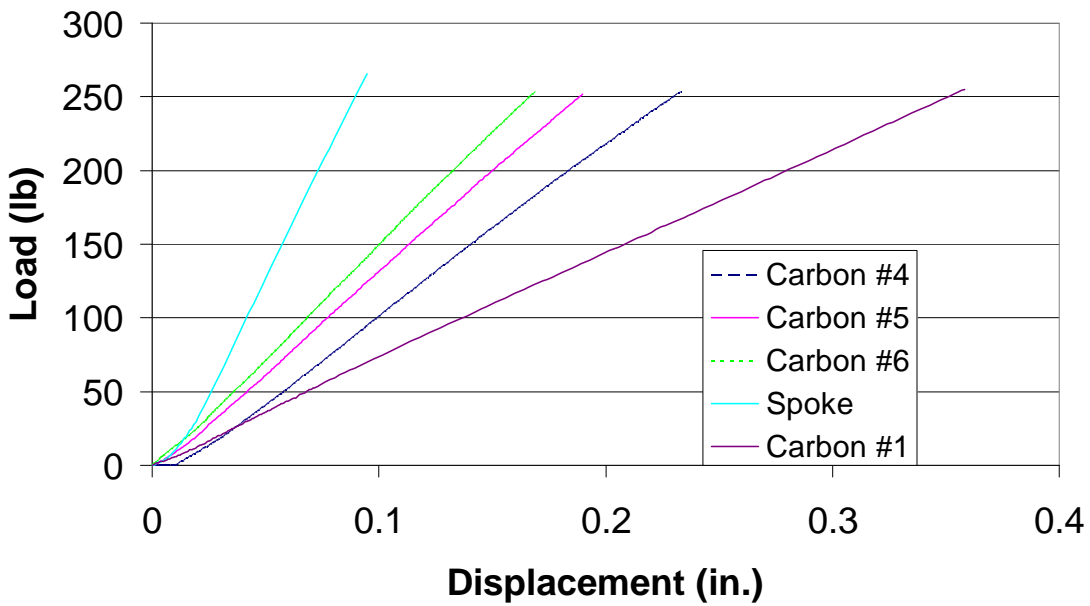


Figure 3. Axial load vs. displacement testing for second generation wheel testing

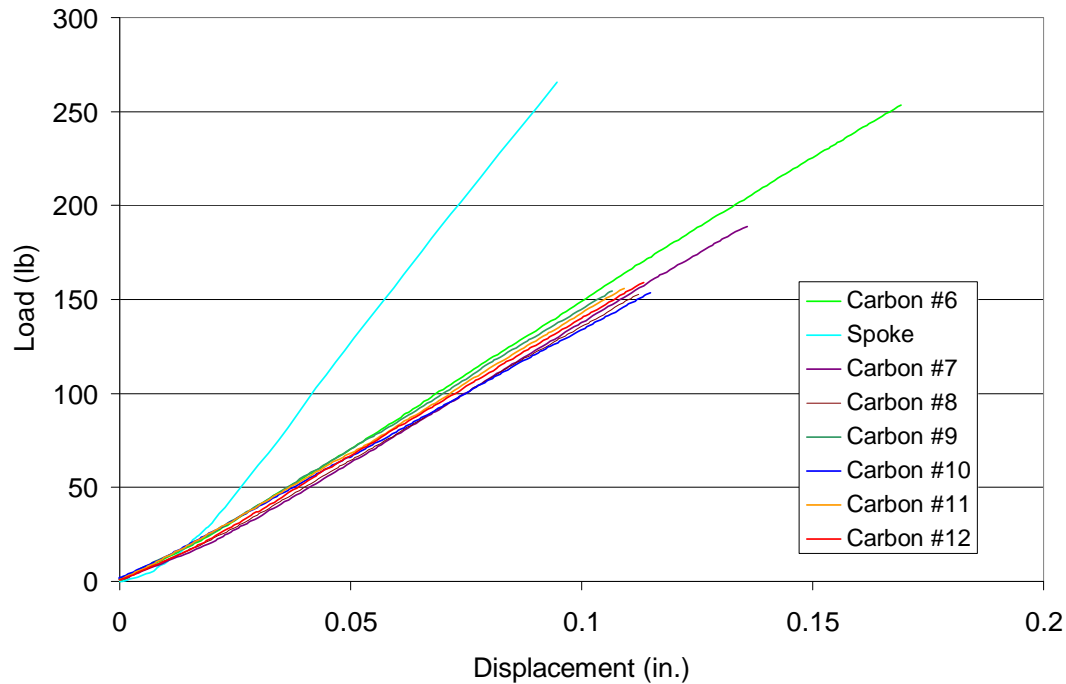


Figure 4. Axial load vs. displacement data for third generation wheel testing.

Bending:

A minimum of 150lbs force was applied to all wheels which produced minimum bending moments of 100 ft-lbs. Wheels were loaded and unloaded a minimum of three times. Representative moment-angular deflection data upon loading are presented in Figure 2. The moment-angular displacement curves were all linear, except for some nonlinearity at the toe of curve which is expected. There was no significant change in the load–displacement data between the three load-unload cycles. This linear elastic behavior is indicative of loading with out any damage. Visual inspection of the wheels under load revealed a slight wrinkle on the top and bottom of the aluminum disc as shown in figure 3. After removal of load no damage was evident in any of the wheels. The spoke wheel was considerably stiffer than either the carbon fiber or glass fiber composite wheels. The carbon fiber composite wheels were slightly stiffer than the glass fiber composite wheels. None of the wheels were tested to failure.

The second generation of composite wheels from magic wheels were three carbon fiber composite wheels with a thicker foam core and two were selectively reinforced with an additional carbon fiber ply, coined “doubblers”. Different adhesives were used in the two reinforced wheels. The objectives of the second generation testing were to determine the effect of: 1) using a thicker foam core, 2) adding additional carbon fiber reinforcement and 3) two different types of adhesives. The load displacement data for these three wheels is given in figure 4. The thicker foam core increased the axial stiffness compared to the first generation carbon fiber wheels. The additional carbon fiber doublers also increased the stiffness. There was a slight difference in the stiffness with the different adhesives. The wheels bonded with the film adhesive was slightly less stiff than the wheel bonded with paste adhesive. The stiffness of the best second generation wheel was approximately twice that of the first generation carbon wheel, however it was still less stiff than a spoke wheel. None of the second generation wheels had any discernable damage after testing. Table I summarizes the second generation testing.

Wheel Type	Description	Slope (lb/in)	Load at "wrinkling" (lbs)
Carbon #4	Prepreg Adhesive w/o Doubler	40.4	155.878
Carbon #5	Prepreg Adhesive w/ Doubler	42.3	211.725
Carbon #6	2 Part Epoxy w/ Doubler	51.7	274.259
Spoke	original spoked wheel	286.5	322.106
Carbon #1	Old Composite Wheel	31.3	n/a

Table I: Bending Stiffness of Magic Wheels

The third generation of composite wheels were first production prototypes with the thicker foam core, selective carbon reinforcement and film adhesive combination chosen from the second generation of wheels. The objective of the third generation testing was to determine product variability, confirm second generation test results on multiple wheels and to test at different wheel orientations with respect to carbon fiber direction. Three wheels nominally identical wheels were tested. The wheels were test at 0, 90, +45 and -45 degrees with respect to carbon fiber orientation in the composite. The load displacement data is given in Figure 5. There were some minor variations in stiffness between the three wheels and the data confirmed the results of the second generation testing. No significant effect of wheel orientation was found as shown in Table II.

Wheel	-45	0	45	90	Average
Carbon #7	49.1	50.2	48.9	49.1	49.3
Carbon# 9	53.7	53.6	54.1	54.7	54.0
Carbon #11	53.1	52.3	55.6	56.6	54.4
Average	52.0	52.0	52.9	53.5	52.6

Table II. : Bending Stiffness of Magic Wheels Carbon wheels # 7, 9 and 11 as a function of wheel orientations with respect to carbon fiber direction.

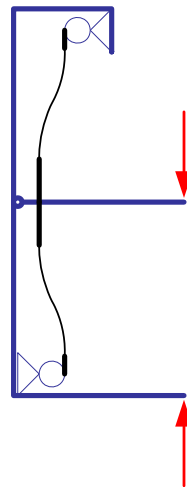


Figure 1: Photo and schematic of out of plane bend loading test

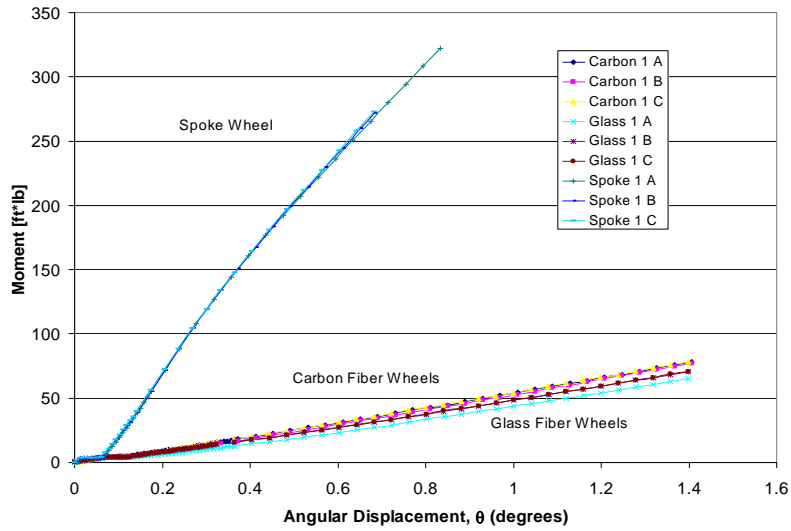


Figure 2. Moment - angular displacement data for first generation testing



Figure 3. Wrinkling of carbon fiber composite wheel while under load. No wrinkles were detectable after load was removed.

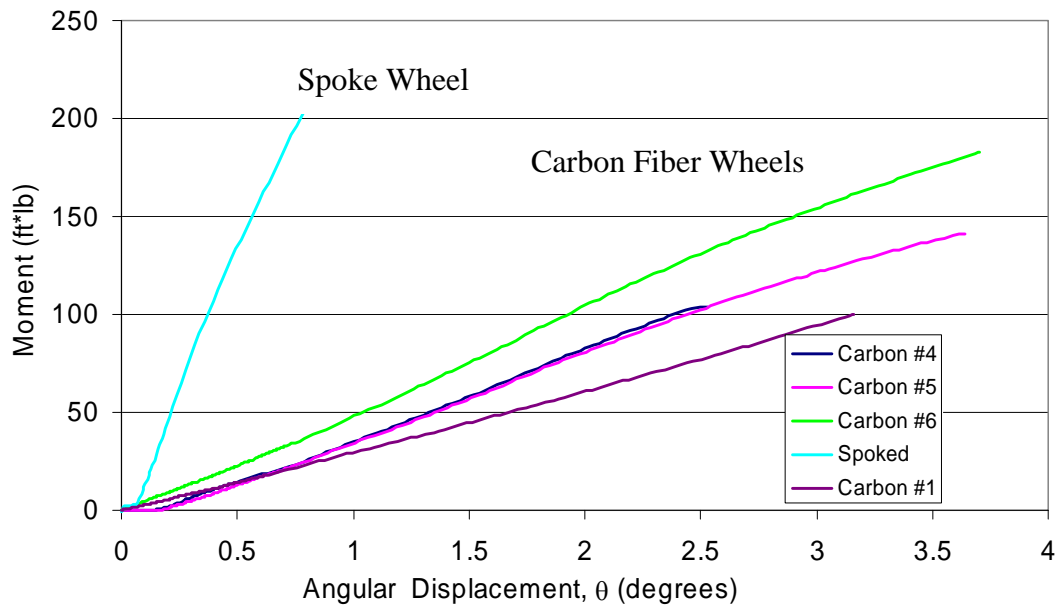


Figure 4. Moment - angular displacement testing for second generation testing

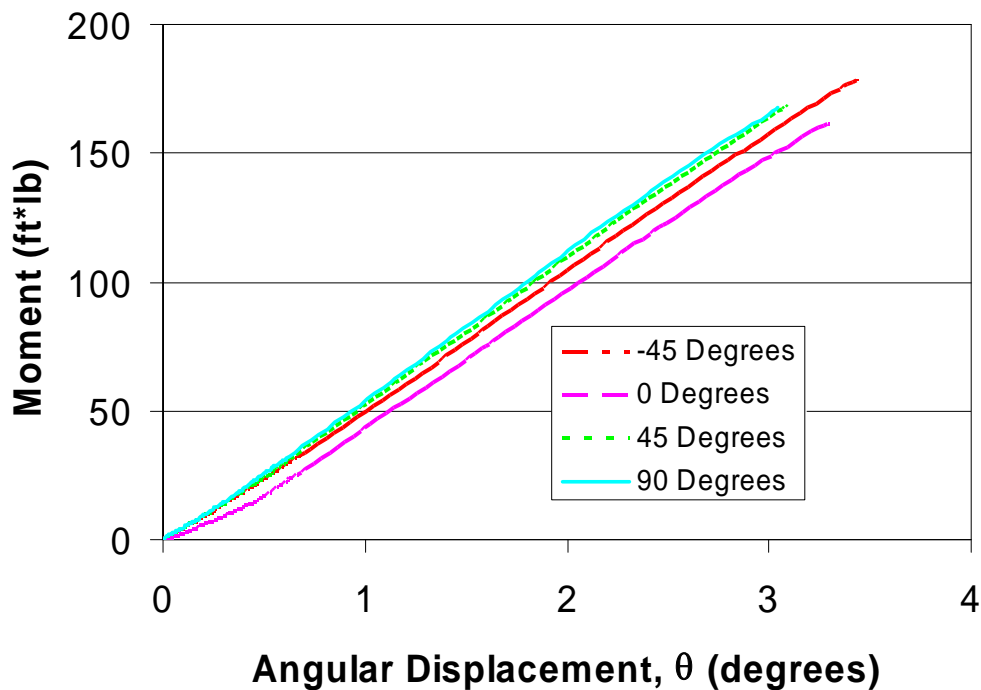


Figure 5. Moment - angular displacement data for third generation testing of Carbon wheel #11 at different orientations with respect to carbon fiber in composite.

Radial Loading

A minimum of 400 pounds of force was applied to all wheels, well past the design load. Wheels were loaded and unloaded a minimum of five times. The composite wheels were tested at 0 and 45 degrees with respect to the fiber direction. Representative load displacement data upon loading are presented in Figure 2. The load displacement curves were relatively linear, except for some nonlinearity at the toe of curve which is expected. There was no significant change in the load–displacement data between the five load-unload cycles. This linear elastic behavior is indicative of loading with out any damage. Visual inspection of the wheels under load and after removal of load did not reveal any damage to the wheels. The composite wheels are significantly stiffer than the spoke wheel. The carbon fiber composite wheels were slightly stiffer than the glass fiber composite wheels. None of the wheels failed during testing.



Figure 1: Photo and schematic of radial loading test

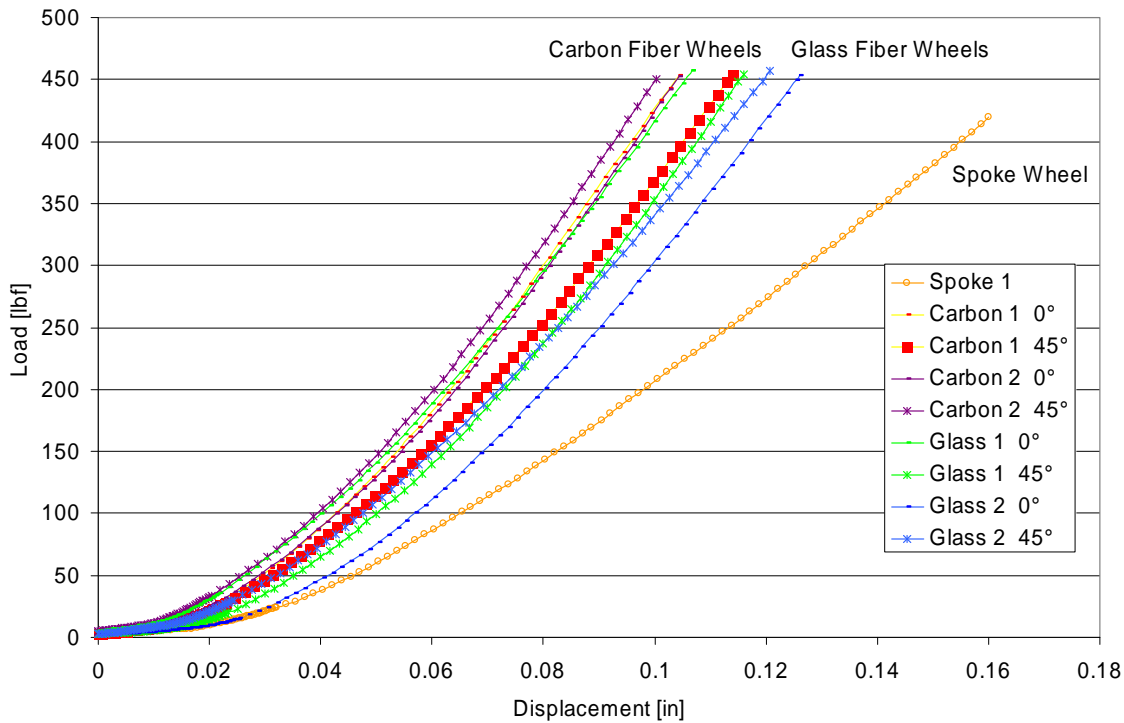


Figure 2. Load vs. displacement data in radial loading.

Torsion Loading

A minimum of 200 ft-lbs of torque was applied to all composite wheels, the spoke wheel was not tested since it was not designed for torque loading. Wheels were loaded and unloaded a minimum of five times. Representative load vs. displacement data upon loading are presented in Figure 2. The load-displacement curves were relatively linear, except for some nonlinearity at the toe of curve which is expected. There was no significant change in the load-displacement data between the five load-unload cycles. This linear elastic behavior is indicative of loading without any damage. Visual inspection of the wheels under load and after removal of load did not reveal any damage to the wheels. The carbon fiber composite wheels were slightly stiffer than the glass fiber composite wheels. None of the wheels failed during testing. The

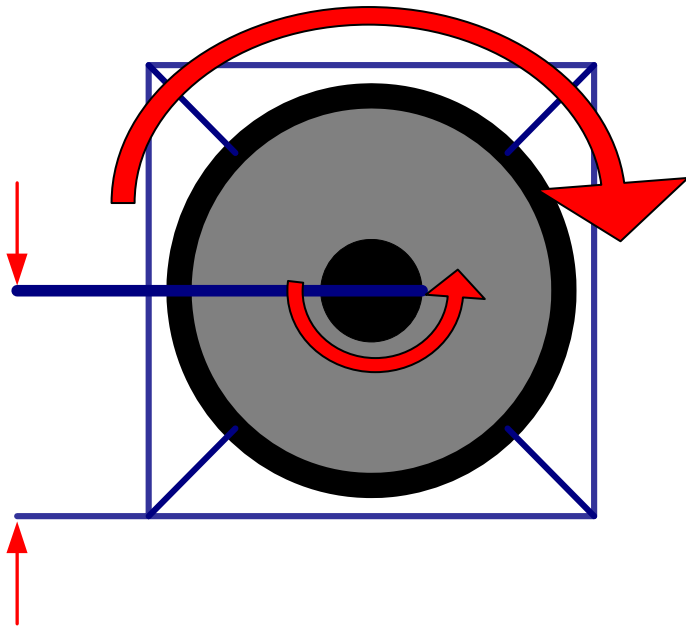


Figure 1: Photo and schematic of torsional loading test

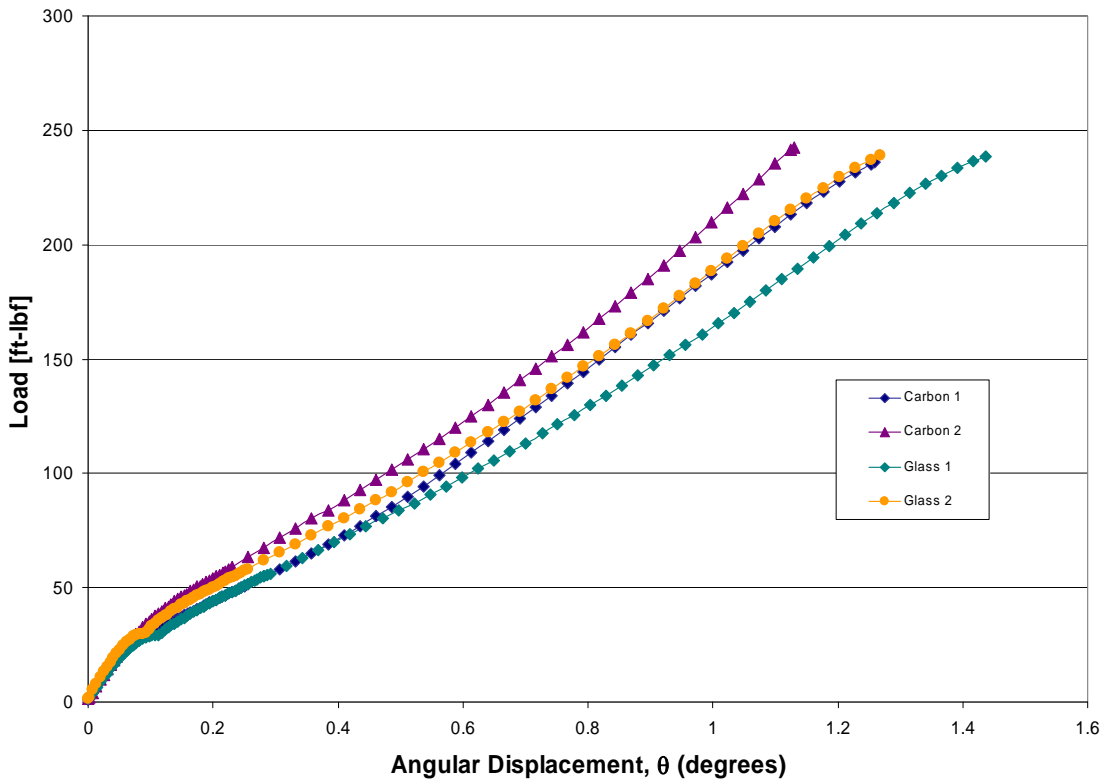


Figure 2. Load Angular Displacement data for composite wheel testing

Straight Curb Drop

Inclined Curb Drop

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