TEXAS TECH UNIVERSITY
Multidisciplinary Research in Transportation

# Testing of Alternative Supporting Materials for Portable Roll-Up Signs Used for Maintenance Work Zones

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16. Abstract

Portable roll-up signs are currently used by the Texas Department of Transportation (TxDOT) for identification of short-term maintenance/work zones and emergency operations. These signs have fiberglass frames to directly support diamond-shaped and rectangular flexible sign faces. It has been frequently reported that the fiberglass frames have failed due to bending caused by natural wind or gust generated by passing vehicles.

The cost of these failures is more than the marginal cost of replacing the broken frame members. It includes the safety cost to workers and the traveling public. Research studies to date on sign structures have focused on permanent signs with rigid faces. However, there has been little formal and in-depth research on wind loading on roll-up signs with flexible facing materials.

This research project was proposed to address three major issues: (1) understanding the nature of wind loading on portable roll-up signs, (2) identifying alternative materials for fiberglass frames, and (3) developing modified/new designs of portable roll-up signs.

The work performed under this project revealed that the vertical frames failed due to progressive cracking at the fiber-matrix interfaces caused by torsion, instead of bending. Therefore, it was determined to increase the torsional stiffness of vertical frames by wrapping high-strength carbon fiber sheets around the existing fiberglass frames in a pre-determined direction to improve the resistance to wind loading.

Prototype roll-up signs with the modified frame design were manufactured in the laboratory and were subjected to various tests including the full-scale vehicle impact tests per MASH impact performance criteria. The test results showed that the modified design showed better serviceability as well as higher resistance to torsion as compared to the original design. In addition, the prototype roll-up signs met MASH impact performance criteria.

The outcome of the project can lead to a significant reduction of the cost for replacing failed roll-up signs, and more importantly, help improve the safety of workers and traveling public in maintenance/work zones.


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# TESTING OF ALTERNATIVE SUPPORTING MATERIALS FOR PORTABLE ROLL-UP SIGNS USED FOR MAINTENANCE WORK ZONES

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Performed in Cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

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**ABSTRACT**

Portable roll-up signs are currently used by the Texas Department of Transportation (TxDOT) for identification of short-term maintenance/work zones and emergency operations. These signs have fiberglass frames to directly support diamond-shaped and rectangular flexible sign faces. It has been frequently reported that the fiberglass frames have failed due to bending caused by natural wind or gust generated by passing vehicles.

The cost of these failures is more than the marginal cost of replacing the broken frame members. It includes the safety cost to workers and the traveling public. Research studies to date on sign structures have focused on permanent signs with rigid faces. However, there has been little formal and in-depth research on wind loading on roll-up signs with flexible facing materials.

This research project was proposed to address three major issues: (1) understanding the nature of wind loading on portable roll-up signs, (2) identifying alternative materials for fiberglass frames, and (3) developing modified/new designs of portable roll-up signs.

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# 1 INTRODUCTION

Fiberglass frame members used for portable roll-up signs flex in windy conditions and have a tendency to break, even in breezes caused by passing vehicles, as shown in Figure 1. When fiberglass frame members break, the sign is rendered useless. The Amarillo District traffic section has experimented aluminum frames of the same cross-sectional dimensions as the fiberglass frame members with little success due to the aluminum frames bending in high winds. This research project was initiated with the primary goal to find alternative materials and designs could provide more durable and reliable service in this application.

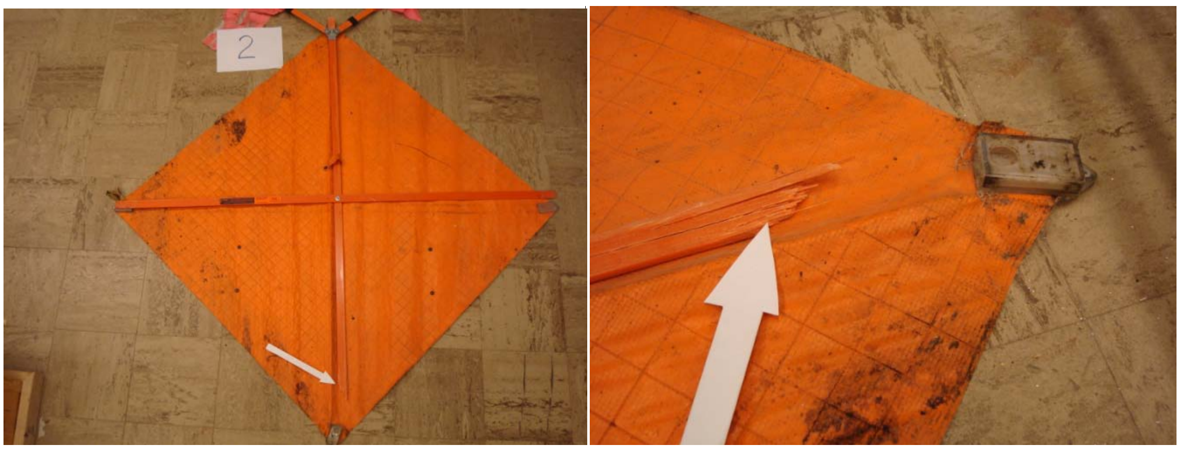



Figure 1.1 A Failed Portable Roll-Up Sign Provided by Amarillo District

A comprehensive analytical and experimental work plan was developed by Texas Tech University and Texas Transportation Institute to address the needs of this project, with a focus on the following major goals:

- Evaluate the current practice
- Find alternative materials to be used as frame members
- Propose modified/new designs using the alternative materials
- Develop specifications for materials selection and design that can be written into the TxDOT General Services Division Specification Number 801-60-66 - Sign Face, Roll-up, Reflective, Construction and Work Zone.

The work flowchart in Figure 2 shows the tasks that have been undertaken in this project to achieve the goals.

**Task 1. Review the Existing Literature and State of the Practice (Texas Tech)**
A review of all academic literature and any available industrial literature was performed to inform the rest of the research project. Topics of particular interest include (1) wind and vehicle gust loads on signs, (2) state and federal sign regulation, (3) dynamic modeling of signs, (4) crashworthiness of signs, and (5) survey of available products through catalogs, manufacturer literature, and U.S. patent information.

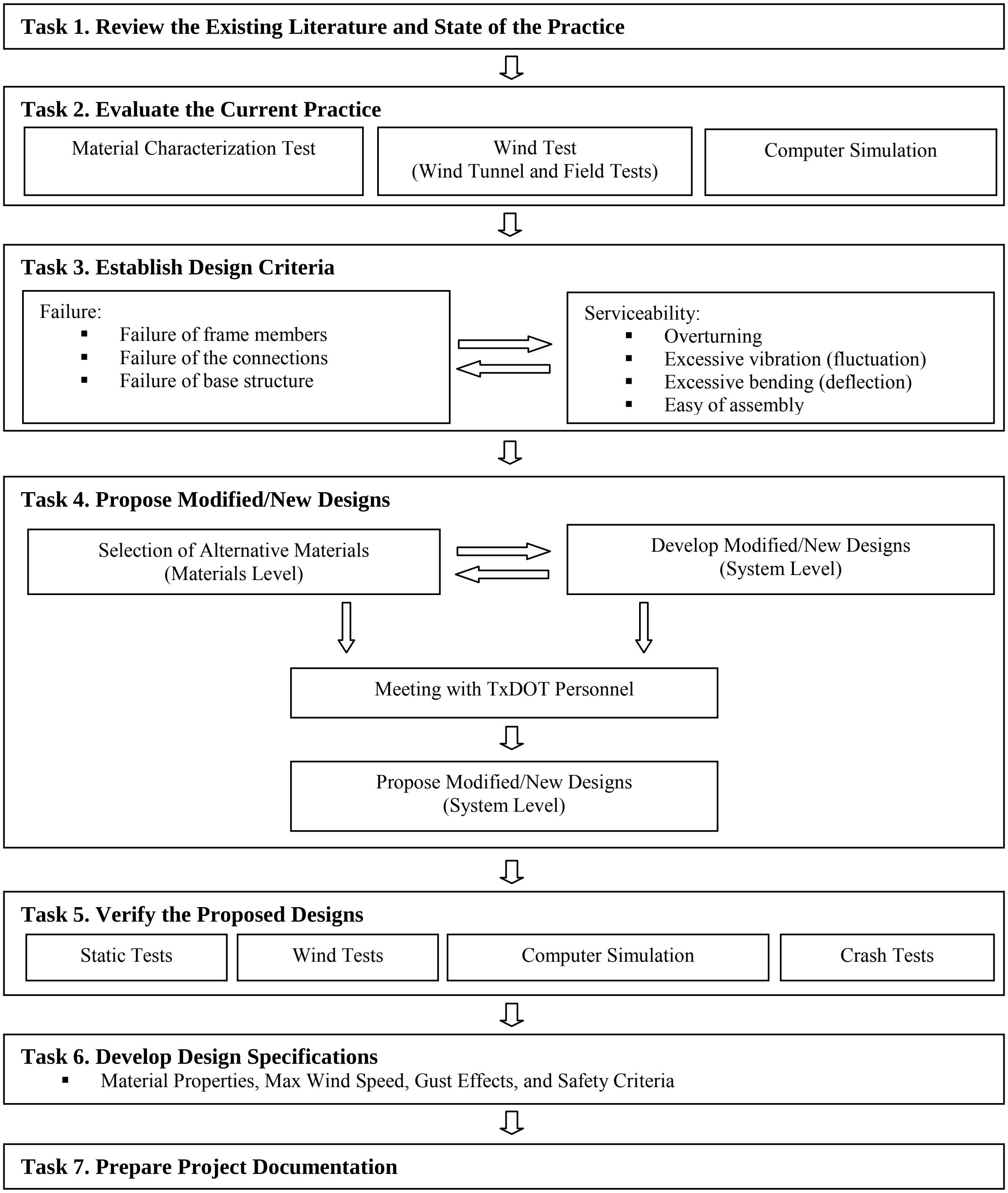



Figure 1.2 Work Flowchart of the Tasks Undertaken in this Project

## Task 2. Evaluate the Current Practice (Texas Tech)

The goal of this task was to evaluate the performance of the portable roll-up signs currently approved and used by TxDOT, to provide information regarding the critical failure modes, and design parameters and requirements. In Texas, the pre-qualified products of sign stands used for portable roll-up signs are identified that conform to TxDOT 801-12-77 and TxDOT 801-12-78, and the pre-qualified products of flexible reflective roll-up sign faces are identified that conform to TxDOT 801-60-66. The materials, composition, quality, services, sampling and testing of flexible roll up reflective signs are stipulated in TxDOT DMS-8310. The research team coordinated with TxDOT to obtain samples of these pre-qualified products for the performance evaluation. The performance evaluation was conducted at the component and system levels. At the component level, the mechanical properties of fiberglass frame members were determined. At the system level, complete assemblies of portable roll-up signs were subjected to wind load in order to observe the overall system behavior and possible failure modes.

**Task 3. Establish Design Criteria (Texas Tech)**
In this task, the design criteria for portable roll-up signs were established based on the findings from Tasks 1 and 2. The criteria considered covers two main areas: preventing failure and maintaining serviceability.

**Task 4. Propose Modified/New Designs (Texas Tech)**
Based on the established design criteria, modified or new designs were proposed in this task.

**Task 5. Verify the Proposed Designs (Texas Tech and Texas Transportation Institute)**
The performance of proposed designs was verified in this task. At the component level, assemblies of frame members and sign face materials will be subjected to static loads. At system level, wind and crash tests were conducted on complete assemblies of the frame members, sign face, and base stand.

**Task 6. Develop Design Specifications (Texas Tech)**
Based on the findings from Tasks 1 through 5, specifications for material selections and design were developed that could be incorporated into the TxDOT General Services Division Specification Number 801-60-66 - Sign Face, Roll-up, Reflective, Construction and Work Zone.

This report presents the findings of this research project in the following chapters. Chapter 2 presents the findings of Task 1. Chapter 3 documents the analytical and experimental results obtained from Task 2. Chapter 4 describes the design criteria developed under Task 3. Chapter 5 presents the modified/new sign assembly designs developed under Task 5. Chapter 6 documents the performance verification procedures and results for the proposed designs. Chapter 7 presents the suggested modifications to the existing TxDOT specifications. Finally, Chapter 8 presents the conclusions and recommendations obtained in this study.

# 2 LITERATURE REVIEW

A comprehensive review on the existing literature has been performed to identify the current status of the use of portable roll-up signs in Texas and other state agencies. The topics of particular interest include (i) history of development of portable roll-up signs, (ii) federal and state regulations/specifications, (iii) existing studies on wind and vehicle gust loads against portable roll-up signs, and (iv) existing studies on crashworthiness of portable roll-up signs.

## 2.1 History of Development of Portable Roll-Up Signs and U.S. Patent Information

Traffic control devices are used to promote highway safety and efficiency by providing information such as regulations, warnings, and guidance to road users (FHWA, 2009). Roll-up traffic signs are one type of traffic control device that is designed to be lightweight and easy to store. Typically a roll-up sign can be divided into three parts: (i) roll-up sign sheeting, (ii) brace (frame), and (iii) sign holder. This review focuses on the brace of the roll-up sign, while also discussing the other two parts for reference.

In accordance with the United States Classification System (USCS) scheme, patents related to signs are classified as Class 40, and collapsible signs are classified as subclass 610. Therefore, the investigation of the patents related to portable roll-up signs was carried out based on patents in Class 40/610. Both accepted patents (409 patents available in this category) and patents in the application process (98 patents available in this category) were identified. In this literature review, 33 patents related with portable roll-up signs from the United States Patent and Trademark Office (USPTO) database were selected for discussion. The date of patents spans 35 years from 1975 to present. Table 2.1 summarizes patents described in this review process.

### 2.1.1 Brace Design

In the first period of portable traffic signs, the braces of the sign were preferably made of steel or aluminum, and the brace contained only one vertical batten. This is because the sign sheeting was made of rigid material rather than the currently-used flexible one. For example, Figure 2.1 presents U.S. Patent 4288053 (Sarkisian, 1981) and 4309836 (Knapp, 1982). The former was filed in 1979, and the latter was filed in 1980.

In U.S. Patent 4490934 (Knapp, 1985) filed in 1983, the author suggested using rigid plastic for the braces rather than using aluminum. In addition, the author suggested that the brace of the sign contain two battens attached at a pivot as shown in Figure 2.2. Those two suggestions were intended to solve two existing problems at that time. First, fabric sheets might be damaged if the batten was not flexible. Second, during the insertion procedure, 'untensioning' the batten might cause injuries to the operating personnel. In U.S. Patent 4507887 ( Seely, 1985) and U.S. 4548379 (Seely and Ursprung, 1985) as shown in Figure 2.2, the authors suggested that rigid material such as fiberglass, wood, and metal should be used as the material for fabricating braces. Since 1990, most of patents began to specify fiberglass or fiberglass composite as the material of the brace.

Table 2.1 List of Patents in the Literature Review

| Patent No. | Name | Date |
|---|---|---|
| 4038769 | Portable Sign Holder | 1975-9-15 |
| 4103445 | Roll-up Sign | 1976-9-2 |
| 4108331 | Safety Warning Kit | 1977-5-11 |
| 4203242 | Sign Standard | 1978-12-7 |
| 4288053 | Adjustable Sign Mounting Bracket | 1979-6-20 |
| 4309836 | Wind Deflectable Sign Holder | 1982-1-12 |
| 4490934 | Rigid Mechanical Cornet Pocket For Tensioning Flexible Signs and Signal Devices | 1983-3-14 |
| 4507887 | Sign and Attachment Apparatus | 1985-4-2 |
| 4548379 | Compact Sign and Stand | 1982-11-17 |
| 4593879 | Compact Sign Stand | 1985-7-3 |
| 4691892 | Sign and Sign Stand | 1985-10-21 |
| 4694601 | Portable Collapsible Highway Sign | 1985-11-18 |
| 5152091 | Highway Sign | 1990-12-5 |
| 5175646 | Reflective Roll-Up Signs | 1990-5-24 |
| 5231778 | Sign System with Rib Lock Mechanism | 1991-6-12 |
| 5318258 | Portable Highway Sign Stand | 1992-9-30 |
| 5446984 | Highway Signs Capable of Being Rolled Up and Improved Mounting Brackets for The Signs | 1993-9-1 |
| 5540007 | Highway Signs Capable of Being Rolled Up | 1993-10-27 |
| 5551177 | Roll-Up Sign with Collapsible Fanning Framework | 1994-11-14 |
| 5598654 | Sign with Collapsible Fanning Framework | 1994-6-1 |
| 5667175 | Versatile Wind Resistant Sign Stand | 1995-6-12 |
| 5725186 | Universal Flexible Sign Mounting Device | 1998-3-10 |
| 5729926 | Roll-Up Sign with Removable Batten | 1996-4-18 |
| 5732911 | Legless Sign Stand | 1996-5-3 |
| 5746406 | Tripod Stand | 1996-3-26 |
| 5895024 | Collapsible Holder for Warning Device | 1997-8-15 |
| 6003827 | Universal Sign Holder | 1997-8-27 |
| 6032908 | Sign Stand with Cam Release Assembly | 1999-2-9 |
| 6237268 | Sign Stand with Single Spring Base Assembly | 1999-2-9 |
| 6237883 | Sign Bracket for Sign Stand | 2000-2-18 |
| 6463687 | Collapsible Safety Sign | 1998-9-25 |
| 6622409 | Collapsible Safety Sign | 2002-10-15 |
| US 2003/0029067 | Collapsible Safety Sign | 2002-10-15 |

### 2.1.2 Sign Holder Design Review

In the emerging period of portable traffic sign development when the brace was made of hollow aluminum, steel, or rigid plastic with a rectangular cross section, the brace was mounted by inserting the batten directly into the stand, which was also made of aluminum or steel. In U.S. Patent 4507887(Seely and Ursprung, 1985), the mounting method adopted spring and channel members to hold the brace as shown in Figure 2.3. In U.S. Patent 5152091(Leach, 1992), buckle members or fastener slides were used to attach the brace to the stand. The most recent mounting method was found in U.S. Patent 6032908 (Hillstrom and Levin, 2000) as shown in Figure 2.3. In the patent, a C AM release assembly for mounting the brace was described. The author suggested that the assembly could be used with various sign designs.

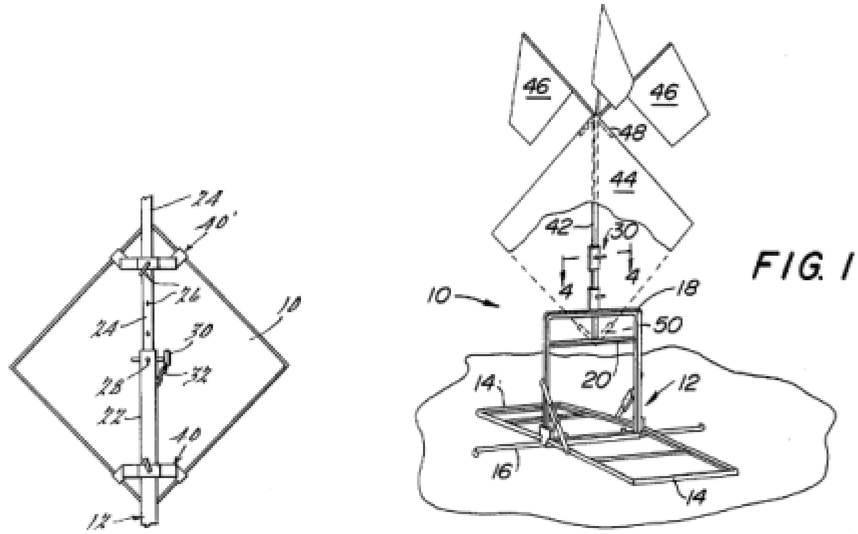



Figure 2.1 Early Brace Design of the Roll-up Sign (Left: U.S. Patent 4280853, Right: U.S. Patent 4309836)

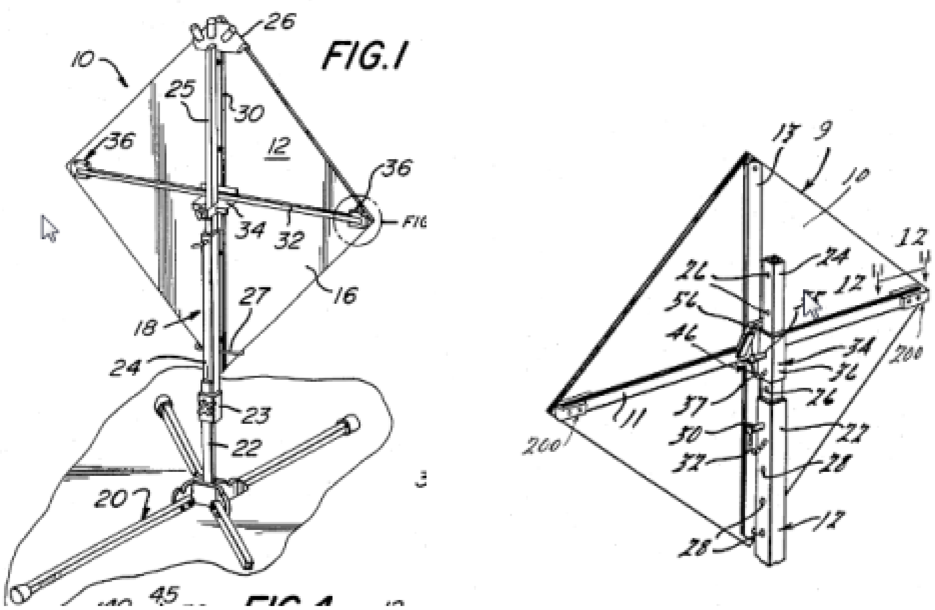



Figure 2.2 Brace Design of the Roll-up Sign (Left: U.S. Patent 4490934, Right: U.S. Patent 4548379)

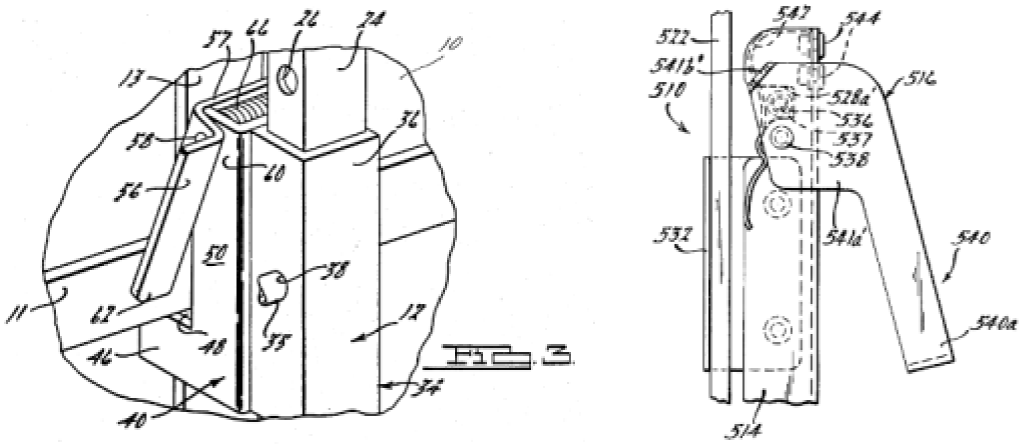


Figure 2.3 Mounting Methods and Rubber Base Stand (Left: U.S. Patent 4507887, Right: U.S. Patent 6032908)

## 2.2 Classifications of the Portable Roll-Up Signs Currently Available on the Market

Product catalogs from eight companies were chosen for review, and they are summarized in Table 2.

Table 2.2 List of Company Catalogs Used in This Review

| **Company** | **URL** |
|---|---|
| Dicke Safety | http://dicketool.com/ |
| Rice Signs | http://www.ricesigns.com/ |
| Sign-Up Corp | http://www.signupcorp.com/ |
| USA-Sign | http://www.usa-sign.com/ |
| Bone Safety Sign | http://www.bonesafety.com/ |
| 3M | http://solutions.3m.com/wps/portal/3M/en_US/Traffic_Safety/TSS/Offerings/Products/Work_Zone/ |
| S&S Signs & Safety Equipment | http://www.signssafety.com/Default.aspx |
| TrafFix Devices, Inc. | http://www.traffixdevices.com/ |

### 2.2.1 Bracing Types

Braces manufactured by Sign-Up Corp (Sign Up Corp, 2010), USA-Sign (USA-Sign, 2007), and TafFix Devices Inc. (TrafFix Devices Inc., 1998-2010) are made of fiberglass. As shown in Figure 2.4, the braces consist of two pieces of fiberglass: one oriented vertically and the other oriented horizontally. The braces are usually attached to the sign sheeting via inserting the horizontal brace into two pockets as shown in Figure 2.5.

Since most products currently adopt fiberglass rather than an aluminum alloy or wood as the material for fabricating braces, typical properties of fiberglass is summarized in Table 2.3. Compared with other materials, fiberglass offers several advantages: versatility and freedom of design, affordability and cost effectiveness, lightweight and durability, better appearance, and electrical insulation. Fiberglass can be fabricated into various cross sections without adding cost. Fiberglass is resistant to corrosion. Such properties give fiberglass longer life expectancy than metals and wood. Finally, fiberglass is non-conductive which makes it suitable for circumstances in which using conductive metal may pose a safety hazard to human beings.

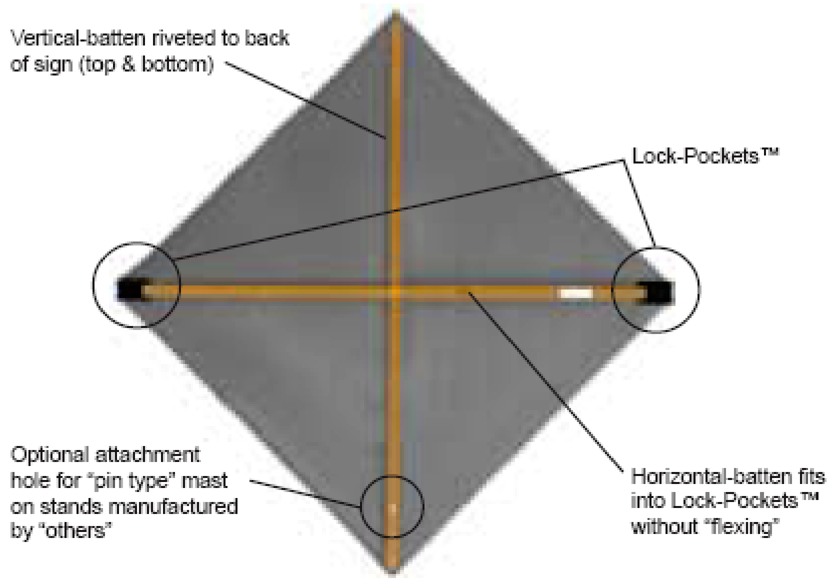



Figure 2.4 Braces of Roll-Up Sign (USA-Sign, 2007)

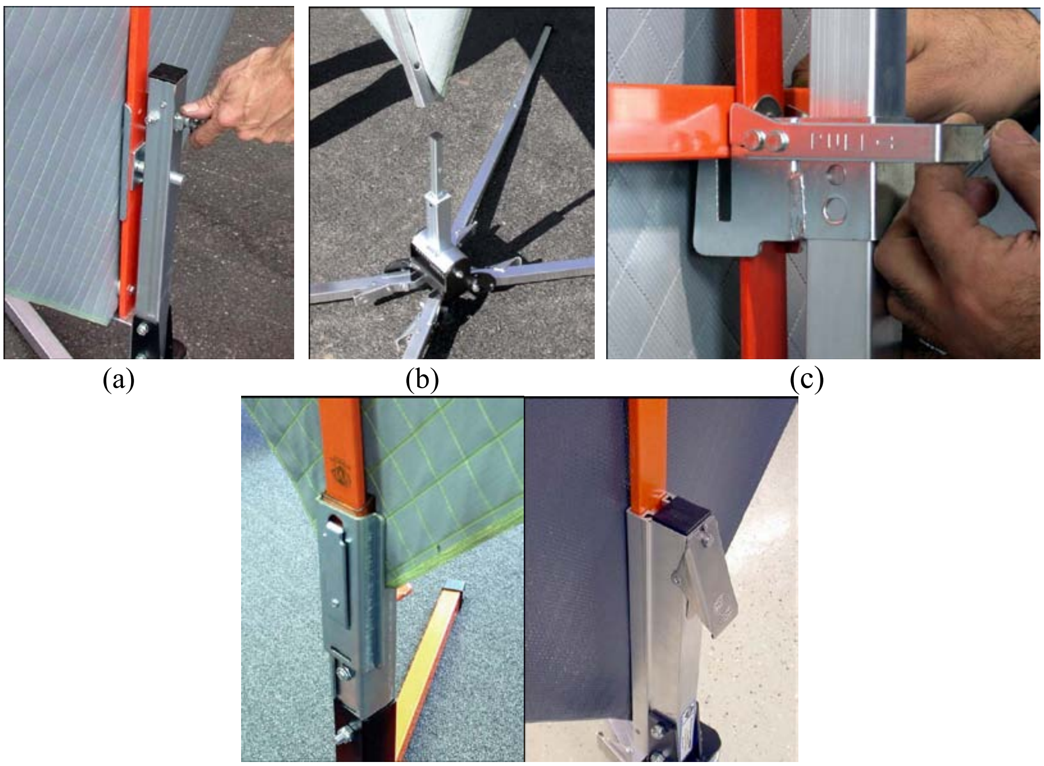
Figure 2.5 Sewn Corner Pocket and Plastic Corner Pocket (TrafFix Devices Inc., 1998-2010)

### 2.2.2 Sign Holder and Base Types

According to catalogs of manufacturers such as Dicke Safety (Dicke Safety Products, 2009), Rice Signs (Rice Signs, 2009), Bone Safety Sign (Bone Safety Signs, 2007-2010), and etc, several mounting methods are available. Figure 2.6 presents the mounting schemes. Since most braces of roll-up sign are made of fiberglass, they are unlikely to be mounted with the Stablock depicted in Figure 2.6(b). The connection between the stand and legs may be made with one or two heavy duty springs in some cases. A rubber base can also be used instead of aluminum legs.

Table 2.3 Typical Fiberglass Properties

| Properties | Value |
|---|---|
| Flexural strength, psi | 16,000 to 32,000 |
| Flexural modulus, psi | 0.8 to 1.4 x106 |
| Tensile strength, psi | 9,000 to 18,000 |
| Tensile modulus, psi | 0.8 to 1.4 x106 |
| Elongation | 1.0% to 2.5% |
| Compressive strength, psi | 15,000 to 25,000 |
| Impact strength izod, lb./in. of notch | 4 to 12 |
| Density, lbs./ft.3 | 80 to 110 |
| Continuous heat resistance | 150 to 350 |
| Thermal Coefficient of Expansion, in/in/Fx 10- | 12 to 20 |
| Barcol hardness | 40 to 60 |



(a) (b) (c)

(d) (e)

Figure 2.6 Mounting Scheme (Dicke Safety Products, 2009): (a) Screwlock, (b) Stablock, (c) Roll-Up Bracket, (d) Pocket, (e) Channel

### 2.2.3 Sheeting Types

3M manufactures roll-up sign sheeting (3M, 2010). In accordance with its product bulletin RS20/24, the sheeting is visible, light-activated, fluorescent, and wide-angle reflective. The sheet is backed with strong, flexible, gray-coated fabric. The retro-reflective surface of the sheeting is weather-resistant. No appreciable racking, blistering, crazing, edge lifting or curling, or dimensional change of more than 0.031 in. (0.08 cm) can be found after one year's unprotected outdoor exposure. Other properties such as impact resistance, shrinkage, flexibility, gloss, tensile strength and tear resistance are also determined by a series of tests. Table 2.4 summarizes the test items, conditions, and requirements.

Table 2.4 Test Items, Conditions and Requirements for Roll-Up Sign Sheeting (3M, 2010)

| Properties | Test Method | Requirement |
|---|---|---|
| Impact Resistance | Apply Scotch™ Double Coated Tape 665 to an etched aluminum panel of Alloy 6061-T6 0.04 inch x 3 inch x 5 inch. Apply RS20/RS24 to the taped surface grey side down and condition as in A1 above. Subject sheeting to 50 inch-pounds (5.7 Nm) impact in accordance with ASTM D-2794. | No separation from panel or cracking outside the immediate impact area. |
| Shrinkage | Following conditioning of 9 inch x 9 inch samples, place specimen on flat surface with gray side up. | Shrinkage not greater than 1/32 inch (0.8 mm) in 10 minutes, or more than 1/8 inch (3.2 mm) in 24 hours in any dimension. |
| Flexibility | Condition a 1 inch x 6 inch sample. At standard conditions, bend in one second around 1/8 inch (3.2 mm) mandrel with gray side facing mandrel. | No cracking. |
| Gloss | Test in accordance with ASTM D523 using an 85° glossmeter. | Rating not less than 50 |
| Tensile Strength | Test in accordance with Federal Standard 191 Method 5100 except using a 2 inch jaw gap and a cross head speed of 6 inches/minute. | Typical force values of:<br>• Warp Direction – 130 pounds force<br>• Fill Direction – 150 pounds force |
| Tear Resistance | Test in accordance with ASTM D1044 except use a cross head of 12 inches/minute. | • Warp Direction – 50 pounds force<br>• Fill Direction – 60 pounds force |

## 2.3 State and Federal Regulations/Specifications

### 2.3.1 Federal Regulations/Specifications

*The Manual on Uniform Traffic Control Devices* (MUTCD) published by the Federal Highway Administration (FHWA, 2009) is the primary standard for traffic control signs, both permanent and temporary. However, the MUTCD is primarily concerned about size and message standardization. It provides no definitive description of materials or sign support structures.

A memorandum from the FHWA dated August 28, 1998 from the Director of the Office of Engineering outlined three device categories, the required crash worthiness in response as evaluated by NCHRP Report 350, and a list of approved devices. Some of the listed devices included in the list did not meet the requirements of Section 3.2.3.2 and/or Test Level 3 of NCHRP Report 350. These have been included to help designers identify failing designs (Federal Highway Administration, 2009; Ross, Sicking, & Zimmer, 1993).

### 2.3.2 State Regulations/Specifications

States are required to comply with federal requirements. To this extent, many states have simply adopted the MUTCD and the Manual for Assessing Safety Hardware (MASH), or NCHRP Report 350 as the controlling specifications for their roll-up signs.

#### 2.3.2.1 TxDOT Regulations/Specifications

TxDOT on the other hand has several such standards. TxDOT Specification 801-60-66 provides guidance on the minimum requirement for portable roll-up signs. Specifically, these signs must be compatible with TxDOT 801-12-77 and TxDOT 801-12-78. The specification goes into great detail concerning visibility requirements. The specification also describes the size and material of the battens. The battens must be fiberglass with maximum cross sectional areas of 1.25 in. by 0.187 in. for the horizontal member and 1.25 in. by 0.330 in. for vertical battens. According to this specification, the cross members may be connected using a bolt, washers and self-locking nut, or rivets. The pockets used to connect the sign face to the supports have their minimum and maximum size specified. An anti-kiting strap is also required. The sign must also be warranted against failures for 24 months. (TxDOT, 2010)

TxDOT Departmental Material Specification DMS-8310 - *Flexible Roll-up Reflective Signs* - provides very specific guidance for the fabric portion of flexible roll-up signs, i.e., sign face. The specification outlines minimum sign face strength, stiffness, reflectivity and corner reinforcing. Very little detail is given concerning the structural material used to support the flexible signs. Section 8310.6.D.2 specifies “glass reinforced resin or other suitable material” for the cross bracing material which must be capable of resisting 40 mph wind speeds “without causing sign material to distort enough to affect legibility of the sign.” Though this does provide some guidance, much more is left open for interpretation. For example, what size sign must be supported? How much distortion can take place before legibility is affected? Section 8310.6.D.3 requires that the cross bracing ends be rounded to increase the sign durability. It also requires a double-head, 1/2in. pop rivet to connect the braces at the center. Additionally, it specifies an aluminum washer spacer between the cross braces. (TxDOT, 2007)

A major interpretive difficulty arises when one attempts to meet both TxDOT 801-60-66 and TxDOT DMS 8310. TxDOT DMS 8310 is more restrictive in terms of connection details than TxDOT 801-60-66. However, TxDOT 801-60-66’s maximum size requirements may prevent any sign from satisfying some of the performance based requirements of TxDOT DMS 8310.

TxDOT Specification 801-12-77 contains specifications for one foot high roll-up sign stands. This requires that sign stands conform to the federal documentation in the MUTCD and NCHRP Report 350. The functional requirements are very detailed in relation to design. It requires a four leg design, adjustable for level terrain, spring-loaded catches and easily deployable/storable by one person. The sign attachment may be either spring-loaded with a snap-in connector or a pressure plate bracket that will receive the signs outlined in TxDOT 801-60-66 and any manufacturers' 48 in. × 48 in. diamond roll-up sign faces. Additionally, the sign must resist 50 mph winds without overturning. Weights such as sandbags are not permitted when evaluating this capability. When stored the sign stand may not exceed 25 in. × 8 in. × 8 in. The maximum permitted weight is 23lbs, presumably to maintain Category II crash test requirements of the MASH (AASHTO, 2009). It also outlines a minimum foot print of 39 in. × 64 in. The sign must be warranted for a minimum of 24 months. This design standard is appropriately detailed. It might be improved by providing more specific wind requirements and minimum deflections under wind loads. Additionally, the language of the specification is ambiguous about whether all signs should be spring supported or if rigid signs are permitted. (TxDOT, 2010)

TxDOT Specification 801-12-78 provides guidelines for a seven foot high roll-up sign stand. The majority of the specification is identical to TxDOT 801-12-77. Additionally, TxDOT 801-12-78 specifies the size of the support mast, a 85 in. × 14 in. × 9 in. storage size and a maximum weight of 47lbs. (TxDOT, 2010)

#### 2.3.2.2 Other State DOTs' Regulations/Specifications

*Alabama DOT*

The Alabama Department of Transportation has two specifications for roll-up signs. Specification 2000-01 provides guidance for 48 in. × 48 in. signs, while Specification 2000-02 provides guidance for 36 in. × 36 in. signs. The specifications are basically identical. They require the signs to satisfy any applicable Federal and ASTM specifications. The sign supports must be fiberglass. The vertical support should be 1.25 in. wide with a thickness to width ratio of less than 0.3. The horizontal support should also be 1.25 in. wide, but with a thickness to width ratio of less than 0.15. The supports must resist 65 mph winds without breaking. The Alabama specifications also require Lexan corner pockets which allow for easy assembly and disassembly with minimum bending stress applied to the support. The supports must be riveted together. Additionally, the signs must be warranted for one year. (Alabama Department of Transportation, 2004; Alabama Department of Transportation, 2004)

*Florida DOT*

The Florida Department of Transportation has several documents pertaining to road side, temporary signage. The bulk of these documents are specific design drawings of various approved signs and supports. These include rigid and spring support systems. The remaining body of literature contains clarifications and reiterations of the federal specifications. (Florida Department of Transportation, 2009)

*Kansas DOT*

The Kansas Department of Transportation has Section 2203 of their state specifications governing roll-up signs. Their only structural requirement for their signs is that they need to meet the requirements for Category II devices under NCHRP Report 350 for crash testing. (Kansas Department of Transportation, 2007)

## 2.4 Existing Research Studies

### 2.4.1 Wind and Vehicle Gust Loads

The research team has not found any reports of previous study dedicated to wind loading of roll-up signs. However, extensive research has been conducted to study wind and vehicle-induced-gust loading on highway signs with flat plates. Most of these previous studies were focused on permanent signs. In assessing loading due to natural wind, the total force was evaluated as the superposition of a mean component due to the mean wind speed and a fluctuating component due to the turbulence in the wind. In particular, a quasi-steady assumption was adopted in evaluation of the fluctuating force, meaning that the force coefficients are independent of frequency and that second order terms can be ignored. Letchford (2001) conducted wind tunnel tests to assess the force coefficients of rectangular signs in the atmospheric boundary layer for a variety of wind attack angles. The outcome of this study has been incorporated in the standard for Minimum Design Loads for Buildings and Other Structures published by the American Society of Civil Engineers (ASCE 2005). Other previous research (e.g., Hosch and Fouad 2009; Kacin et al. 2010), however, neglected the fact that the signs are located in the lower level of the atmospheric boundary layer, where wind can be highly sheared and often turbulent, and used the force coefficients of the plates associated with uniform, smooth wind to calculate wind force acting on signs. As a result, the estimated wind force can be significantly different from that acting on the prototype signs in the field. Furthermore, many previous studies often only considered the situation when the wind is perpendicular to the face of the sign and neglected the effect of oblique wind. This can also lead to an underestimation of the torque acting on the sign support.

Both experimental and analytical studies have been done to investigate wind loading on highway signs due to vehicle-induced gusts. Cali and Covert (2000) conducted a series of full-scale tests to measure the effect of, for example, vehicle size, speed, and the gap between the vehicle and the sign plates on the loading of rectangular highway signs. On the basis of the experimental studies, Sanz-Andrés et al. (2003) and Barrero-Gil and Sanz-Andrés (2009) developed analytical models to enable qualitative characterization of the response of a rectangular traffic sign when a vehicle passes close to it. However, some overly simplified assumptions, such as the boundary layer generated by the vehicle, were made in the models. This limits practical application of the models.

In addition to the research associated with permanent traffic signs, a limited number of studies have also been conducted to study wind loading of temporary portable signs. Quinn et al. used both full-scale measurement and analytical study to investigate the loading on portable signs due to both natural wind (Quinn et al. 2001a) and vehicle-induced gusts (Quinn et al. 2001b). This research highlighted the significance of the sheared and turbulent nature of the wind in the bottom atmospheric boundary layer in the loading of traffic signs. It is also revealed that the transient effect of vehicles was in the form of static pressure pulse rather than in the form of a consistent vehicle-induced "gust" effect.

The major difference between behavior of flat sign plates and that of roll-up signs with fabric faces when subjected to wind pressure lies in the fact that the fabric faces deform significantly under loading, while the deformation of the flat plates can be neglected. As a consequence, the force coefficients of flat plates is only a function of the wind attack angle, while those of roll-up signs are a function of both the wind attack angle and the shape of the sign face, which makes determination of the loading much more difficult. Although some previous studies have investigated the wind loading of deformable faces, the nature of the problems subjected to study was very different from the loading of roll-up signs. For example, extensive studies have been conducted to study the loading of sails (e.g., Flay and Jackson 1992; Viola and Fossati 2008). The objective of those studies, however, was to optimize the shape of the sail in order to maximize the wind loading. As another example, studies have been previously conducted to study the loading of membrane type building or vehicle roofs (e.g., Knight et al. 2010). The focus of these studies, however, was on the lift force acting on the membrane due to wind induced external pressure instead of the drag force, which is the most significant force acting on the fabric face of roll-up signs.

### 2.4.2 Crashworthiness

Crashworthiness of a portable roll-up sign is based on full scale crash testing in accordance with MASH (AASHTO, 2009). The evaluation criteria of MASH are based on three areas, structural adequacy, occupant risk, and vehicle trajectory after collision. AASHTO's most recent update to crash testing, the Manual for Assessing Safety Hardware (MASH) was published in 2009. The full scale crash tests of temporary portable signs found in the literature preceded MASH and conformed to NCHRP Report 350. Significant changes from NCHRP Report 350 to MASH include the elimination of the marginal pass criteria, as well as replacement of the 820C test vehicle, which is the vehicle used in the crash testing of portable sign supports, with the 1100C test vehicle.

Several studies have been made in order to address the crashworthiness of portable sign supports and signs. Some studies concluded that the portable sign supports are acceptable according to NCHRP Report 350, while others had mixed results, or only a marginal pass (Bligh, 2000; Bligh et al., 2000, Bryden, 1990; Mak et al., 2000; Mak et al., 1998; FHWA, 1998). NCHRP Report 553 recommends that each portable sign system consisting of the structure and sign be tested as a system (NCHRP, 1993). Polivka confirms this by stating that relatively small design modifications could affect performance, and restate that full scale crash testing is necessary for any small design changes (Polivka, 2002). Studies of Finite Element Analysis with the use of LS-DYNA have also been conducted in order to determine the crashworthiness of traffic control devices and barricades and to compare FEA predictions with full scale crash testing data (Atahan, 2006; Concolazio et al., 2003; Linzell and Rado, 2007). These studies have promising results, but full-scale crash testing is still a requirement in order to determine the crashworthiness of a structure.

## 2.5 Concluding Remarks

A comprehensive literature review has been performed in Task 1 of this project which includes the historical development of portable roll-up signs based on U.S. patent, existing studies on wind load effects on portable roll-up sign structures and crashworthiness, and state and federal specifications. The results showed that (i) very limited information is available regarding the behavior of portable roll-up signs under the wind/gust load, and (ii) state and federal specifications related to the portable roll-up sign design do not consider the wind load effects. In addition, there are a great number of variations in the portable roll-up signs in terms of "corner pocket" and "base stand." Therefore, it is necessary to classify the different designs into several groups and identify the most widely used in the State of Texas and other states.

# 3 EVALUATATION OF THE CURRENT PRACTICE

This section presents the findings of Task 2 in which performance evaluation on the portable roll-up signs currently approved and used by TxDOT was conducted. The performance evaluation was conducted on samples obtained from prequalified manufacturers at the component and system levels. At the component level, the mechanical properties of fiberglass frame members were determined. At the system level, complete assemblies of portable roll-up signs were subjected to various wind loads in order to observe the overall system behavior and possible failure modes.

Based on the results obtained through Task 1- Literature Review and the discussion with TxDOT Project Monitoring Committee (PMC) members, a representative type of portable roll-up sign system was determined as shown in Figure 3.1. The representative type is made of fiberglass frames, clip-on pockets and telescopic sign stand. This representative type roll-up sign system was used for the experiments conducted in this task.


Figure 3.1 The Representative Type of Roll-Up Sign Used for the Experimental Work of this Project

## 3.1 Material Characterization Tests

A comprehensive testing program was developed to determine the material properties and understand the behavior of the fiberglass battens as a result of various loadings including tension, compression, flexure, torsion, and combined torsion and bending moment. The tests were conducted on the fiberglass battens from failed sign samples provided by TxDOT to Texas Tech University. The tests were conducted with an MTS machine equipped with a load cell that has a capacity of 55 kips. The data were collected using a Vishay 5100B scanner in conjunction with StrainSmart 5000 software.

### 3.1.1 Types of Test Performed

Table 3.1 summarizes the types of test performed, properties investigated, specimen sizes and the corresponding ASTM standard for the test if applicable.

Table 3.1 Summary of Material Characterization Tests Conducted in Task 2

| Types of Tests | Material Properties Investigated | Specimen Size | | | | Number of Specimens | ASTM Standards |
|---|---|---|---|---|---|---|---|
| | | Type | L (in.) | W (in.) | T (in.) | | |
| Tension | Tensile Strength, $\sigma_{tfu1}$<br>Ultimate Tensile Strain, $\varepsilon_{tfu1}$<br>Young's Modulus, $E_{1t}$<br>Poisson's Ratio, $\nu_{12}$ | 1 | 15 | 1.25 | 0.3125 | 6 | D3039-08 |
| | | 2 | 15 | 1.25 | 0.1875 | 6 | |
| Compression | Compressive Strength, $\sigma_{cfu1}$<br>Ultimate Compressive Strain, $\varepsilon_{cfu1}$<br>Young's Compressive Modulus, $E_{1c}$ | 1 | 1.25 | 1.25 | 0.3125 | | D695-10 |
| Bending | Flexural Strength,$\sigma_{ffu1}$<br>Ultimate Flexural Strain, $\varepsilon_{ffu1}$<br>Flexural Modulus, $E_b$ | 1 | 10.5 | 1.25 | 0.3125 | 5 | D790-10 |
| | | 2 | 10 | 1.25 | 0.1875 | 5 | |
| Torsion | Torsional Capacity<br>Angle twisted, $\theta$ | 1 | 8 | 1.25 | 0.3125 | | N/A |
| Combined Bending and Torsion | Torsional Capacity<br>Angle twisted, $\theta$<br>Bending-Torsion –<br>Interaction Diagram | 1 | 8 | 1.25 | 0.3125 | | N/A |

The tension tests were performed in accordance with *ASTM D3039-08 – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*. The material properties measured from the tension tests included tensile strength in the fiber direction ($\sigma_{cfu1}$), the ultimate strain in the fiber direction ($\varepsilon_{tfu1}$), the modulus of elasticity in the fiber direction ($E_{t1}$), and Poisson's ratio ($\nu_{12}$). The tensile strength ($\sigma_{fu1}$) was defined as the largest load that the specimen was able to withhold before necking or failure, whichever occurs first. Specimens of two different sizes were used for the tension tests as shown in Table 3.1. Type 1 specimens were from the vertical battens and were 15 in. long in the fiber direction with a cross section of 1.25 in. in width and 0.3215 in. in depth. Type 2 specimens were from the horizontal battens and were 15 in. long in the fiber direction with a cross section of 1.25 in. in width and 0.1825 in. in depth.

The compression tests were conducted in accordance with *ASTM D695-10 – Standard Test Method for Compressive Properties of Rigid Plastics*. A fiber reinforced composite material gains its tensile strength primarily from the fibers, but this is not the case for the compressive strength. The fibers are laterally supported by the resin encompassing the fibers. Once the resin begins to crack, the fibers lose this lateral support and begin to buckle. Compression tests in unidirectional fibers always result in a matrix (resin) failure causing the fibers to buckle. The properties determined from the data collected during the compression test included the compressive strength in the direction of the fibers ($\sigma_{cfu1}$), ultimate compressive strain in the direction of the fiber ($\varepsilon_{cfu1}$), and Young's modulus in the direction of the fiber ($E_{1c}$). The compressive strength ($\sigma_{cfu1}$), was defined as the largest load the specimen can withhold before failure. Specimens of one size (i.e., Type 1) were used for this testing as shown in Table 3.1.

The bending tests were conducted in accordance with *ASTM D790-10 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*. The bending test was important because the high wind loads caused the signs to undergo large bending deformations. The material properties determined from the bending tests included flexural strength in the direction of the fibers ($\sigma_{ffu1}$), ultimate flexural strain in the direction of the fibers ($\varepsilon_{ffu1}$), and the flexural modulus in the direction of the fibers ($E_b$). The flexural strength ($\sigma_{ffu1}$) was defined as the ultimate stress the material can withstand as a result of bending. Specimens of two different sizes (i.e., Types 1 and 2) were used for this testing.

Currently, there is no ASTM standard for torsion testing of a fiber reinforced polymer composites of a rectangular cross-section. *ASTM D790-10 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials* was modified to design an appropriate testing set-up. The torsion test was particularly important since the wind loading causes the portable roll-up signs to twist in order to remain perpendicular to the direction of the wind. The material properties determined from the torsion test included the torsional strength and the angle twisted ($\theta$). The torsional strength of the material was determined as the maximum load the material could withstand while being twisted about its longitudinal axis before failure. Specimens of one size (i.e., Type 1) were used for this testing.

The combined torsion - bending testing is another particularly important test since portable signs are subject to this combination of bending and torsion. The combined torsion - bending tests do not currently have an ASTM standard to comply with. As a result, the proposed torsion testing set-up was modified to accommodate bending as well. Specimens of one size (i.e., Type 1) were used for this testing as shown in Table 3.1.

### 3.1.2 Test Set-Ups and Instrumentation

#### 3.1.2.1 Tension Testing

The tension tests were performed under deformation control in accordance with *ASTM D3039-08 – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*. Each specimen was subjected to a constant rate of 0.05 in./min up to failure. Four strain gauges were applied to each specimen to measure the longitudinal and transverse strains. The locations of the strain gauges and the testing set up are shown in Figure 3.2. The actual length of the specimens being tested was 10 in. after 2.5 in. of each end was securely inserted into the grips.

#### 3.1.2.2 Compression Test

The compression tests conducted are in accordance with *ASTM D695-10 – Standard Test Method for Compressive Properties of Rigid Plastics*. The compression test consisted of axially loading the specimen at a constant deformation rate of 0.05 in./min until failure. The compression testing apparatus was fabricated to comply with ASTM 695-10 as shown in Figure 3.2. Strain gauges were applied to each side of the specimens in the direction of the loading.

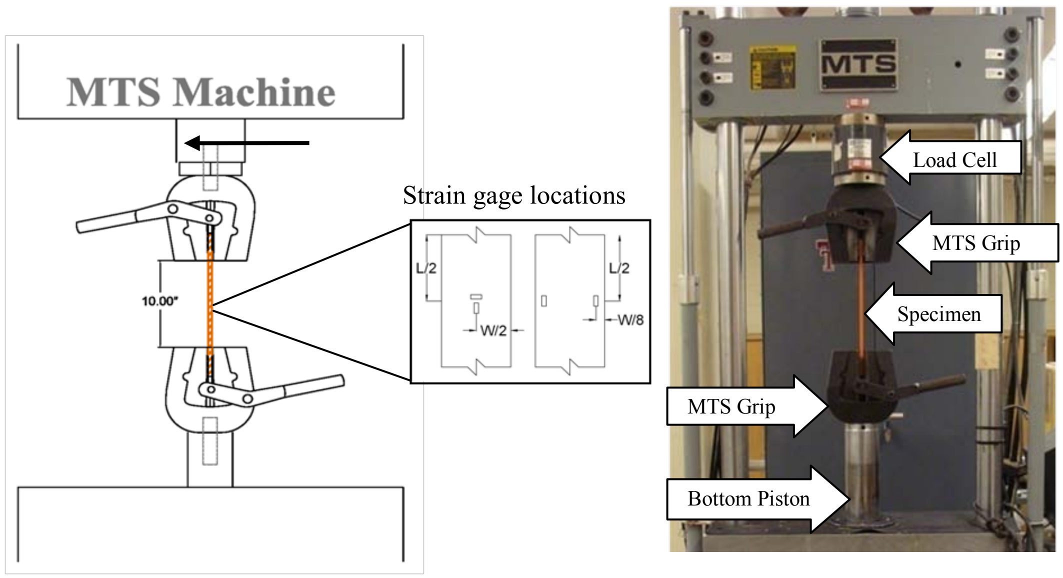



Figure 3.2 Tension Test Set-Up

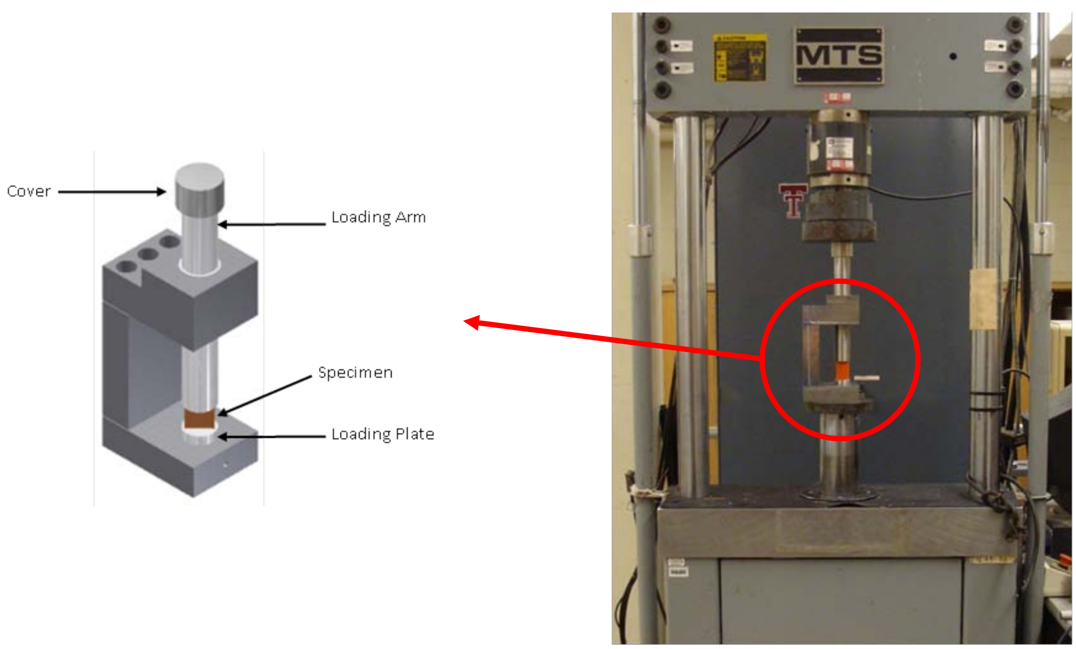



Figure 3.3 Compression Test Set-Up

3.1.2.3 Bending Test

Five specimens of each type were subject to the bending test which consists of a three point loading system in accordance with *ASTM D790-10 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*. The specimen was loaded at a constant rate until the extreme tensile fiber reached a strain of 0.5 in/in or failure, whichever occurred first. Figure 3.4 shows the flexure test set-up. An LVDT is placed at the mid-span to measure the deflection resulting from the load.

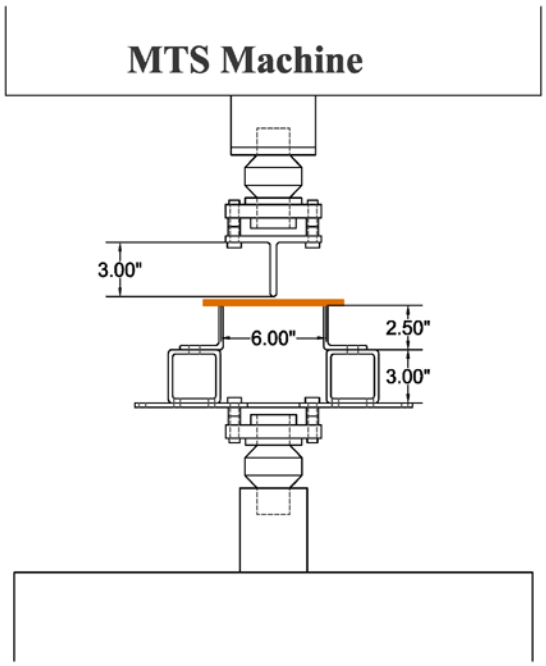




Figure 3.4 Bending Test Set-Up

3.1.2.4 Torsion Test

There is no ASTM standard that can be used to determine torsional capacity of specimens made of polymeric composite materials. Therefore, a test set-up was developed as described in this section. The torsion test consisted mainly of a supporting plate and a loading mechanism. Figure 3.5 depicts the torsion testing apparatus. The supports for the specimen are attached to the supporting plate. The supporting plate is securely attached to the bottom piston of the MTS machine with a special adaptor plate and double threaded coupler. The use of the adaptor plate and double threaded coupler can be seen in the design of the torsion testing apparatus in Figure 3.6. The supports are used to restrain the specimen with one fixed end and one free end which does not allow the displacement of the specimen in the vertical direction but does allow the rotation. A pillow block bearing is used as the fixed end. The pillow block bearing is used to load the specimen in torsion with special adaptor attachments that are used to provide the fixed support needed and to attach a loading pulley to the system. A 0.25-in. cable is welded to the pulley. The cable runs through another pulley that is attached to the load cell on the top crosshead of the MTS machine. The cable then runs back down to the supporting plate where it is attached with an eyebolt. The simple support consists of two plates with a cylindrical attachment in the center that is free to rotate. This cylindrical attachment can accommodate specimens up to 0.325 in. in thickness. The support is able to rotate to facilitate the insertion of the specimen into the apparatus. The specimen is then secured with shims to prevent any unwanted rotation. The total testing span for the specimen is 6.0 in.. The specimen is first inserted into the special adaptor attachments, placed into the pillow block bearing and secured with set screws. The other end is inserted into the simple support and secured with shims. The loading pulley is then attached to the special adaptor attachments with set screws. The test begins by lowering the bottom piston at a constant rate of 0.048 in/min until failure for a 0.325 in. thick specimen. The actual testing setup is depicted in Figure 3.6.

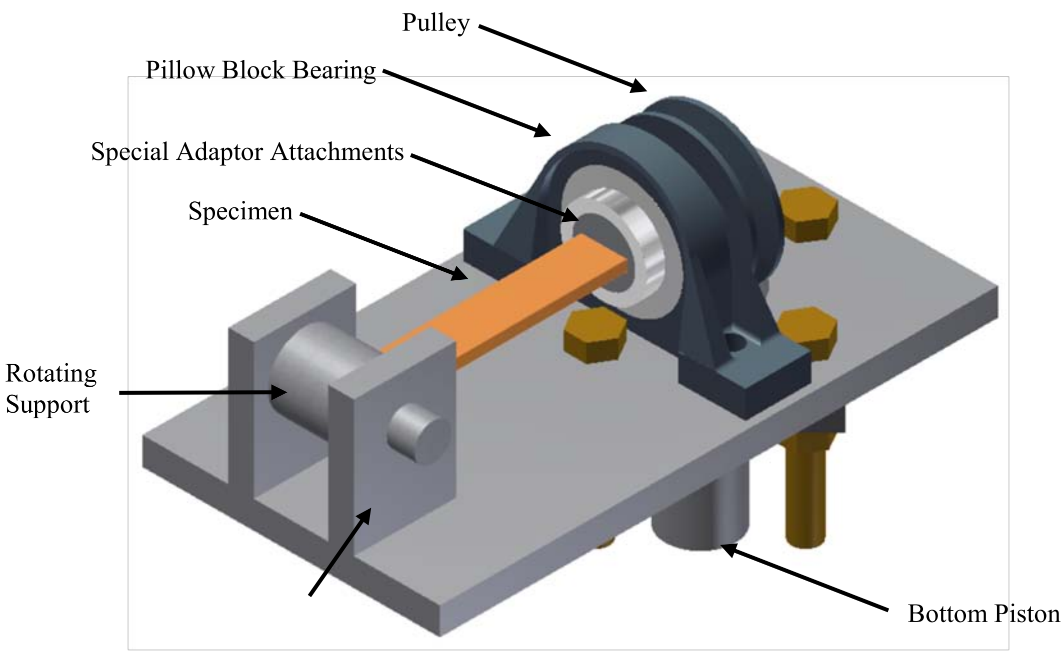
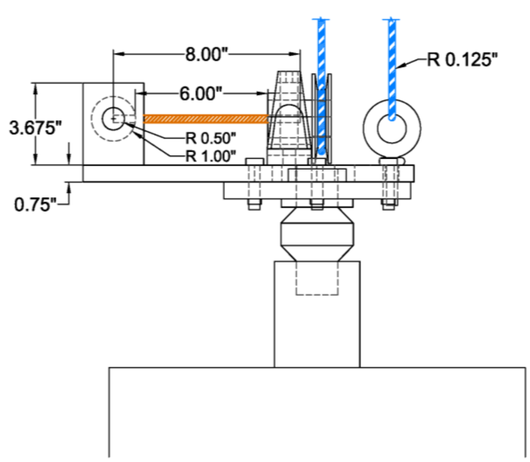



Figure 3.5 Prototype of Torsion Testing Apparatus



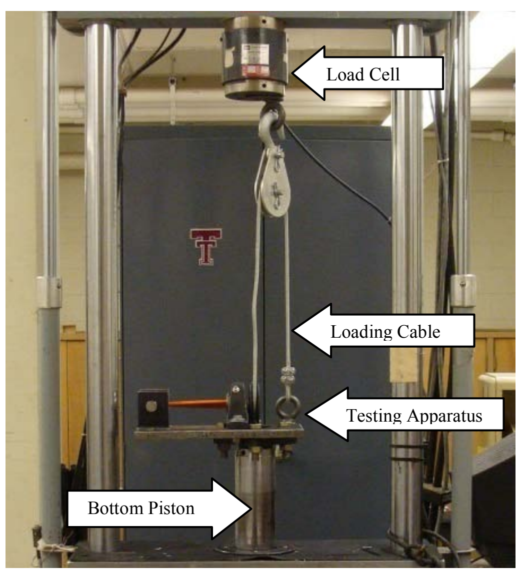




Figure 3.6 Close up of Torsion Test Supporting Plate Design and Actual Torsion Test Set-Up

3.1.2.5 Combined Torsion-Bending Test

The MTS machine and torsion testing apparatus are also used to conduct the combined torsion and bending test. Spacers 0.125 in. in thickness were fabricated in order to add a vertical deflection to the fixed end of the specimen, which then causes a required bending in the specimen. The location of the spacers used to add the displacement is shown in Figure 3.7. The spacers are placed beneath the pillow block bearing. The bending portion of the test is modeled as a cantilever beam using the flexural modulus determined from the data obtained from the flexure tests. Each test consists of one displacement value and the specimen is loaded in torsion until failure. The correct number of spacers is added up to a deflection up to a total of 1 in. for each desired deflection. Deflection is added in 0.125 in. increments. The test is set up identical to the torsion test. Once the test is set up is completed, the bottom piston is lowered which then causes the pulley connected to the special attachments to twist which then causes the special attachments to twist as well. These attachments then begin to twist the specimen accordingly. A close up of the combined torsion and bending test set up is depicted in Figure 3.7.

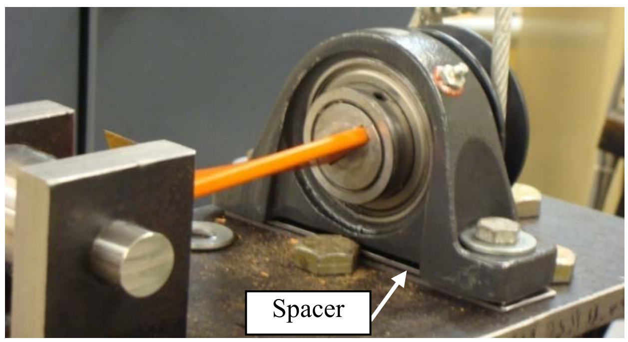



Figure 3.7 Combined Torsion and Bending Test Showing the Spacers Added.

### 3.1.3 Results and Discussion

3.1.3.1 Tension Tests

The material properties determined from the tension tests include tensile strength, ultimate strain, Young’s modulus, and Poisson’s ratio. The stress-strain relationships were created using the longitudinal strain gauges and the load recorded from the load cell on the MTS machine. The stress-strain relationship for the 5/16-in. thick specimen (Type 2) is illustrated in Figure 3.8 while Table 3.2 summarizes the material properties determined from the tension test. The failure mode appeared to be due to the rupture of fibers at various locations. A typical failure for the tension tests conducted is depicted in Figure 3.9.

3.1.3.2 Compression Tests

The stress-strain relationships obtained from the tests on Type 2 specimens (5/16-in. thick) is shown in Figure 3.10 while Table 3.3 summarizes the material properties determined from the compressive tests. Matrix (resin) failure was observed in the compression test specimens. Matrix failure caused the longitudinal fibers to lose the continuous lateral support needed to sustain the load. The fibers ultimately begin to buckle as the matrix damage progresses. The matrix-type failure is illustrated in Figure 3.11. The matrix damage is not localized in one location, but is through the entire member. This can be seen in Figures 3.11(a) and 3.11(d) in the form of vertical striations. A better view of the matrix damage can be seen in Figures 3.11(b) and 3.11(c). The buckling of the fibers, however, is localized at the top and bottom of the specimens.

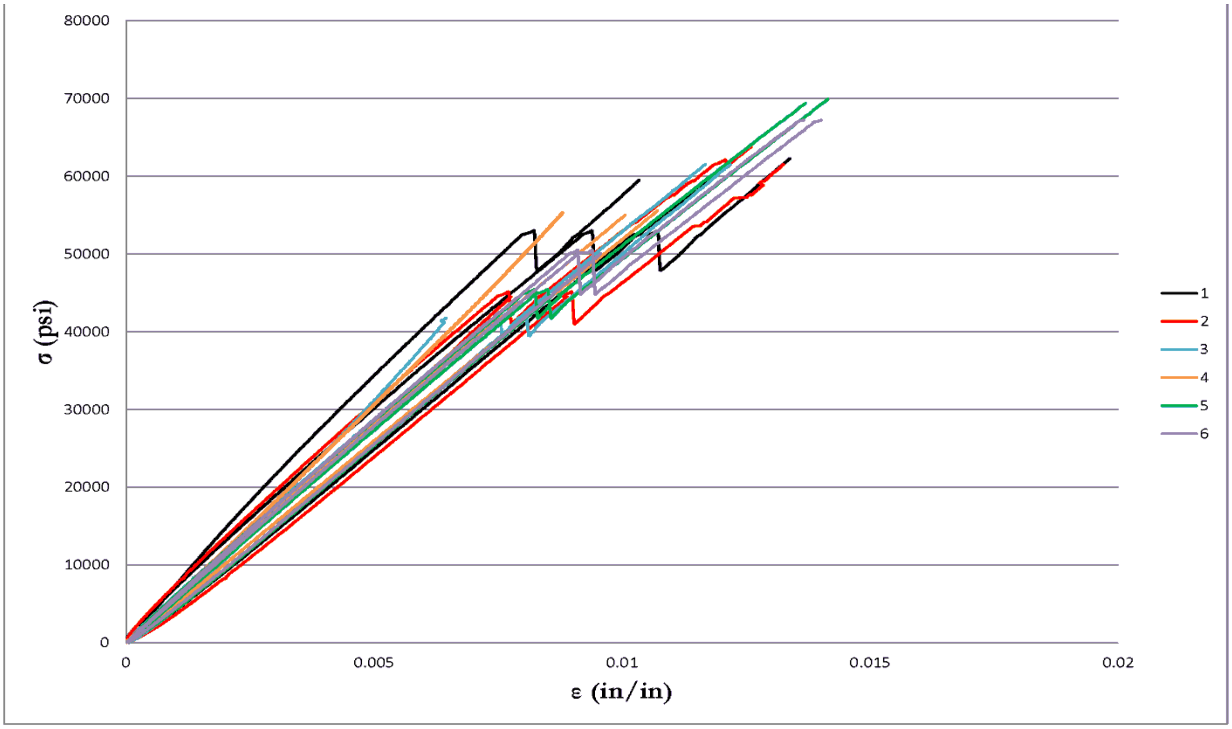



Figure 3.8 Stress-Strain Relationship from Tension Tests on Type 2 Specimens.

Table 3.2 Material Properties Determined from Tensile Tests.

| | **Young's Modulus** | **Poisson's Ratio** | **Tensile Strength** | **Ultimate Strain** |
|---|---|---|---|---|
| Specimen Type 1 - 3/16 in. Thick Fiberglass Bars used for Horizontal Members | | | | |
| Average | 5830 ksi | 0.304 | 86.5 ksi | 0.0149 |
| STD | 350 ksi | 0.053 | 6.5 ksi | 0.0015 |
| COV | 6% | 17% | 8% | 10% |
| Specimen Type 2 - 5/16 in. Thick Fiberglass Bars used for Vertical Members | | | | |
| Average | 5580 ksi | 0.284 | 66.5 ksi | 0.0120 |
| STD | 180 ksi | 0.057 | 5.4 ksi | 0.0011 |
| COV | 3% | 20% | 8% | 9% |

* $\varepsilon_{ult}$ (psi) based on linear behavior

Figure 3.9 Failed Specimen after Tensile Failure.

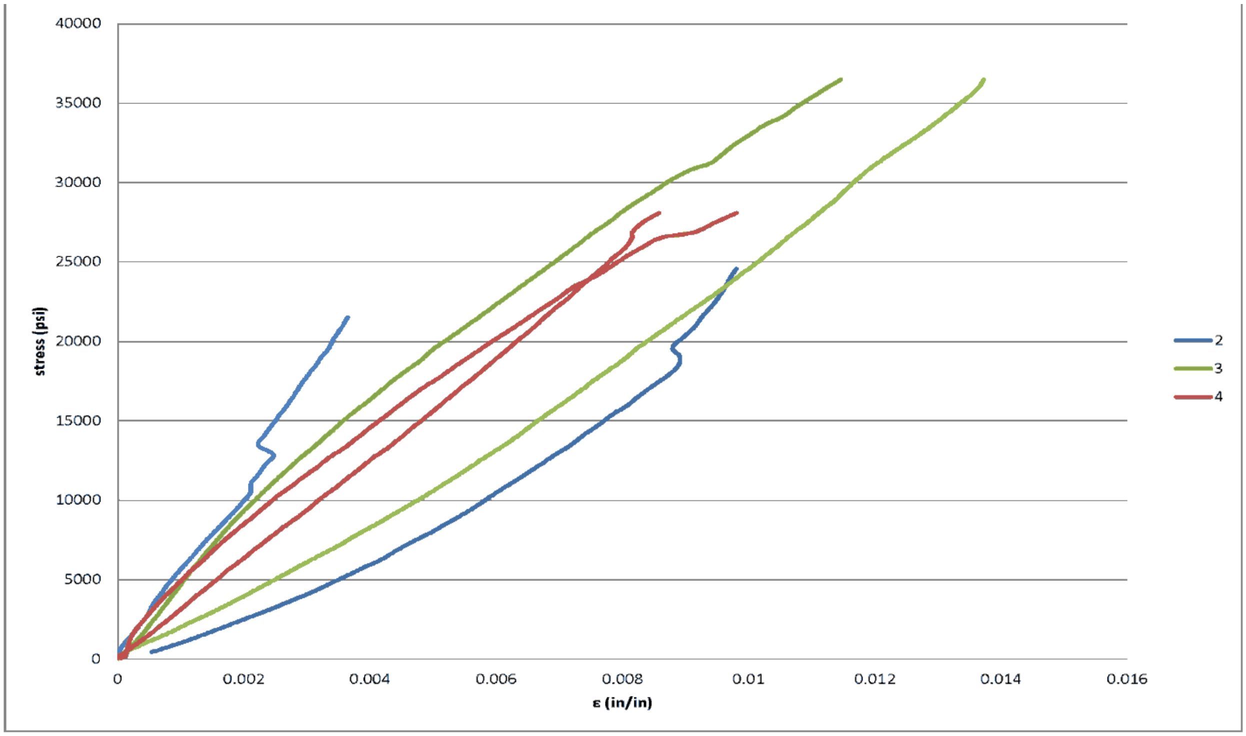
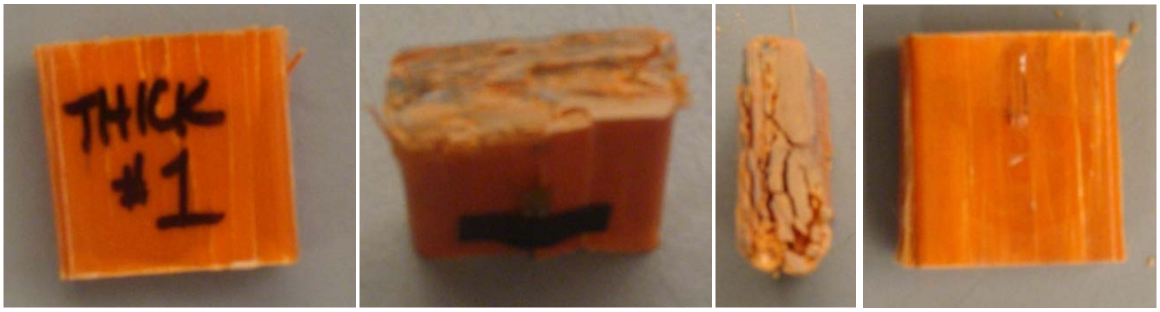



Figure 3.10 Stress Strain Diagram from Compression Test in the Longitudinal Direction.

Table 3.3 Material Properties Determined from Compression Test.

| | **Young's Modulus** | **Compressive Strength** | **Ultimate Strain** |
|---|---|---|---|
| Specimen Type 1 - 5/16 in. Thick Fiberglass Bars used for Vertical Members Transverse Direction Properties | | | |
| Average | 941 ksi | 5.7 ksi | 0.0060 |
| STD | 80 ksi | .5 ksi | 0 |
| COV | 9% | 9% | 0% |
| Specimen Type 1 - 5/16 in. Thick Fiberglass Bars used for Vertical Members Longitudinal Direction Properties | | | |
| Average | 3360 ksi | 35.2 ksi | 0.0103 |
| STD | 84 ksi | 3.6 ksi | 0.0007 |
| COV | 3% | 10% | 7% |




(a) (b) (c) (d)
Figure 3.11 Failed Specimens as a Result of Compressive Failures

### 3.1.3.3 Bending

The moment-deflection relationships for Type 2 specimens (5/16-in. thick specimens) are presented in Figure 3.12 while Table 3.4 summarizes the flexural properties of the materials obtained from the bending tests. The failure mode of the bending specimens was fiber rupture of the outermost fibers of the specimen as shown in Figure 3.13.

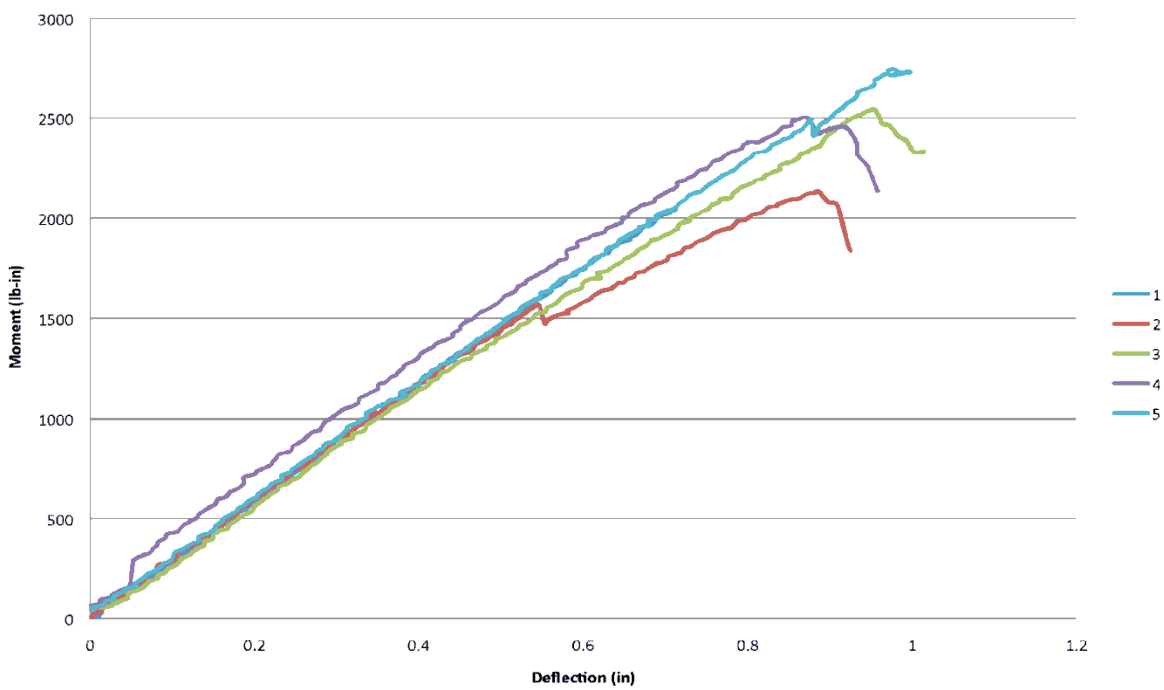



Figure 3.12 Moment-Displacement Curves from Bending Tests

Table 3.4 Material Properties Determined from Bending Tests

| | Flexural Strength | Ultimate Strain | Flexural Modulus |
|---|---|---|---|
| Specimen Type 1 - 5/16 in. Thick Fiberglass Bars used for Vertical Members | | | |
| Average | 128 ksi | 0.0248 | 5040 ksi |
| STD | 12 ksi | 0.0013 | 200 ksi |
| COV | 9% | 5% | 4% |
| Specimen Type 1 - 5/16 in. Thick Fiberglass Bars used for Vertical Members | | | |
| Average | 172 ksi | 0.0190 | N/A |
| STD | 4.3 ksi | 0.00083 | N/A |
| COV | 3% | 4% | N/A |

*Note - According to the ASTM standard, the equation provided for the flexural modulus does not apply for materials that undergo extremely large deformations.

Figure 3.13 Failed Specimen - Bending Failures

3.1.3.4 Torsion and Combined Torsion and Bending

The torsional capacity and the torsional capacity with an added bending moment are the material properties determined by the torsion and combined torsion and bending tests. Figure 3.14 presents the torsion-angle curves for the specimens. The values in the legend represent the amount of displacement (i.e., amount of bending moment) added to the fixed end of the torsion testing jig. The torsional capacity is determined from drawing a line tangent to the initial linear portion of the curve and another line tangent to the slope of the second portion of the curve as shown in Figure 3.15.

Figure 3.16 presents the relationship between the torsion and bending moment. It can be seen from the figure that the bending moment does not have a significant effect on the torsional capacity of the specimen. Table 5 summarizes the torsional capacities determined with the various moments from the added displacements.

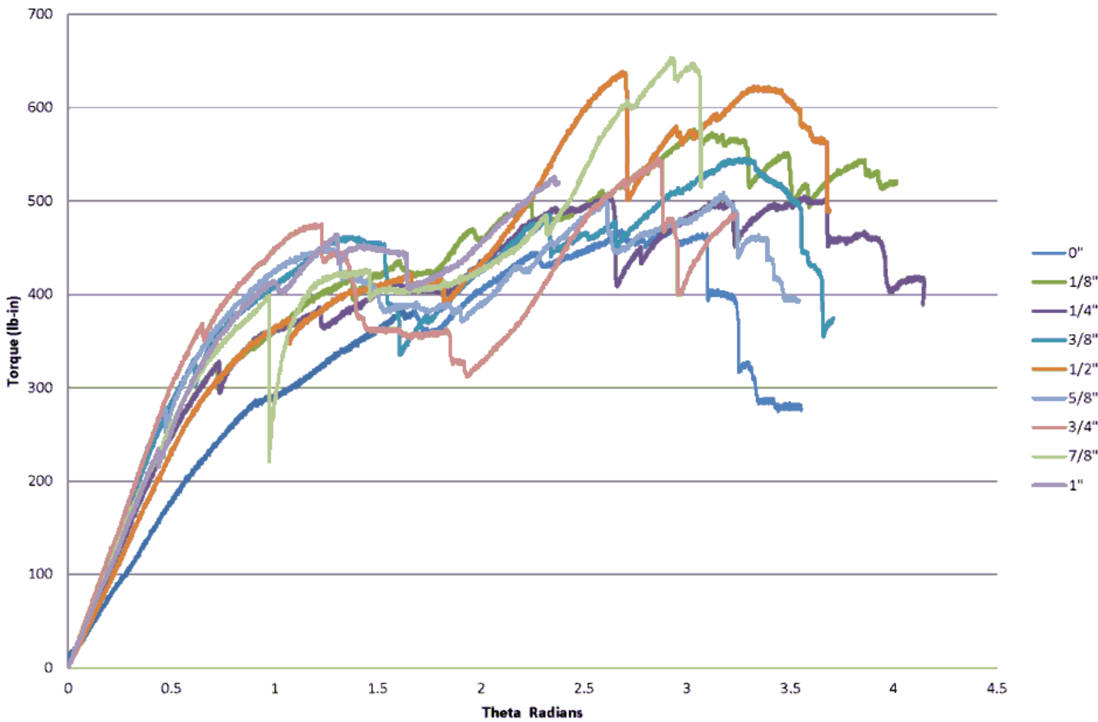



Figure 3.14 Torsional Capacity of 5/16 in. thick Specimen with Respect to the Angle Twisted.

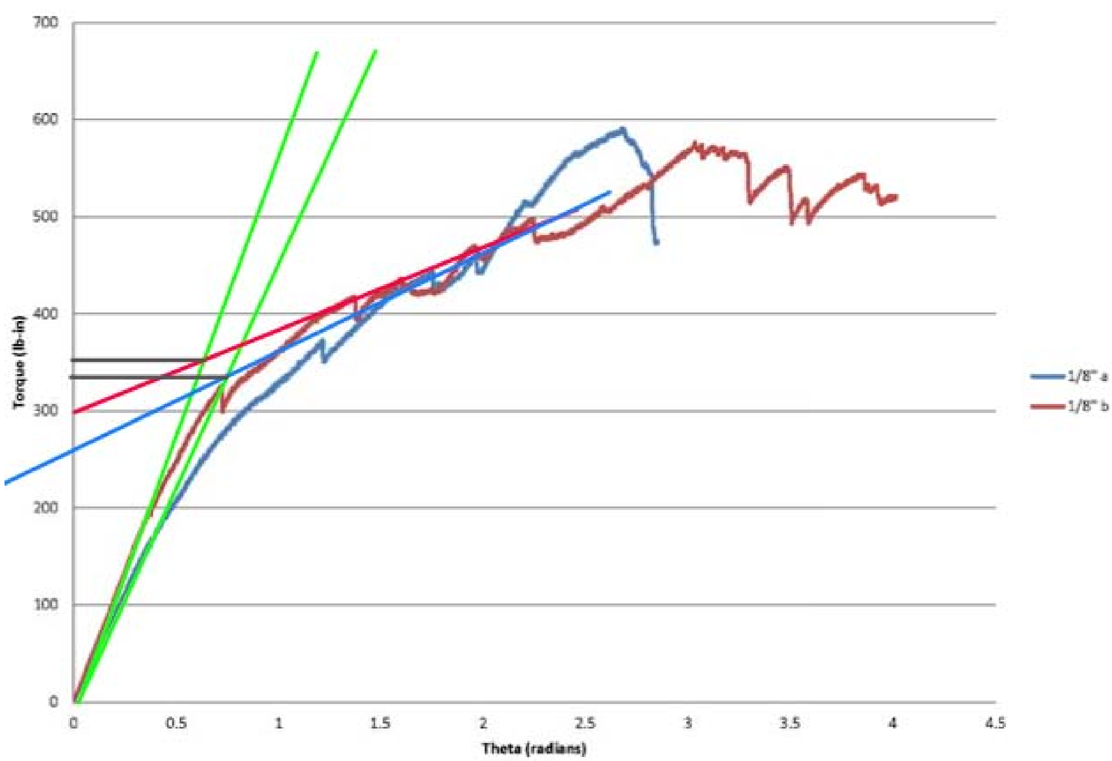



Figure 3.15 Method used to Determine the Torsional Capacity of the Specimen.

The failure of the specimens subjected to the torsion or the combined torsion and bending was due to cracking at the matrix-fiber interface. It is also interesting to observe that the failure was progressive. In other words, the drops in the torsion-angle curve as shown in Figure 3.14 indicate an initial cracking at some fiber-matrix interfaces. However, once the stress was redistributed, the member was still able to withstand the load until the cracking occurred over the entire cross-section as shown in Figure 3.17. Notice that the striations on the member. These striations represent the progressive damage of the member as a result of the loading and redistribution of the stresses.

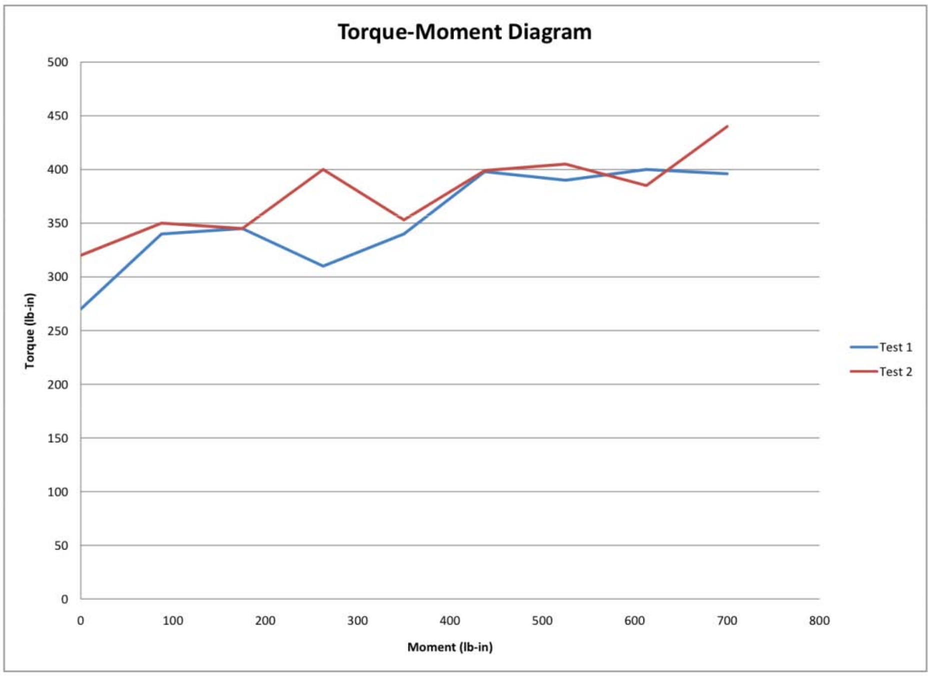



Figure 3.16 Torque-Moment Diagram from Data Obtained in Combined Torsion-Bending Tests.

Table 3.5 Material Properties Determined from Torsion and Combined Torsion-Bending Tests.

| Disp | Avg. | STD | COV |
|---|---|---|---|
| 0" | 295 lb-in | 35 lb-in | 12% |
| 1/8" | 345 lb-in | 7 lb-in | 2% |
| 1/4" | 345 lb-in | 0 lb-in | 0% |
| 3/8" | 355 lb-in | 64 lb-in | 18% |
| 1/2" | 347 lb-in | 9 lb-in | 3% |
| 5/8" | 399 lb-in | .71 lb-in | 0% |
| 3/4" | 398 lb-in | 11 lb-in | 3% |
| 7/8" | 393 lb-in | 11 lb-in | 3% |
| 1" | 418 lb-in | 31 lb-in | 7% |

Figure 3.17 Failure of Specimens Subjected to Torsion

When this project was initiated, it was presumed that the failure of the roll-up signs could be due to the bending of the vertical batten. However, the torsional tests and the combined torsion-bending tests clearly revealed that the failure was due to cracking at the fiber-matrix interface due to torsion. Figure 3.18 compares the failure modes of three samples: (a) vertical batten of a roll-up sign during service, provided by TxDOT, (b) laboratory specimen failed due to bending, and (c) laboratory sample failed due to torsion. Therefore, it would be necessary to increase the torsional capacity of vertical battens to avoid the failure of roll-up signs.

(a) Vertical batten of a roll-up sign during service, provided by TxDOT

(b) Laboratory specimen failed due to bending

(c) Laboratory specimen failed due to torsion

Figure 3.18 Comparison of Failure Modes of Specimens Subjected to Various Loading Conditions.

## 3.2 WIND TESTS

Three different tests were conducted to investigate the behavior of sign assembly under different wind loadings: (i) continuous field tests, (ii) truck-generated wind (tow) tests, and (iii) vehicle gust tests.

### 3.2.1 Continuous Field Tests

The continuous field test represents the typically accepted approach to collecting data regarding naturally occurring wind events. Namely, a sign and instrumentation is deployed at an open field site and data is collected continuously over the course of months and years. The benefits of such an approach include the fact that the data collected is real, that is, represents actual conditions. In addition, the duration allows for the collection of a statistically significant dataset. The drawbacks are the time investment and the potential lack of "**worst case**" loading conditions.

#### 3.2.1.1 Method

The method for collecting the data was to place an instrumented sign and sonic anemometer at the Wind Science and Engineering Research Center field site at the Reese Technology Center, located at the North West of Lubbock, TX.

The sign was instrumented in such a way that the load magnitudes for sign designs might be approximated. Figure 3.19 identifies the approximate location of five linear displacement gages with respect to load locations. The gages were mounted with 2.2 in. gage lengths and are capable of ±0.5 in. displacement measurements. The load cell at the base measured the resultant forces in 6 degrees of freedom. Wind and structural response data was collected at 32Hz using a National Instruments FieldPoint connected to a server.

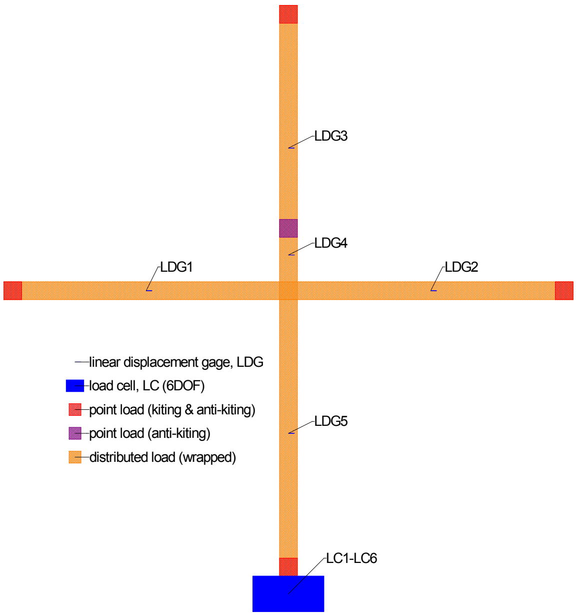



Figure 3.19 Instrumentation


Figure 3.20 Sign at the Field

3.2.1.2 Results and Discussion

The results of these tests have been provided specifically in those areas where the sign seems to fail, namely by combined torsion and bending at the base of the vertical batten. The independent variables of interest include wind angle and attack and the loading condition. There are two potential load configurations currently in use as shown in Figure 3.21 (as determined by examination of the TxDOT Specifications and anecdotal observation):

i. Anti-kiting

Kiting case can occur when the wind hits the back (message-less side a sign). In other words, the sign behaves like a kite. However, this case is not allowed by the current TxDOT specifications. Anti-kiting case is similar to the kiting case. In this case, however, an "anti-kiting strap" adds an additional connection point on the vertical batten, slightly above the center point. This is typical of the TxDOT design.

ii. Wrapped

The wrapped case occurs when the wind hits the front or messaged side of the sign. In this case the sign fabric wraps back onto the cross bracing. This results in a continuous, distributed load on the cross bracing. This load is assumed to be non-linear especially on the vertical batten.

Figure 3.21 Examples of Anti-Kiting and Wrapped Cases

The dependent variables which influence sign failure are bending moment and torsion in the upright member. Throughout the following sections, the results are provided for each bending and torsion load plotted by load case against wind speed and attack angle. Each point was calculated by analyzing 5 minute data subsets to determine statistical means and maximums. The blue lines on each chart represent a rough 95% upper bound based on the average plus 3 standard deviations.

Weak Axis Bending

The weak axis bending should be the controlling bending case. Figure 3.22 compares the weak axis bending moment to wind speed and angle for the anti-kiting and wrapped cases. Unsurprisingly, weak axis bending moment is strongly dependent on wind speed. However, there appears to be no strong correlation with wind angle. The anti-kiting case appears to be generating 40-60% more weak axis bending for a given wind speed than the wrapped case.

Strong Axis Bending

The strong axis bending should not be the controlling bending case. Figure 3.23 shows strong correlation between wind speed and moment. The anti-kiting case appears to be generating 40-50% more strong axis bending than the wrapped case for a given wind speed. There also appears to be some correlation between wind angle and strong axis bending, particularly for the anti-kiting case. Intuitively it makes sense that this should be the case, the more the wind direction runs parallel to the sign face, the more bending moment should be induced in the strong axis direction. It seems odd that the trend only seems to hold for the anti-kiting load case.

Combined Bending

The combined bending (i.e. vector sum of the strong axis bending moment and the weak axis bending moment) case appears to be similar to the weak axis bending case, as shown in Figure 3.24. The moment is directly dependent on the wind speed; while for a given wind speed, the anti-kiting case appears to generate 40-50% more load than the wrapped case. The wind angle does not appear to have nearly the same significance.

Torsion

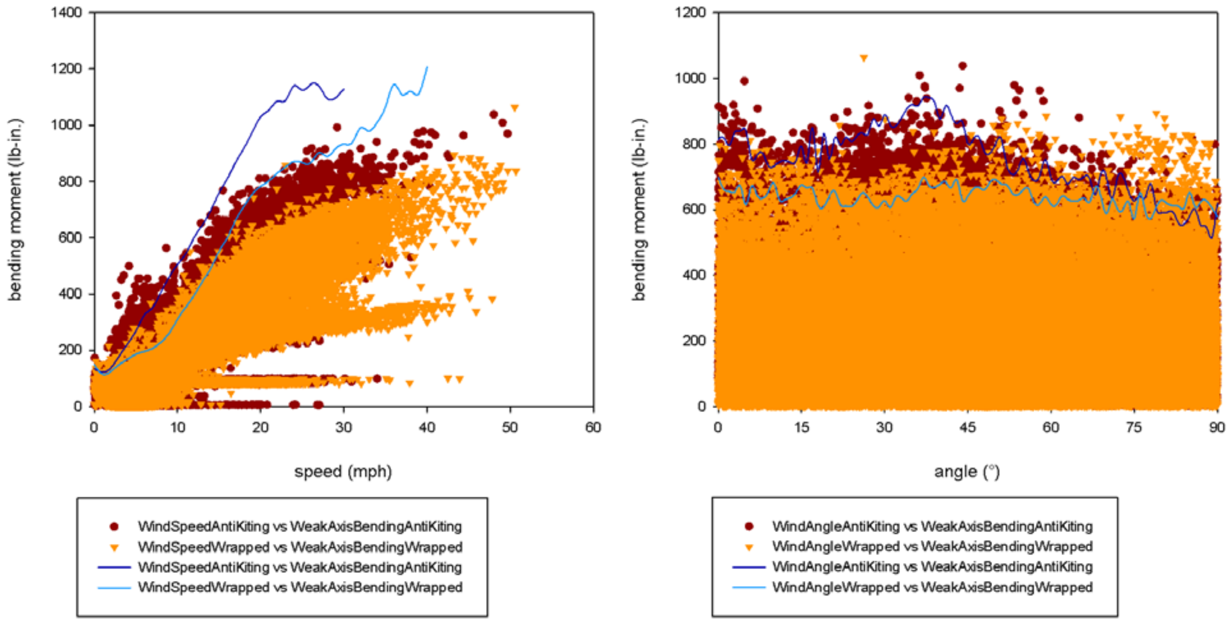
Torsion appears to be proportional to wind speed as shown in Figure 3.25(a). However, there appears to be no discernible difference between anti-kiting and wrapped cases in relation to wind speed. There does appear to be a correlation between wind angle and torsion which suggests that more oblique wind angles produce higher torsion as shown Figure 3.25(b).

Relationship between Torsion and Bending Moment

The signs provided by TxDOT as well as the two signs which failed at the field site indicate that the probable failure is a combination of bending and torsion. Figure 3.26 shows the various bending moments plotted against torsion. The most critical condition is the weak axis bending vs torsion shown in green on the plot. This provides a definable moment-torsion interaction curve. Any replacement material needs to have a moment-torsion strength which falls outside this curve.

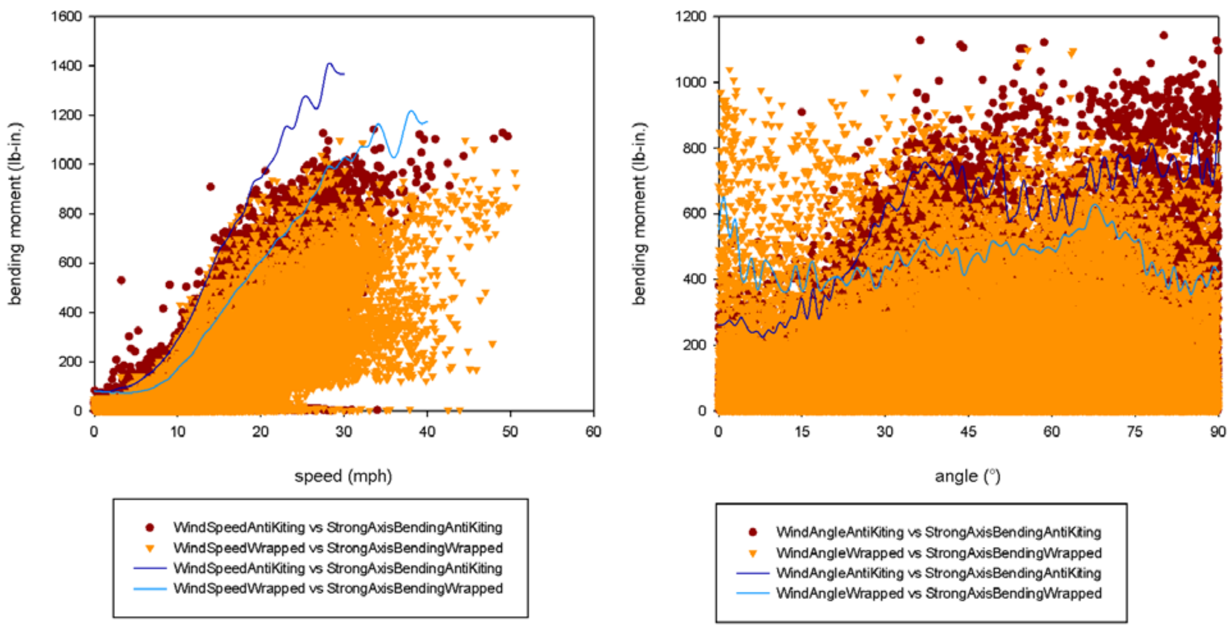
Observations

Several important observations can be made. First, it appears that the anti-kiting case produces as much as 60% more bending moment than the wrapped case. This suggests that a design improvement would ensure the wrapped case over the anti-kiting case. Another critical observation is that loads appear to be dependent on wind speed far more than they are upon wind direction. This is certainly the case for weak axis and combined bending. There is some relationship between wind angle and torsion and strong axis bending. However, these indicate that oblique winds produce higher loads. Finally, the weak axis-torsion plot shows a distinct load case that must be bettered by replacement material properties.



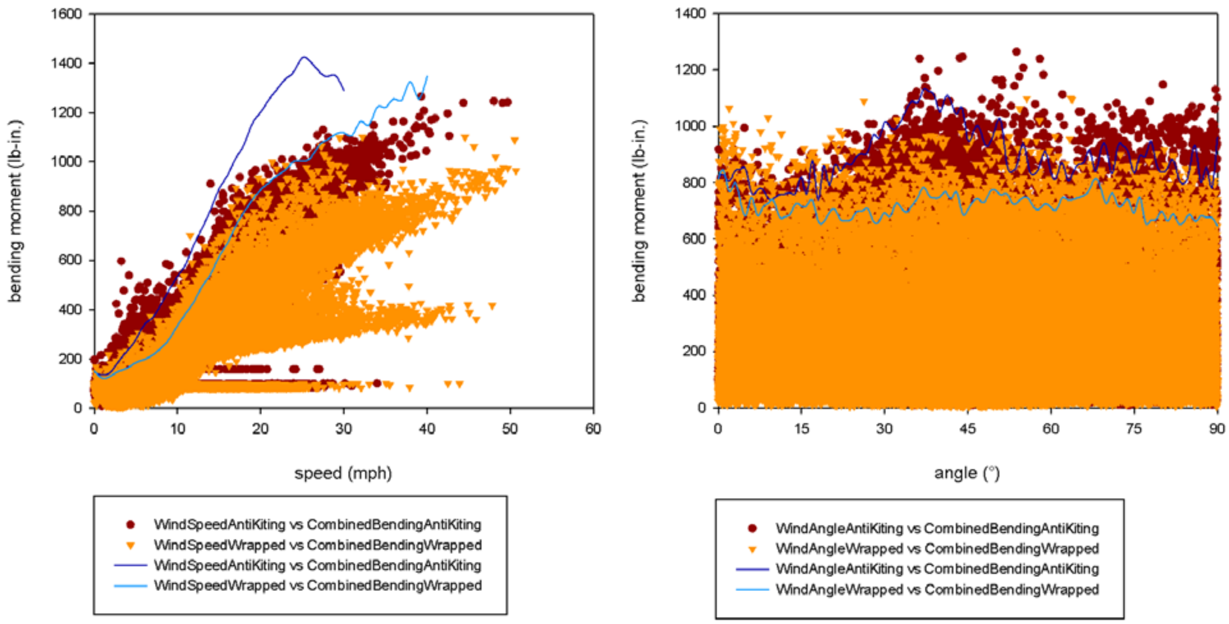

(a) Bending moment vs wind speed (b) Bending moment vs wind angle

Figure 3.22 Weak Axis Bending vs. Wind Speed and Angle Relationship



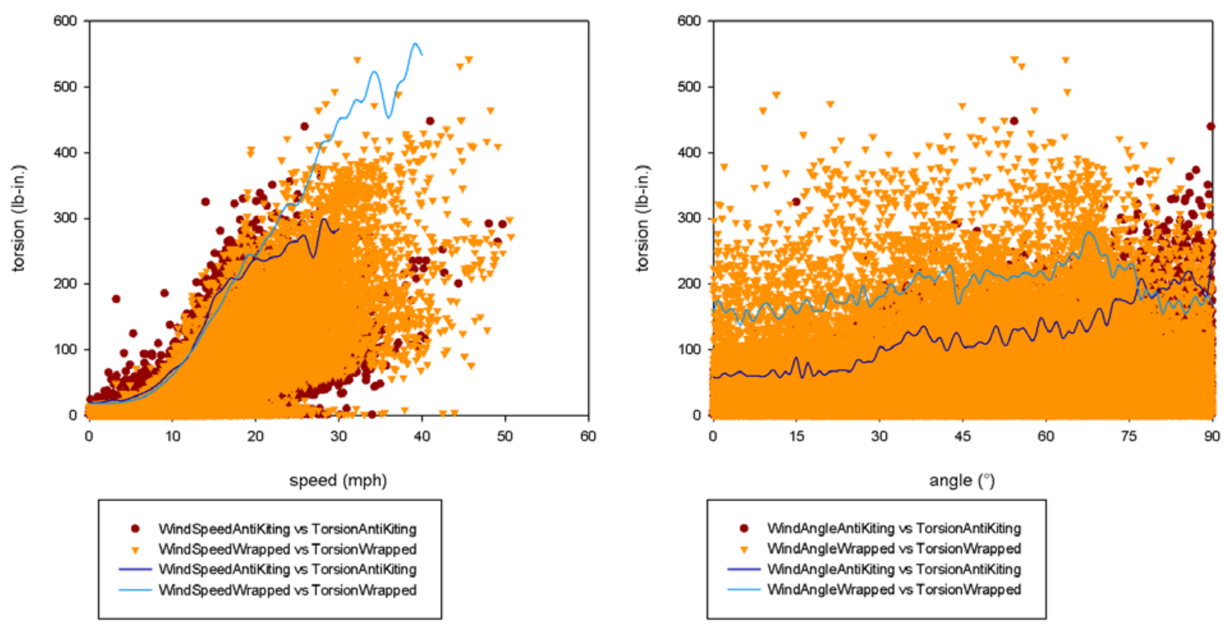

(a) Bending moment vs wind speed (b) Bending moment vs wind angle

Figure 3.23 Strong Axis Bending vs. Wind Speed and Angle Relationship




(a) Bending moment vs wind speed (b) Bending moment vs wind angle

Figure 3.24 Combined Bending vs. Wind Speed and Angle Relationship




(a) Torsion vs wind speed (b) Torsion vs wind angle

Figure 3.25 Torsion vs. Wind Speed and Angle Relationship

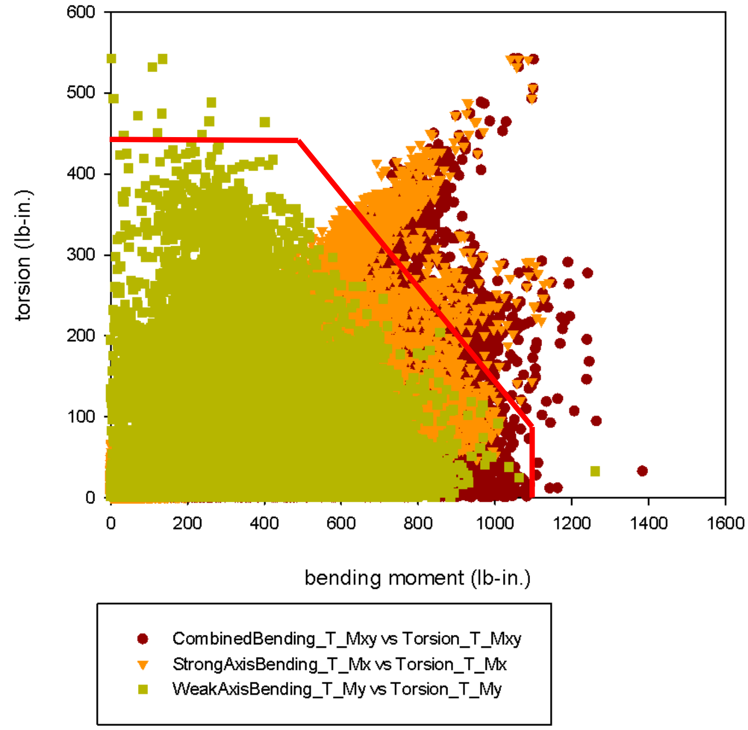



Figure 3.26 Relationship between Torsion and Bending Moment

### 3.2.2 Truck-Generated Wind (Tow) Test

The truck-generate wind tests replaced the originally proposed wind tunnel tests. In this test method, the goal was to control the wind speed and direction in order to test the sign at loads which might not occur in the continuous field test. The benefit of such an approach was that it provided nearly complete control over the testing variables. However, the drawback was that the generated wind was not exactly natural; rather it was more likely to be slightly more laminar than true natural winds at similar speeds. However, the drawbacks to this system could be overcome by using the field data to validate the test method.

#### 3.2.2.1 Method

The method for this testing was simply to mount the instrumented sign (same as the field site) and sonic anemometer to a truck and drive the truck to generate the required wind speeds. To facilitate this, a grill guard replacement was built for a TechMRT pickup truck. This grill guard has two arms which placed the sign ten feet to the left of center line and the sonic anemometer ten feet to the right of center line. This can be seen in Figure 3.27.

The truck was driven at the runway at the Reese Technology Center located in Lubbock, TX. The truck speed was adjusted in order to hit target wind speeds which were measured real time. The sign was rotated through various attack angles. The test matrix as shown in Table 3.6 was completed for the wrapped load cases. The same test matrix was completed for the anti-kiting case at 60mph.

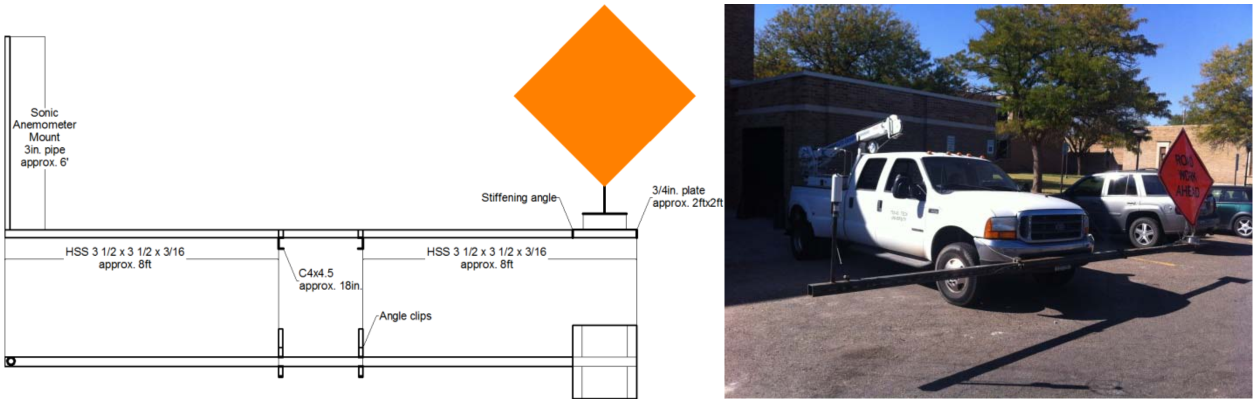



Figure 3.27 Truck Instrumented with a Sign Assembly and Sonic Anemometer

Table 3.6 Test Matrix for Truck-Generated Wind (Tow) Test

| | | Wind Angle (°) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0 | 15 | 30 | 45 | 60 | 75 | 90 |
| "Wind" Speed (mph) | 15 | √ | √ | √ | √ | √ | √ | √ |
| | 30 | √ | √ | √ | √ | √ | √ | √ |
| | 45 | √ | √ | √ | √ | √ | √ | √ |
| | 60 | √ | √ | √ | √ | √ | √ | √ |

#### 3.2.2.2 Results and Discussion

Visual Observations

Several observations were made visually during the testing. The first observation is that the bending in the sign is dependent and proportional to the wind speed as shown in Figure 3.28. Another observation is that the sign flapped more violently at higher speeds as shown in Figure 3.28. At 60mph, the flapping caused delamination of the sign face along the top edges. Another key observation is that the sign always twisted into the wind. The result was such that the observed torsional displacement was much higher for oblique wind directions. Also interesting is that the degree of bending did not appear to depend strongly on wind angle. This can be seen also in Figure 3.29.

Another observation occurred at the higher wind speeds as shown in Figure 3.30. First, the anti-kiting test could not be completed at 60mph because at approximately 50mph the horizontal batten bent enough to allow the sign corner pockets to slide off the cross member. In the wrapped case, the sign had single torsion cracks form in the base of the vertical batten at 60mph particularly at attack angles greater than 30°. At 60mph and 90° skew, the vertical batten completely exploded with many torsional cracks. Additionally, the horizontal batten showed some cracking around the bolt hole as well as compressive damage on the vertical batten.

#### 3.2.2.2 Weak Axis Bending

The first step in evaluating the weak axis bending moment data was to validate it in relation to the field data. Figure 3.31 shows the truck-generated wind test data as points while the blue lines represent the field data. The truck generated data seems reasonably correlated with the field data upper bounds.

a) wrapped 30mph at 30° | b) wrapped 45mph at 30° | c) wrapped 60mph at 30°

Figure 3.28 Bending vs. Wind Speed Relationship

a) wrapped 45mph at 0° | b) wrapped 45mph at 30° | c) wrapped 45mph at 75°

Figure 3.29 Sign Deformation vs. Wind Angle

a) horizontal member damage - wrapped 60mph at 60° | b) vertical member damage - wrapped 60mph at 60° | c) vertical member damage - wrapped 60mph at 90° | d) vertical member damage - wrapped 60mph at 90°

Figure 3.30 Sign Member Failure

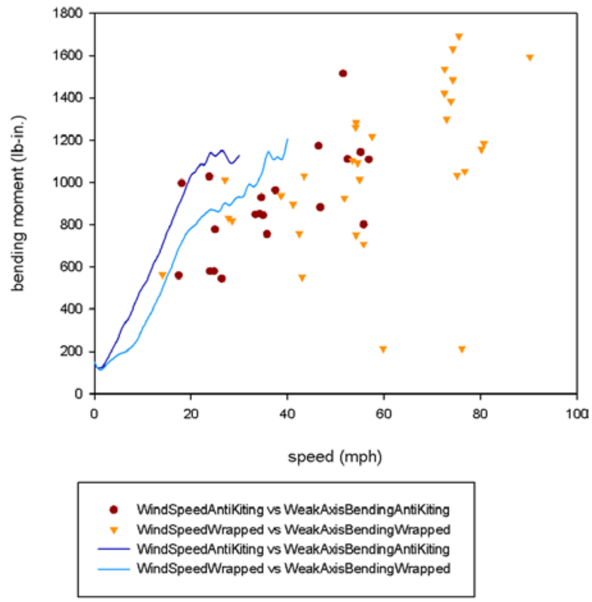



Figure 3.31 Correlation between the Data obtained from the Continuous Field Data and Truck-Generated Wind Tests - Weak Axis Bending

Figure 3.32 show the data with roughly calculated upper bounds. Clearly, the weak axis bending is dependent on wind speed. There appears to be some correlation with respect to wind angle, though the worst case weak axis bending loads appear to occur at lower attack. There does not appear to be a clear difference between the anti-kiting and wrapped case with respect to wind speed.

Strong Axis Bending

Again, the data seems to correlate nicely with the field data as shown in Figure 3.33. There appears to be a trend between strong axis bending and both wind speed and wind angle as shown in Figure 3.34. No meaningful difference is discernible between the anti-kiting and wrapped cases with respect to wind speed.

Combined Bending

Much like the strong axis and weak axis bending, there appears to be good correlation between the field data upper bounds and the truck generated data in Figure 3.35. Also, the trend continues that the combined bending is highly dependent on wind speed and far less dependent on wind angle as shown in Figure 3.36. Again, there is little difference between the anti-kiting and wrapped conditions as shown in Figure 3.36.

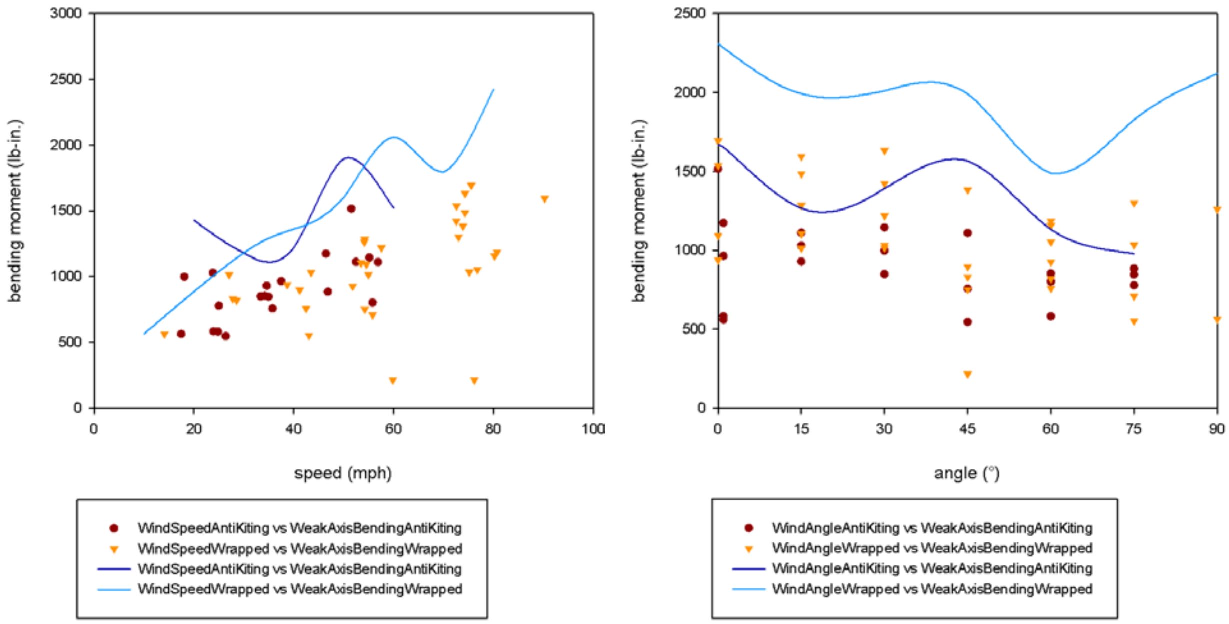



Figure 3.32 Weak Axis Bending vs. Wind Speed and Wind Angle

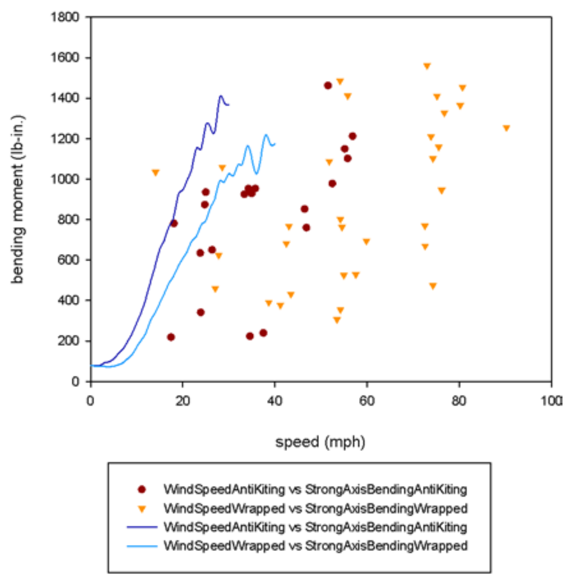



Figure 3.33 Correlation between the Data Obtained from the Continuous Field Data and Truck-Generated Wind Tests - Strong Axis Bending

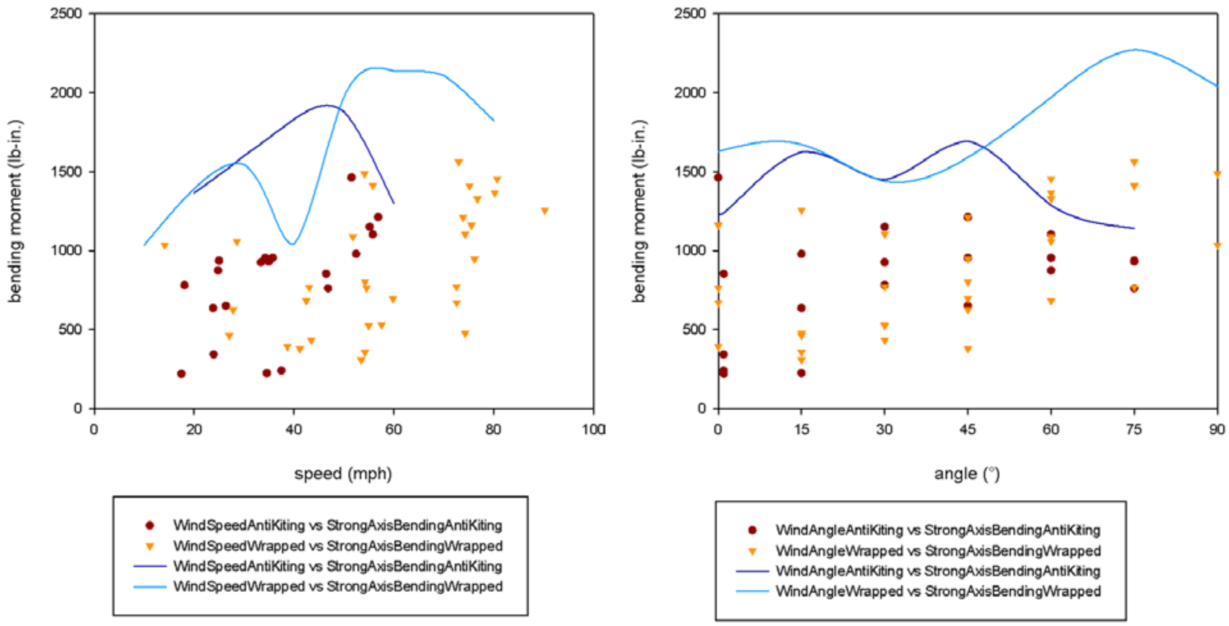



Figure 3.34 Strong Axis Bending vs. Wind Speed and Wind Angle

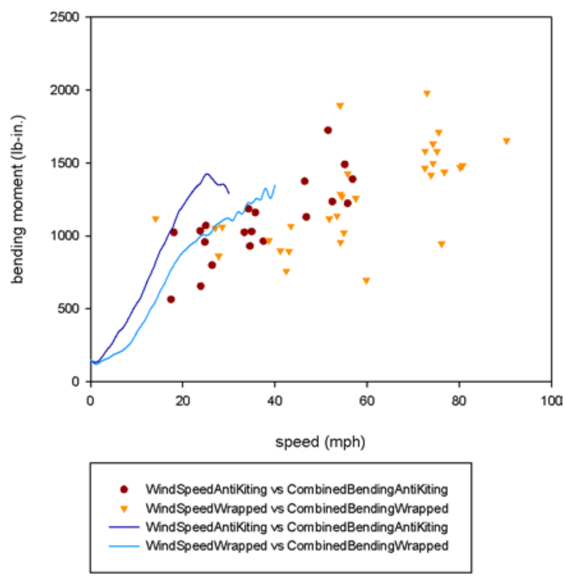



Figure 3.35 Correlation between the Data Obtained from the Continuous Field Data and Truck-Generated Wind Tests - Combined Bending

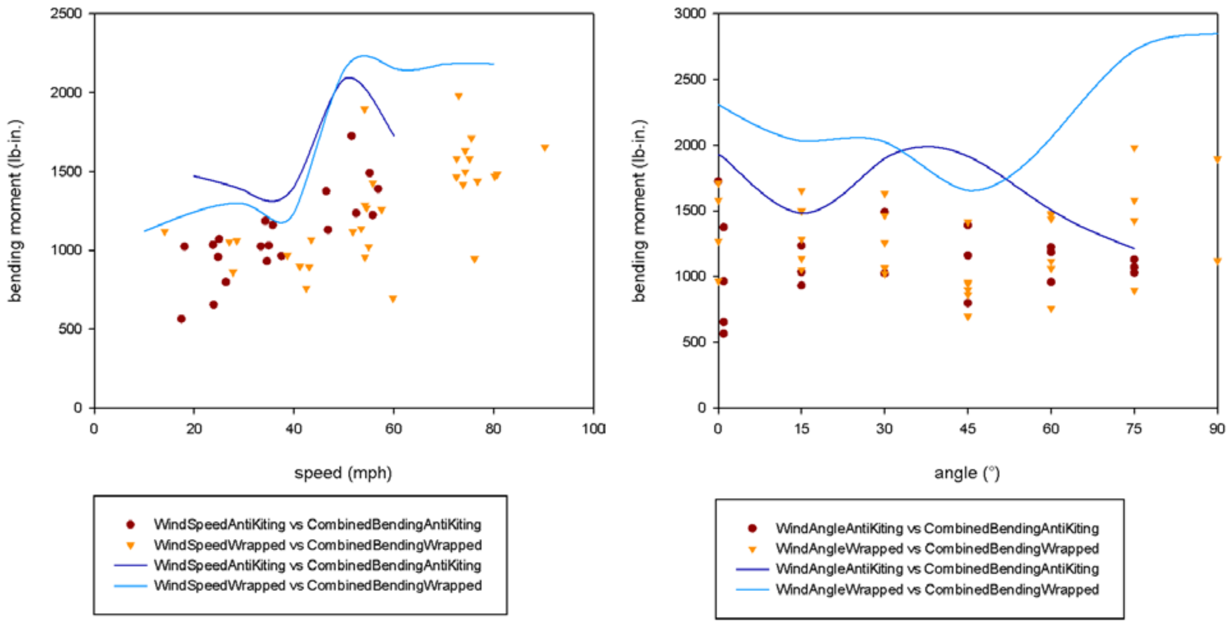



Figure 3.36 Combined Bending vs. Wind Speed and Wind Angle

3.2.2.5 Torsion

Torsion is the first variable which does not closely correlate with the field data as shown in Figure 3.37. This may be due to the prolonged nature of the torsion with added gusts to create torsion in the continuous field data. Nevertheless, the truck-generated wind data seemed to be conservative.

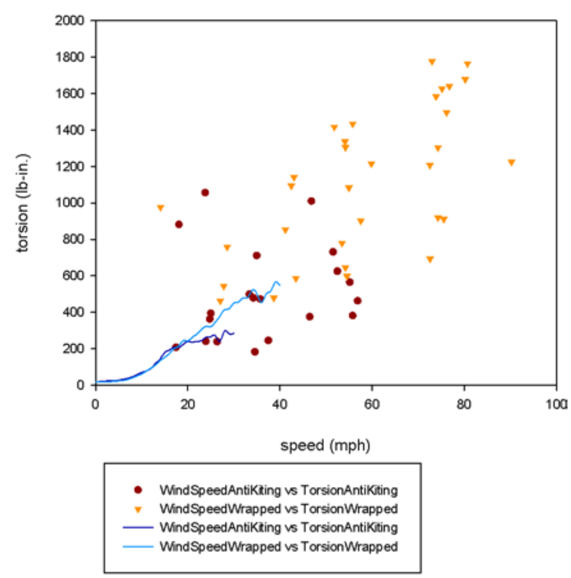



Figure 3.37 Correlation between the Data Obtained from the Continuous Field Data and Truck-Generated Wind Tests - Torsion

In this case, torsion again appears proportional to wind speed, particularly for the wrapped case as shown in Figure 3.38. For some reason, it appears that there is less torsion produced by the anti-kiting case as shown in Figure 3.38. The wrapped case also shows a distinctive relationship between wind speed and wind angle indicating that 60° and 75° attack angles may produce the worst torsion.

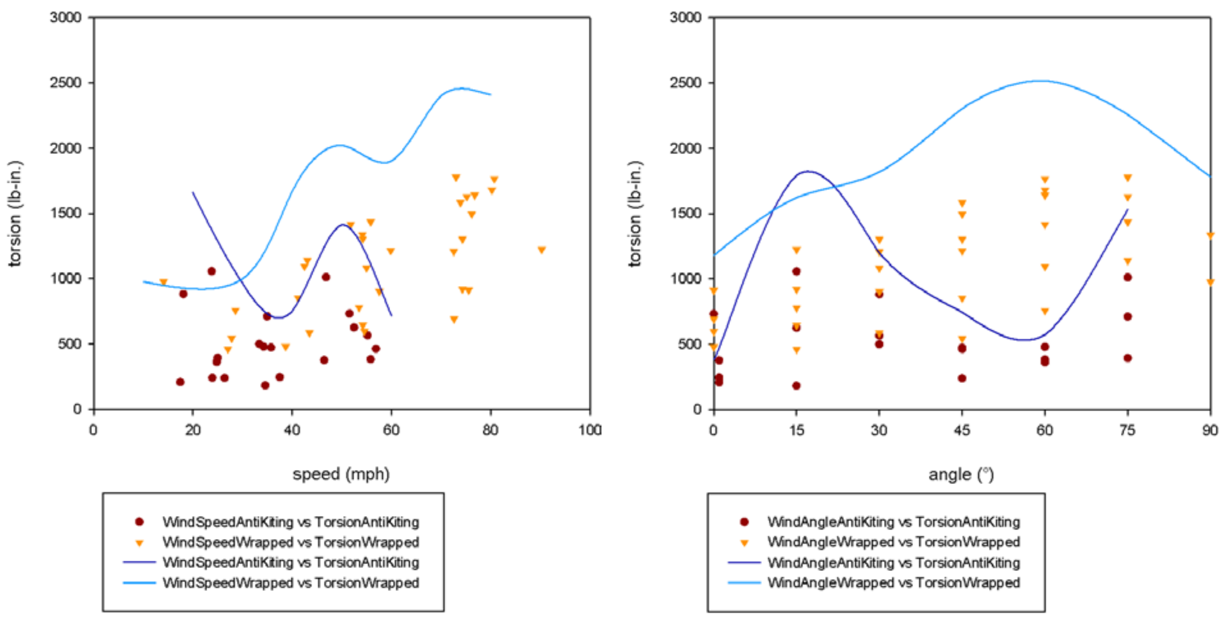



Figure 3.38 Torsion vs. Wind Speed and Wind Angle

<u>Relationship between Torsion and Moment</u>

Figure 3.39 shows the interaction between torsion and bending moment. The critical case is the weak axis bending vs. torsion shown in green. This shows a similar shape to the field data but with naturally much larger magnitudes. Again this can be used to generate a torsion moment curve that must be resisted by any replacement materials.

<u>Observations</u>

The major observations from this test can be discussed in terms of serviceability. What has been seen is that the wind speed and direction, even if they do not break the sign, can significantly affect the readability of the sign. Wind speeds on the order of the 45mph range can cause the sign to fold in on its self in such a way that the sign is unreadable. The majority of this issue is correctable by increasing the weak axis bending stiffness of primarily the horizontal member. The wind angle also affects readability. If the wind blows strongly across the roadway, the sign will twist into the wind. The sign would no longer face traffic. This can be corrected by increasing the torsional stiffness of the vertical member particularly from the base to midpoint where the horizontal member is attached.

The magnitude of the loads is also a major finding. The truck test allowed for much high wind loads, but the loads, particularly the torsion loads appear to be considerably larger than the loads shown in the field test. The difficulty is that two signs were broken at the field site at far smaller loads than those required to break a sign on the truck. This suggests that the failure of the signs may be a progressive rather than sudden and catastrophic. Therefore, a replacement sign support needs torsional strength with a measure of fatigue resistance.

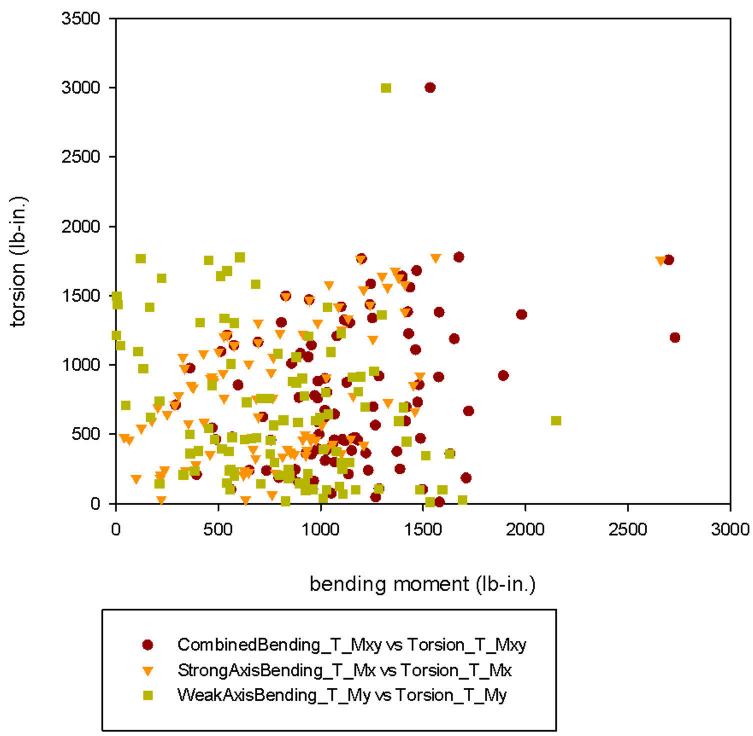



Figure 3.39 Interaction between Torsion and Moment

### 3.2.3 Vehicle Gust Test

The vehicle gust test is an attempt to quantify the effect of wind gust generated by passing trucks.

#### 3.2.3.1 Method

The test was performed at the runway at the Reese Technology Center located in Lubbock, TX as shown in Figure 3.40. Sign and anemometer were placed on the ground 20ft apart. The truck with a large box trailer was driven along the runway between the sign and anemometer. Various speeds and angles were attempted. Each test in test matrix summarized in Table 3.7 was repeated three times.

#### 3.2.3.2 Results

Visual Observations

The first observation is that the amount of energy imparted was only significant at higher speeds. Secondly, the sign would bounce after the truck passed. The more the sign angled toward the roadway, the greater the bending and torsion deformation.

Figure 3.40 Vehicle Gust Test

Table 3.7 Test Matrix for Vehicle Gust Test

| | | Wind Angle (°) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | 15 | 30 | 45 | 60 | 75 |
| Truck Speed (mph) | 15 | √ | √ | √ | √ | √ | √ |
| | 30 | √ | √ | √ | √ | √ | √ |
| | 45 | √ | √ | √ | √ | √ | √ |
| | 60 | √ | √ | √ | √ | √ | √ |
| | 75 | √ | √ | √ | √ | √ | √ |

Weak Axis Bending

In terms of weak axis bending, the results were not as expected based on the visual observations. Specifically, the truck speed did not appear to directly increase the degree of bending moment as shown in Figure 3.41. The wind angle also seems odd, because the visual observations showed more deformation at more oblique angles. Apparently the portion that caused weak axis bending was actually maximized when the sign face was perpendicular to the direction of travel. It is worth noting that the weak axis bending induced by the truck is on the same order of magnitude as the weak axis bending moments recorded during field testing.

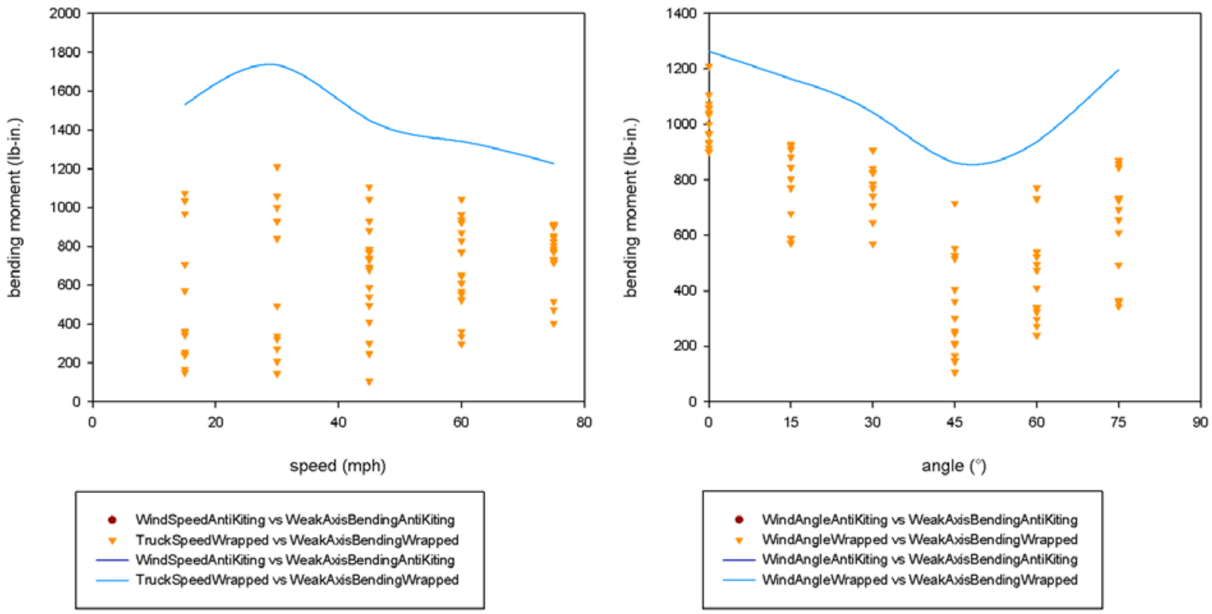



Figure 3.41 Weak Axis Bending vs. Wind Speed and Wind Angle

<u>Strong Axis Bending</u>

Strong axis bending on the other hand shows a strong correlation with truck speed as shown in Figure 3.42. Additionally, it agrees with the visual interpretation that more energy is imparted as the sign face is rotated toward parallel with the road. Again, the order of magnitude is similar to the field site tests.

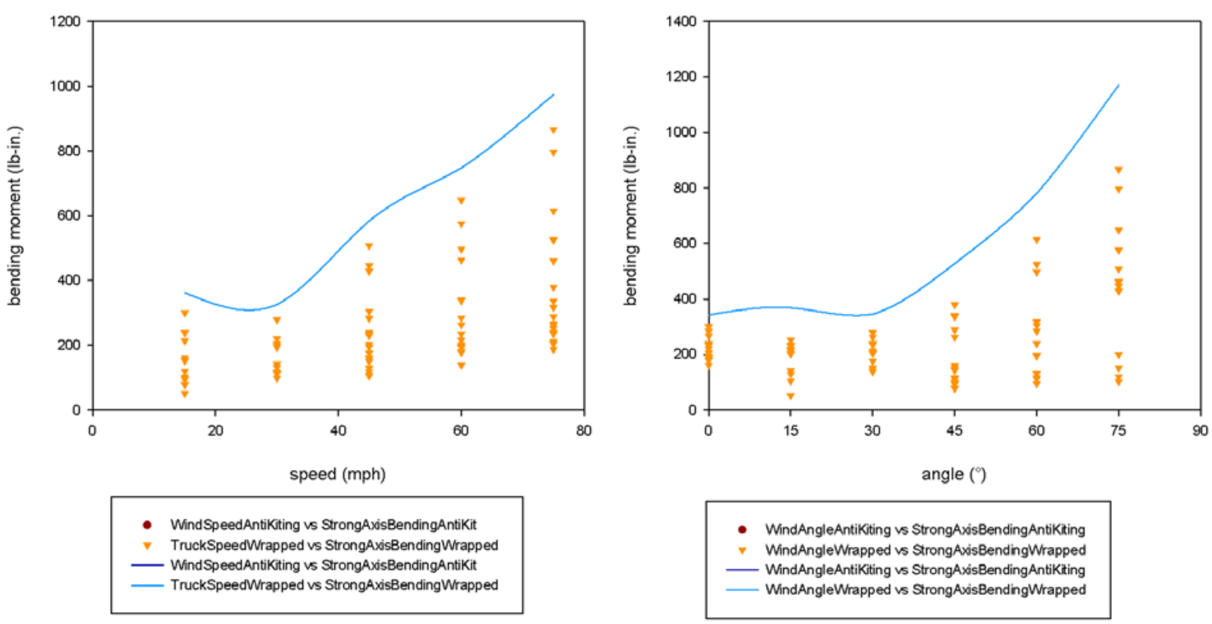



Figure 3.42 Strong Axis Bending vs. Wind Speed and Wind Angle

Combined Bending

The combined bending shares the majority of its trends with the strong axis bending as shown in Figure 3.43; it is directly proportional to both truck speed and angle.

Torsion

Figure 3.44 shows the relationship between torsion and wind speed and angles. The torsional load on the sign is both directly proportional to both truck speed and angle. The torsional load maximizes at the top speed and 75° off perpendicular. This torsional moment is significantly larger than any torsional moment measured at the field site.

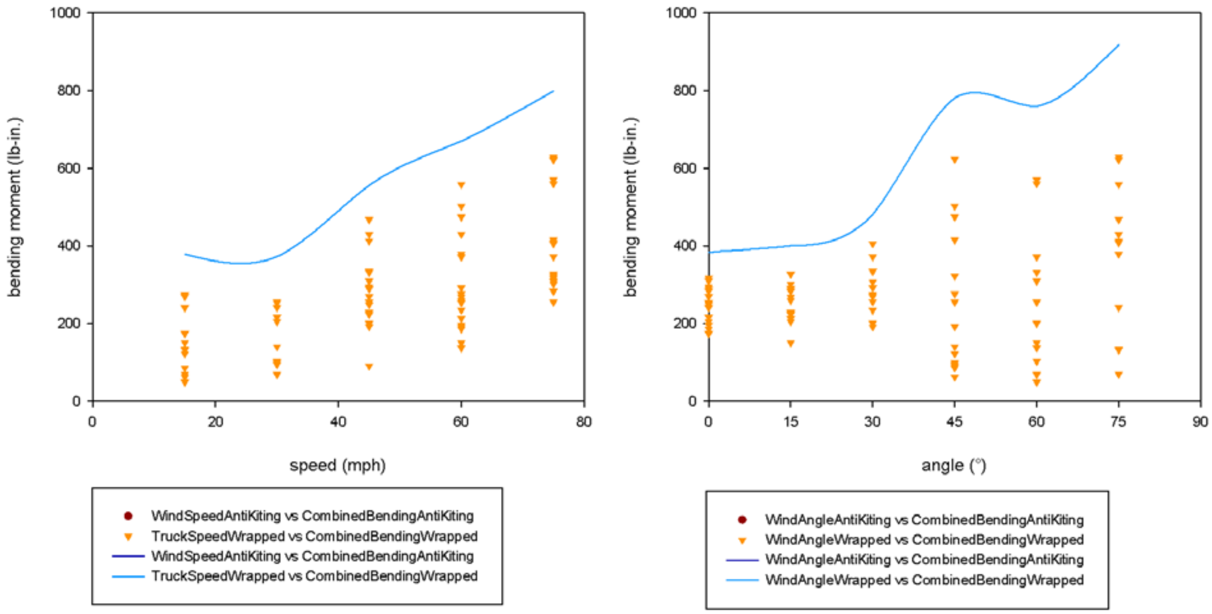


Figure 3.43 Combined Bending vs. Wind Speed and Wind Angle

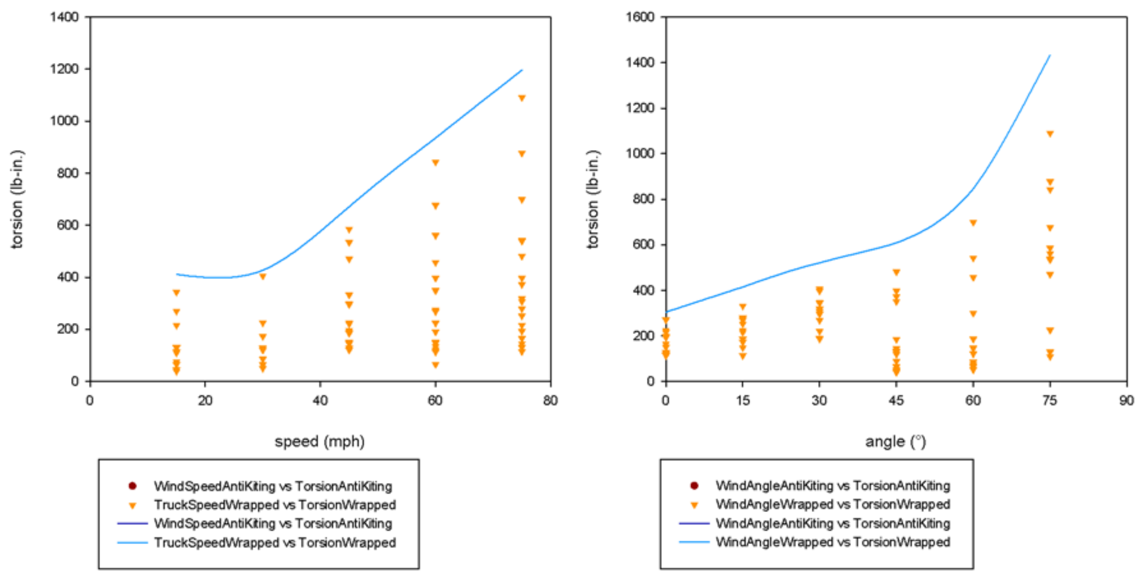


Figure 3.44 Torsion vs. Wind Speed and Wind Angle

<u>Relationship between Torsion and Moment</u>
The torsion-moment envelope must be super-positioned with the torsion-moment plot from the field and/or truck tests as shown in Figure 3.45 to produce the worst case torsion and moment combined loading that any replacement members must resist.

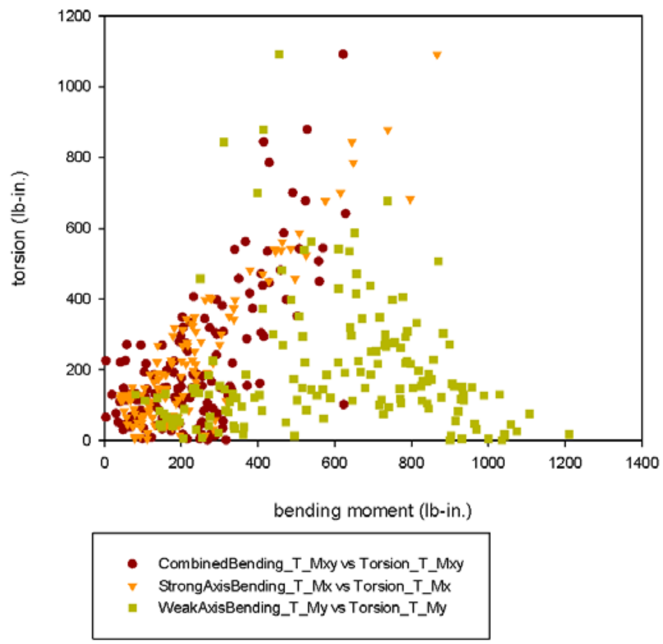



Figure 3.45 Interaction between Torsion and Moment

# 4 DESIGN CRITERIA FOR PROTOTYPE PORTABLE ROLL-UP SIGNS

This section presents the design criteria for portable roll-up signs as well as the basis for the criteria. The failure of a sign assembly can be divided into two cases: (1) failure of components and (2) loss of serviceability.

## 4.1 Failure of Sign Components and Assembly

The first step to initiate the development of new designs was to identify the failure modes. The information collected from the following sources was used:

- The failed sign samples provided by TxDOT Amarillo District
- The test results from the material characterization tests
- The signs placed at the Field Site and subjected to the natural wind for the extend duration (more than 6 months)
- signs subjected to the vehicle-induced wind

Four different failure modes have been observed: (1) cracking in vertical frames, (2) rupture of horizontal frames, (3) failure of plastic corner pockets, and (4) bending of steel base brackets.

### 4.1.1 Cracking in Vertical Frames

Cracking in the fiber direction of vertical battens were one of the primary reasons why roll-up signs failed. Figure 4.1 presents two failed sign samples provided by TxDOT Amarillo District, showing the typical cracking patterns in the fiber direction. This type of cracking also appeared to be the major cause for the failure of the signs subjected to the natural wind and the vehicle-induced wind, as shown in Figures 4.2 and 4.3, respectively. In order to find the causes to develop this type of cracking, different laboratory tests were conducted including bending and torsion tests. Based on the laboratory tests, it was concluded that the cracks in the fiber direction of vertical frames was caused by the torsional moment as shown in Figure 4.4.

Figure 4.1 Failed Samples Provided by TxDOT Amarillo District


Figure 4.2 Failure of the Vertical Frame of the Sign Subjected to the Natural Wind

Figure 4.3 Failure of the Vertical Frame of the Sign Subjected to the Vehicle Induced Wind

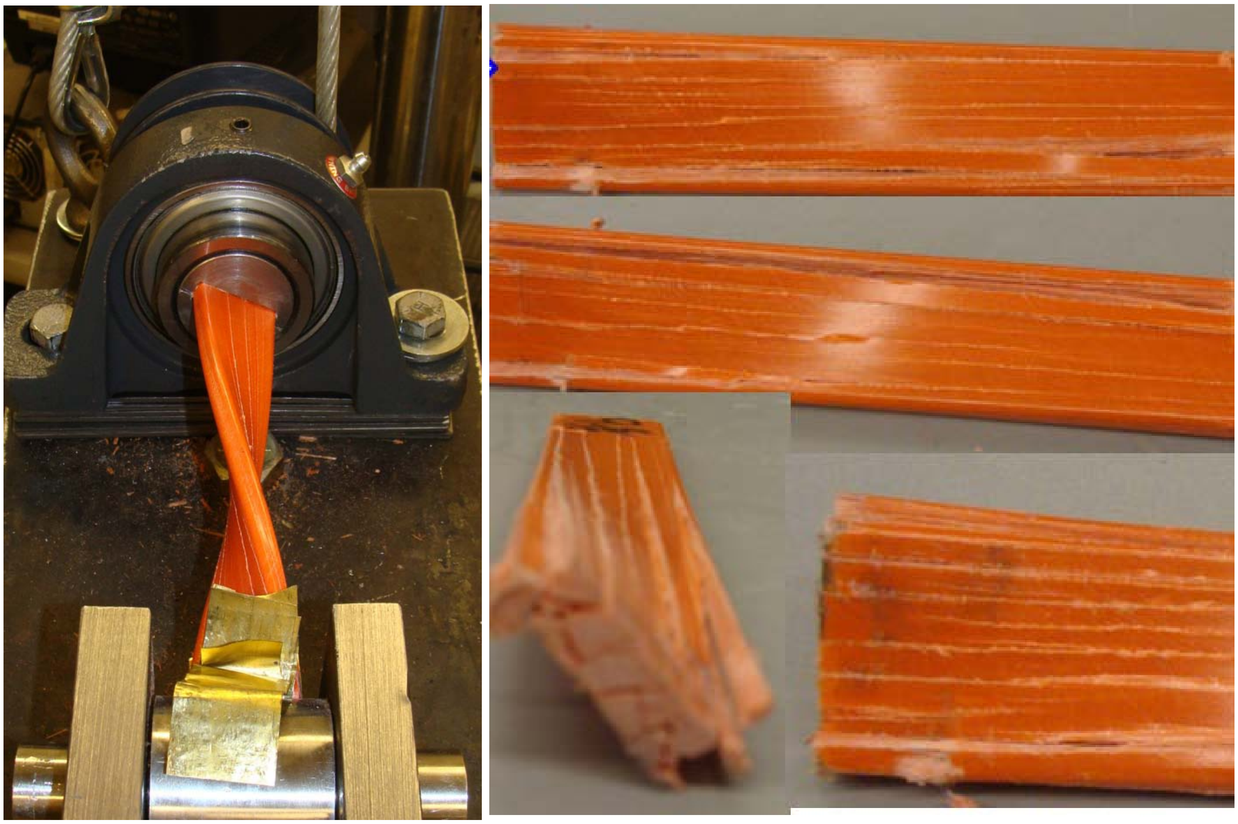


Figure 4.4 Failure of the Vertical Frame of the Sign Subjected to the Torsion Test

### 4.1.2 Rupture of Horizontal Frames

The horizontal member of a sign was ruptured due to bending moment as shown in Figure 4.5 during the vehicle-induced wind tests.

Figure 4.5 Rupture of the Horizontal Frame of a Sign Subjected to the Vehicle-Induced Wind

### 4.1.3 Cracking of Plastic Corner Pockets

Some signs failed to function as intended due to the broken plastic corner pockets as shown in Figure 4.6.

(a) Failed Signs Provided by Amarillo District

(b) Sign Subjected to the Natural Wind

Figure 4.6 Failure of the Plastic Pockets

### 4.1.4 Bending of Steel Base Brackets

The steel bracket of a sign that connect the vertical frame to the base was bent over due to bending moment during the vehicle-induced wind tests. As a result, the bracket had to be reinforced with two steel bracings as shown in Figure 4.7.


Figure 4.7 Failure of the Steel Bracket

## 4.2 Serviceability Issues

Serviceability is impacted by ultimate failures; however, the primary meaning of serviceability issues in this context is on sign behavior that makes the sign message unreadable during vehicle-induced wind tests. This definition is subjective, particularly when identifying marginal performance. However, the given observations will be sufficient for this discussion.

The discussion in this section was made based on two different materials (fiberglass and steel frames) and two different loading cases (wrapped and anti-kiting loadings). The wrapped loading means that the wind blows onto the front side of sign faces while the anti-kiting loading means that the wind blows onto the back side of sign faces.

### 4.2.1 Current Fiberglass Sign Frame

Photographic evidence was collected alongside quantitative date. Table 4.1 shows images from the wrapped loading cases, while Table 4.2 shows images from the anti-kiting loading cases. The discussion in this section was made based on the observations on the tables.

Table 4.1 Photographic Data for Fiberglass Frame under Wrapped loading

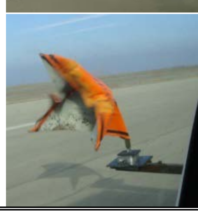
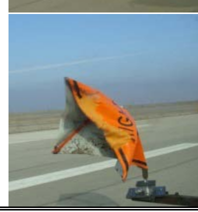
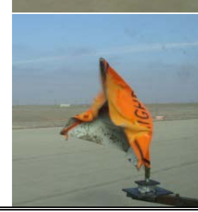
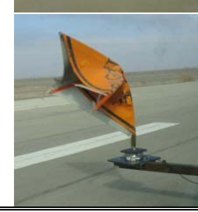
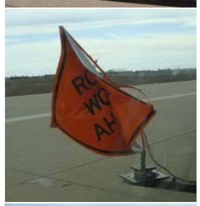
| | *Wind Angle (°)* | | | | |
|---|---|---|---|---|---|
| *"Wind" Speed (mph)* | 15 | 30 | 45 | 60 | 75 |
| 15 | | | |  |  |
| 30 | |  |  |  |  |
| 45 |  |  | |  |  |
| 60 |  |  |  |  |  |

Table 4.2 Photographic Data for Fiberglass Frame under Anti-kiting Loading

| "Wind" Speed (mph) | Wind Angle (°) 15 | 30 | 45 | 60 | 75 |
|---|---|---|---|---|---|
| 15 | |  |  |  |  |
| 30 |  |  |  |  |  |
| 45 |  |  |  |  |  |

First, under even the lowest winds, the sign rotates such that the face (front of the sign in wrapped case, back of the sign in anti-kiting case) is pointed into the wind. Conceptually, this means that if the wind hits the sign at an oblique angle, the sign turns into the wind, inducing greater torsional stress on the vertical frames. This rotation is a serviceability failure. Consider the case when the wind is blowing perpendicular to the road way. In this case, the sign is going to rotate into the wind. The sign message will no longer be pointed toward oncoming traffic. The torsional stiffness must be increased, particularly between the base and the bolted connection between the sign members, to keep the sign facing the appropriate direction.

Secondly, at each wind speed and load case, the sign undergoes roughly the same degree of bending deformation. The sign rotation causes the cross section offered to the wind to be the same regardless of the wind attack angle. This suggests that bending moments will be independent of wind angle.

The bending deformation introduced another serviceability issue: specifically, the degree to which the sign face maintained a readable, square face. In the wrapped case, the sign face was very readable at 45mph; however, the sign deformed so much that it became unreadable at 60mph. The anti-kiting case was far less readable. The sign folded in on itself under 45mph winds. The sign was untestable at 60mph because the horizontal member deformed enough to cause the pockets to slip off the horizontal member.

There are two obvious options for addressing this serviceability issue. The most straight forward choice is to increase the bending stiffness of the horizontal member. However, this stiffness increase must still allow the user to flex the horizontal member enough to slide the sign face pockets onto the end of the sign member. The second improvement would be to ensure a wrapped load case from both sides. This would require the sign face to be redesigned with some sort of pockets or ties.

### 4.2.2 Steel Sign Frame

The major actionable observation from the testing of the current sign design was the need for greater torsional and bending stiffness. To this end, a sign frame of the same dimensions but made of steel was tested.

Fewer serviceability failures were observed in the steel frames sign. As expected, the steel frame greatly increased the serviceability of the sign. Specifically, the sign was able to resist much higher winds while maintaining readability. The wrapped case was able to maintain serviceability under 60mph winds as shown in Table 4.3. The anti-kiting case performed well through the 45mph tests as shown in Table 3.4. Additionally, the torsional stiffness increase was able to keep the sign oriented appropriately. This resulted in the bending deformations in both members to be a function of both wind speed and attack angle.

Consistent with the fiberglass frame, the wrapped case proved far more serviceable than the anti-kiting case. At high wind speeds, some permanent deformation in the horizontal member was observed. Overall, the increase in serviceability was as expected; however, this lead to different ultimate failures, i.e. bending failure of vertical frames.

Table 4.3 Photographic Data for Steel Frame under Wrapped Loading

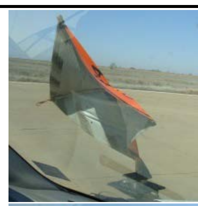
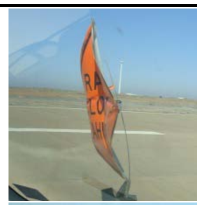
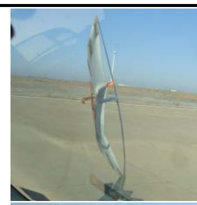
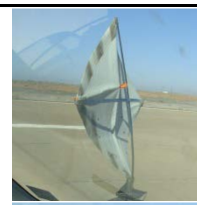
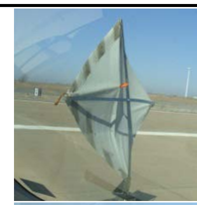
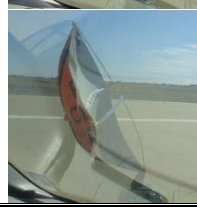
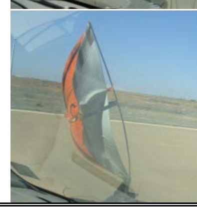
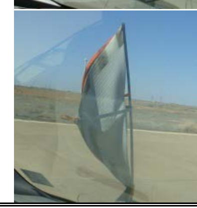
| "Wind" Speed (mph) | *Wind Angle (°)* 15 | 30 | 45 | 60 | 75 |
|---|---|---|---|---|---|
| 45 |  |  | | | |
| 60 | |  |  |  |  |
| 75 |  |  |  | | |

Table 4.4 Photographic Data for Steel Frame under Anti-kiting Loading

| "Wind" Speed (mph) | Wind Angle (°) 15 | 30 | 45 | 60 | 75 |
|---|---|---|---|---|---|
| 30 | |  |  |  |  |
| 45 |  |  |  |  |  |
| 60 |  |  |  |  |  |

### 4.2.3 Sign Surface Delamination

Another serviceability failure observed during the vehicle-induced wind tests was delamination of sign face due to excessive flapping when the wind direction was very oblique (i.e., more than 60 degree), as shown in Figure 4.8.

Figure 4.8 Fiberglass-Sign Face Delamination

## 4.3 Summary of Failure Modes and Possible Solutions

The discussion on the failure mode as well as the serviceability was made in detail in the previous section. The failure modes observed were summarized in Table 4.5 along with the possible solutions.

Table 4.5 Summary of Failure Modes and Possible Solutions

| Failure modes | Effects | Possible Solutions |
|---|---|---|
| Vertical cracking | Sign collapses<br>Permanent loss of function | Increase the torsional capacity |
| Plastic pocket cracking | Sign collapses<br>Permanent loss of function | Revise the pocket design |
| Base connection bracket failure | Sign collapses<br>Permanent loss of function | Revise the bracket design |
| Fiberglass cracking at the joint | Horizontal rib failure<br>Sign is not readable | Strengthen the rib |
| Torsional rotation into the wind | Sign may not face traffic<br>Sign is not readable | Increase the torsional stiffness |
| Excessive Bending and Vibration | Sign is not readable | Increase the horizontal member bending stiffness<br>Ensure wrapped loading from both sides of the sign<br>Limit the wind speed |

## 4.4 Ideal and Marginal Technical Specifications

The signs subjected to the natural winds as well as the vehicle induced winds exhibited hairline cracks in the fiber direction in the vertical frames, and then the cracks became more significant as the sign was used, eventually causing ultimate failure. The objective of developing new designs, therefore, was to avoid the failure. As a r esult, the signs require an increase in the torsional capacity and fatigue life of vertical frames. In addition, it is desirable to use the dimensions currently used for the fiberglass frames so that any new designs will be compatible with the sign bases and faces that have already passed the crashworthiness test and are thus currently adopted by TxDOT. In addition, it is acknowledged that the current sign design is easy to carry and assemble. Furthermore, drastic increases in weight should be avoided to increase the chance that the new design would pass the crash tests. Finally the torsion capacity requirement should meet the torsional capacity as presented in Section 4.5.

## 4.5 Development of Design Loads

The torsion and bending moments at the bottom of vertical members induced by wind loads changes as the stiffness of both vertical and horizontal frames changes. Figures 4.9 and 4.10 show the torsion and bending moments for the fiberglass frame signs and steel frame signs. As shown in the figures, the torsion and bending moments increased as the stiffness of frames increased. However, it should be noted that the torsional moment increase was not as large as the increase in bending moment. Thus, increased torsional stiffness is recommended to avoid cracking in the fiber direction. The vertical member must be able to resist at least the torsion of 2,000 lb-in measured from the fiberglass frame signs, but without increasing the bending stiffness.

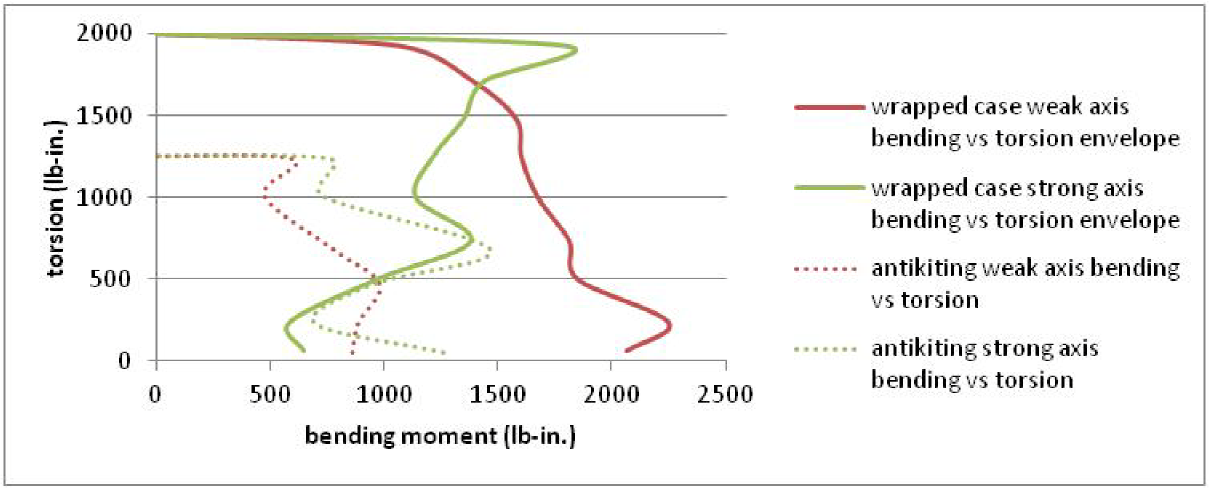



Figure 4.9 Torsion-Bending Moment Interaction of Fiberglass Frame Signs

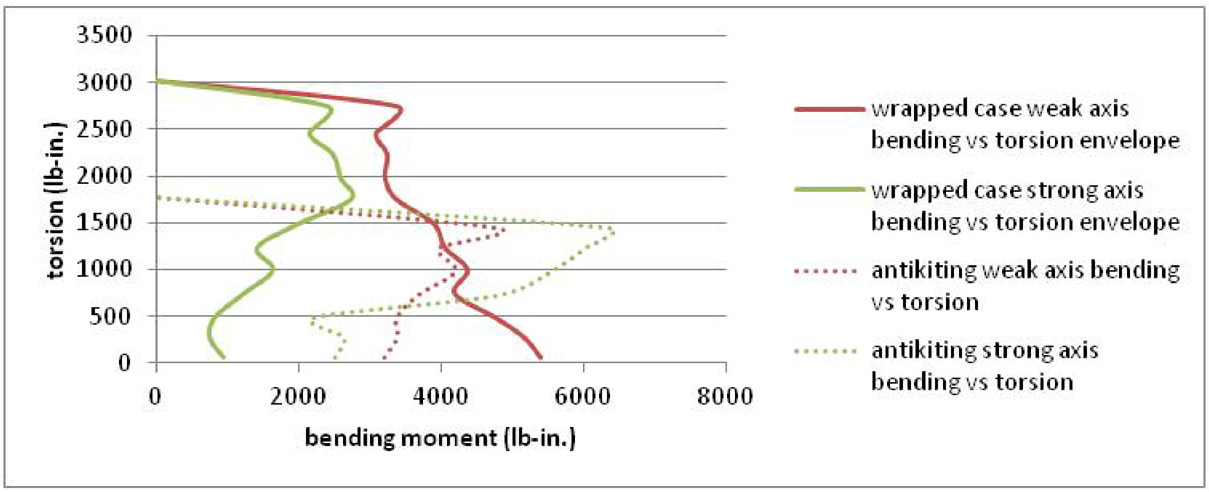



Figure 4.10 Torsion-Bending Moment Interaction of Steel Frame Signs

# 5 MODIFY THE CURRENT DESIGNS

## 5.1 Selection of Component Geometry and Materials

The selection of component geometries and alternative materials was based on the discussion made in Section 4, particularly, based on the proposed ideal and marginal technical specifications. It is, therefore, recommended that the dimensions of vertical and horizontal frames of new designs not be changed significantly from the current fiberglass frame dimensions so that they are compatible with the sizes of plastic pockets of the current size faces available in the market. The torsional capacity as well as the fatigue life in the new designs should also be increased. The weight of the new design should not be increase much as compared to the fiberglass frames. To this end, carbon fiber sheets were recommended because they have:

1. High strength to weight ratio: It can add significant strength without adding significant weight.
2. Excellent resistance to creep and fatigue: It can withstand sustained and cyclic loading conditions as compared to fiberglass.
3. Thickness: Carbon fibers can be supplied in the form of very thin and flexible sheet. Thus, the weight change will be minimized.

In this project, a carbon fiber sheet product available in the current US market, so called "Mbrace CF 130", was adopted to fabricate prototype test signs. Mbrace CF 130 is a dry fabric constructed of very high strength, aerospace grade carbon fibers in a unidirectional alignment. These fibers are applied using polymeric resin. The result is carbon fiber reinforced polymer (CFRP). The tensile strength is known to be 550 ksi and the modulus of elasticity is 33,000 ksi while Grade 60 steel usually exhibits the yield strength of 60 ksi and 29,000 ksi. The thickness and the weight are 0.0065 in. and 0.062 lb/ft$^2$, respectively.

## 5.2 Development of Frame Members (Battens) Using CFRP

A new design concept for vertical and horizontal battens was proposed as shown in Figure 5.1 to improve the performance of vertical frames. As shown in Figure 5.1, a currently used glassfiber frame was still used. The glassfiber frame was then reinforced with a layer of carbon fiber sheets in the transverse direction (that is, perpendicular to the glassfiber direction). This carbon fiber reinforcement is intended to provide additional torsional stiffness as well as the better fatigue life. The new design concept was presented to the PMC members on June 22, 2013. The PMC members approved the new design concept and determined that the performance of the new design should be verified through the crashworthiness tests.

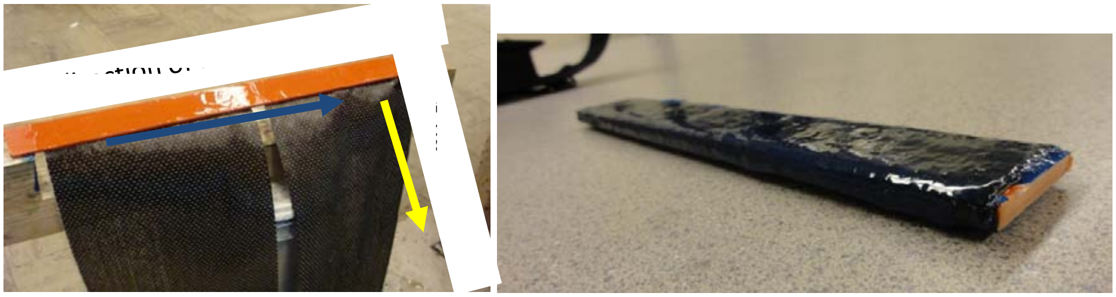
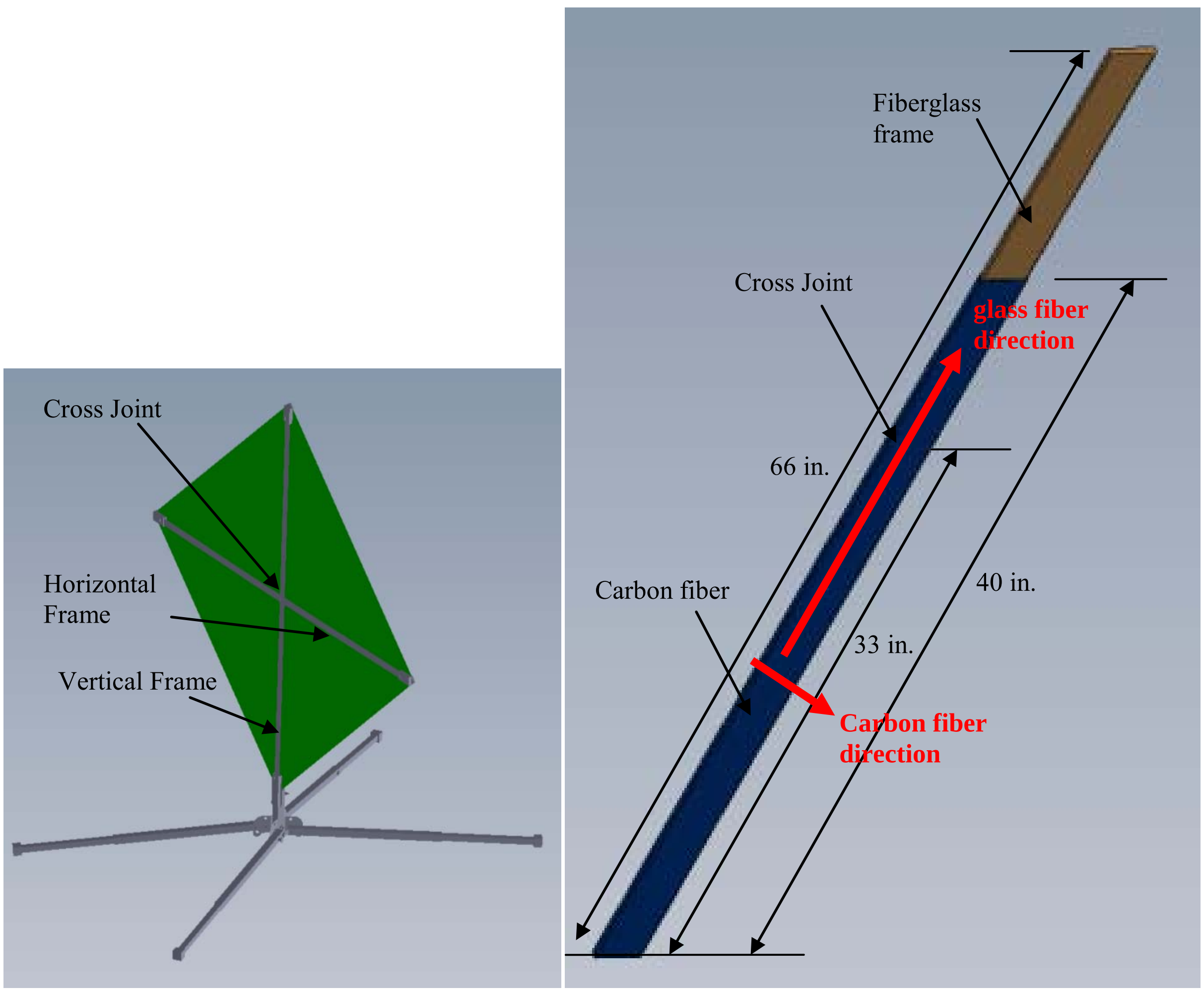


Figure 5.1 New Design Concept to Improve the Performance of Fiberglass Frames

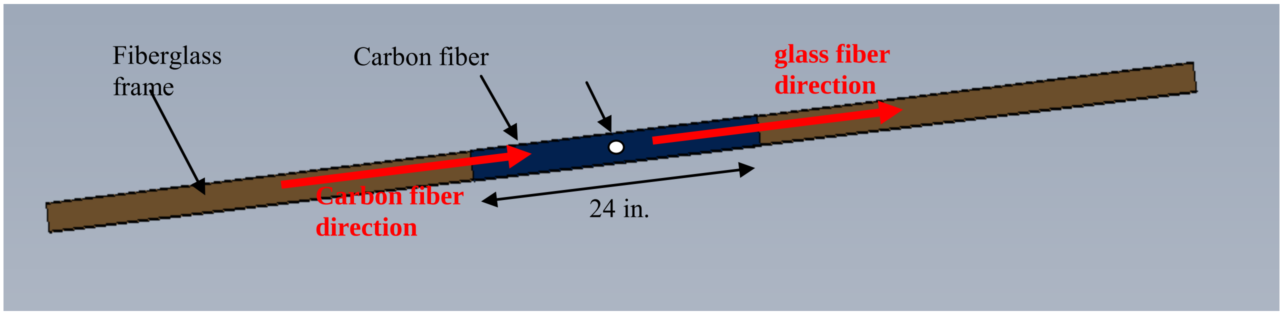
### 5.3 Proposed Sign Assembly Design

Upon the PMC members' approval of the new design concept for vertical and horizontal battens using CFRP, a final design was performed on a sign assembly. Figure 5.2 shows the details of the proposed design while Figure 5.3 show a roll-up sign assembled with the frames.




(a) A Sign Assembly (b) Vertical Frame

Cross Joint




(b) Horizontal Frame

Figure 5.2 Details of the Proposed Design

The vertical frame is wrapped with carbon fiber sheets up to 40 in. from the bottom, passing the cross joint location. The direction of carbon fiber is perpendicular to the fiberglass fiber so that it increases only the torsional capacity while not changing the bending capacity. The horizontal frame is also reinforced with a layer of carbon fiber sheets on both sides of the fiberglass frame. The direction of carbon fibers is parallel to the fiberglass direction so that the bending capacity can increase to avoid the rupture failure at the cross joint. A set of vertical and horizontal frames were fabricated in the laboratory at Texas Tech University.

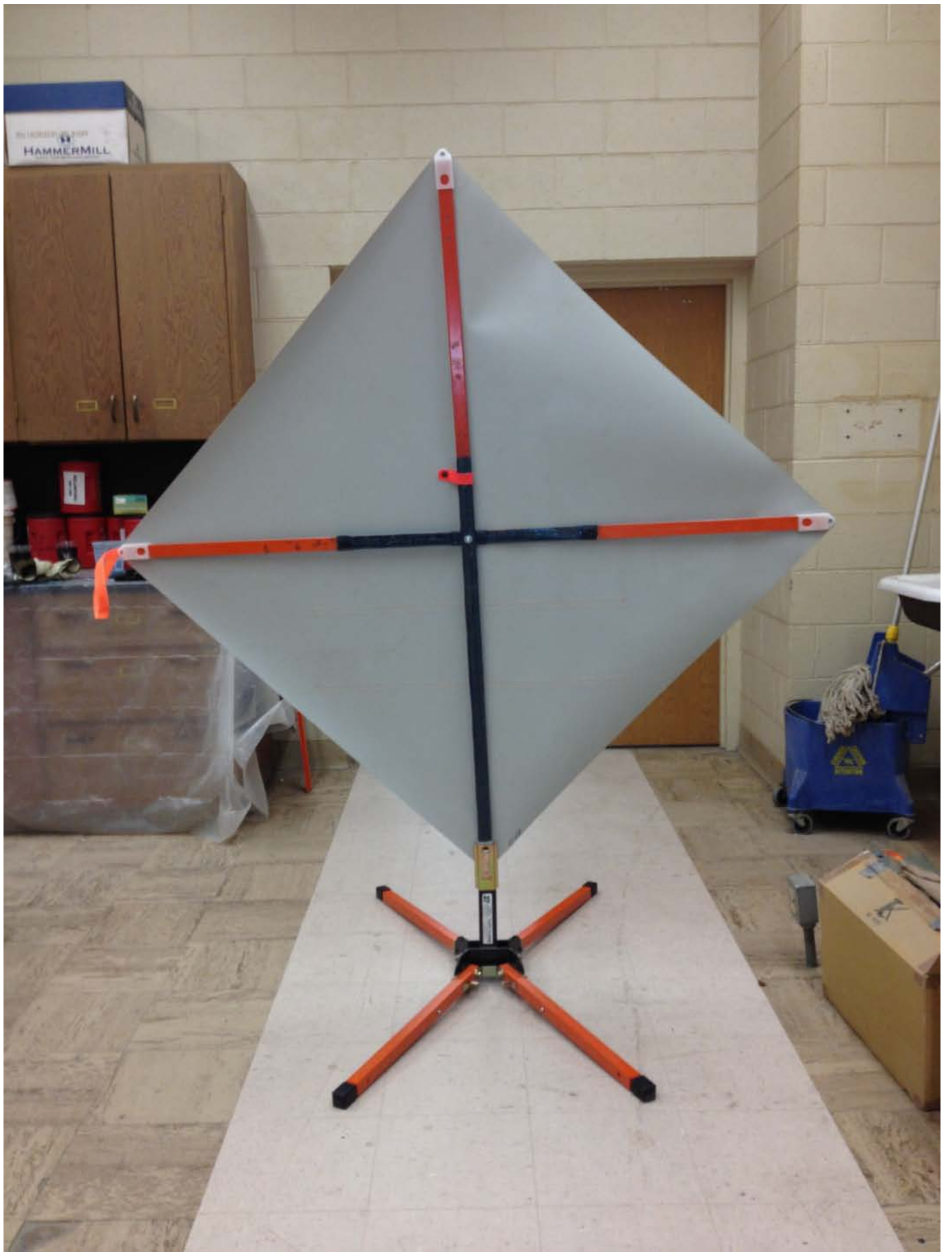



Figure 5.3 Photos of a Sign Fabricated with the Proposed Vertical and Horizontal Frames

# 6 VERIFY THE PROPOSED DESIGNS

The vertical members were manufactured in the laboratory based on the procedures described in Section 5. They have a fiberglass core wrapped with high-strength carbon fiber sheets. The use of carbon fiber sheets was intended to increase the torsional capacity of vertical frame members, without significant increase in bending capacity. The horizontal members were also produced in the laboratory according to the procedures described in Section 5. The performance verification was based on four categories (1) static tests on vertical members, (2) wind tests on sign assemblies, (3) computer simulations for crashworthiness, and (4) crashworthiness tests.

## 6.1 Static Tests on Vertical Members

The torsional capacity of the vertical frame members with/without carbon fiber reinforcement was measured using 20-in. long specimens in the materials laboratory at Texas Tech University. Figure 6.1 shows the torsion test results of fiberglass frames without carbon fiber reinforcement. As shown in the figure, all fiberglass samples exhibited a decrease in the torsional stiffness in the middle of testing (i.e., at approximately 250 lb-in. to 410 lb-in. of torque), which occurred due to the initial cracking along the fiber direction. However, the ultimate failure occurred at around 470 lb-in. to 630 lb-in. of torque, depending on the bending moment applied to the test samples. On the contrary, the frame members reinforced with carbon fiber sheets did not show the significant stiffness decrease due to the initial cracking in the fiberglass direction at the initial state of the loading as shown in Figure 6.2. As a matter of fact, a slight change in the torsion stiffness was observed at approximately 400 lb-in. to 700 lb-in. of torque as shown in Figure 6.2 which was close to the ultimate torsional capacity of fiberglass samples without carbon fiber sheet reinforcement. This implies that the carbon fiber reinforcement could be very effective even after the fiberglass core inside the carbon fiber reinforcement cracks due to the applied torsion. The ultimate torsional capacity of the frame members with carbon fiber reinforcement appeared to be from 2194 lb-in. and 2714 lb-in., which are 3.7 to 4.5 times greater than the ultimate torsional capacity of the frame members without carbon fiber reinforcement. Therefore, it could be concluded that the use of carbon fiber sheet was effective.

## 6.2 Wind Tests

Vehicle-induced wind tests were performed to evaluate the performance of the fiberglass frames reinforced with carbon fiber sheets. A ‘modified sign’ assembly was prepared using a vertical frame member and a horizontal member with carbon fiber sheet reinforcement as shown in Figure 5.3.

The modified sign performed much better than the unmodified sign as shown in Figure 6.3. Serviceability was reasonable through 45mph as shown in Tables 6.1 and 6.2. Around 50-60mph, the serviceability began to degrade as the sign rotated away from perpendicular under oblique wind loads. The increased bending stiffness in horizontal member successfully resisted the wind loads. However, the increase horizontal stiffness also resulted in greater bending in the vertical member. The wrapped case performed much better than the anti-kiting case. In the anti-kiting case, the sign pockets slipped off the horizontal member, but this happened at a higher wind speed than in the unmodified sign.

The most amazing improvement was the increase in elastic response provided by the carbon fiber. At the higher speeds, several times, the vertical members were thought to be broken, but when the wind loads were removed, the member fully recovered.

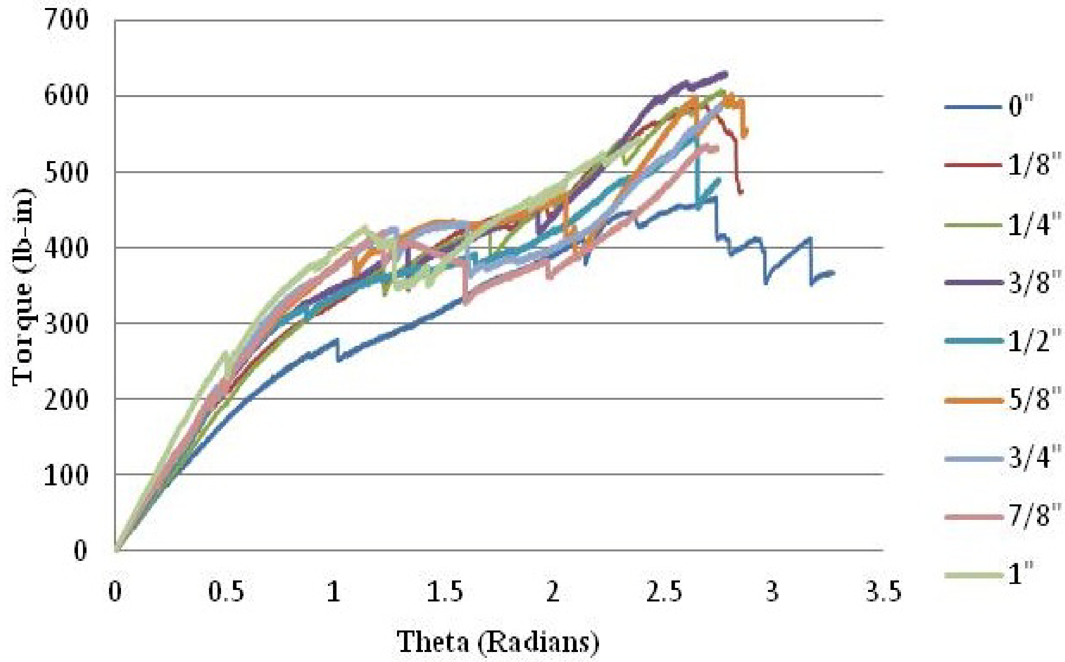



Figure 6.1 Torsion Test Results - Fiberglass Frames

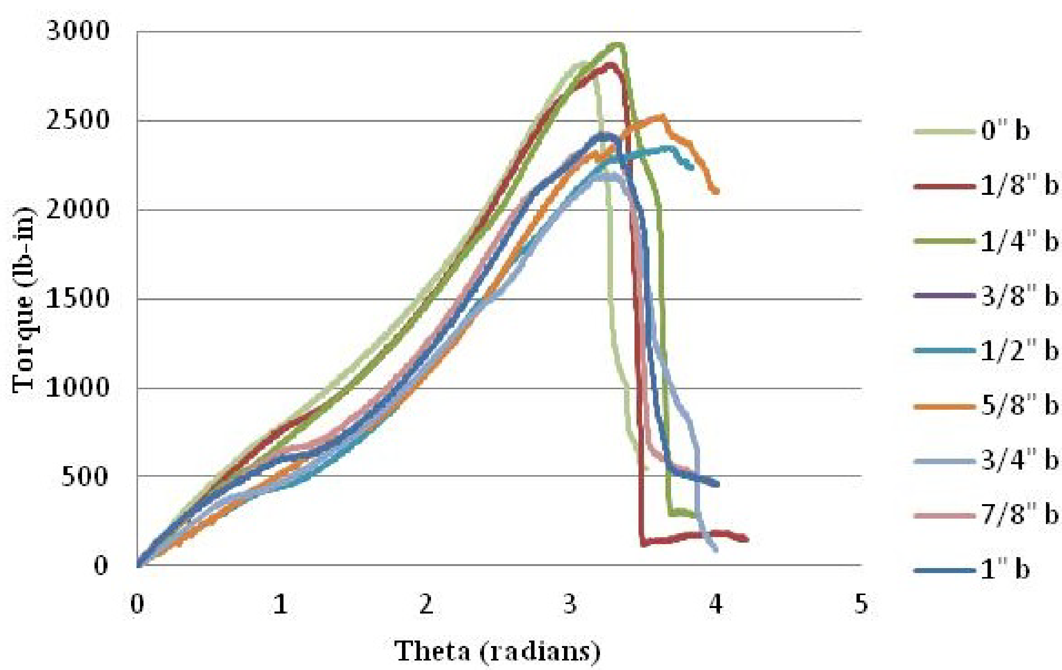



Figure 6.2 Torsion Test Results - Fiberglass Frames Reinforced with Carbon Fiber Sheets

(a) At 45 mph with 15 degree of Wind Angle

(b) At 60 mph with 15 degree of Wind Angle

Figure 6.3 Comparison of Modified (right) and Un-modified Design (left)

The horizontal member of the modified sign suffered catastrophic failure in the last 105mph test. During that test the horizontal member failed in bending at the bolt hole as shown in Figure 6.4. In the same test, the carbon fiber wrap at the base of the vertical member also failed due to abrasion as shown in Figure 6.5.

In addition to the ultimate failure of the sign frames, the sign face also suffered ultimate failures. A new sign face was purchased for this test. At the highest wind speeds the sign face had begun to delaminate. The plastic pocket failed by crushing at 105 mph.

Table 6.1 Photographic Data for Modified Fiberglass Frame under Wrapped Loading

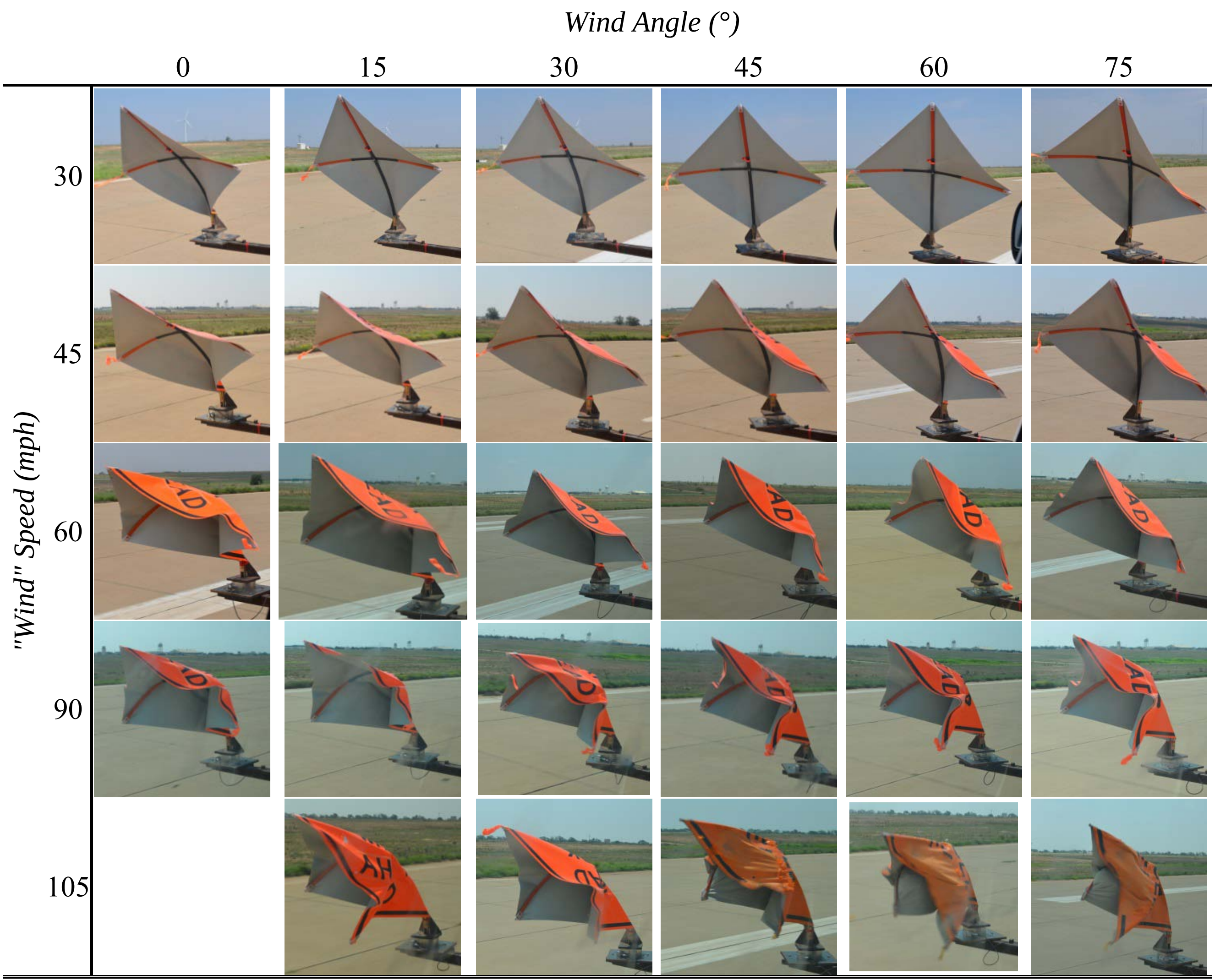



Table 6.2  Photographic Data for Modified Fiberglass Frame under Anti-kiting Loading

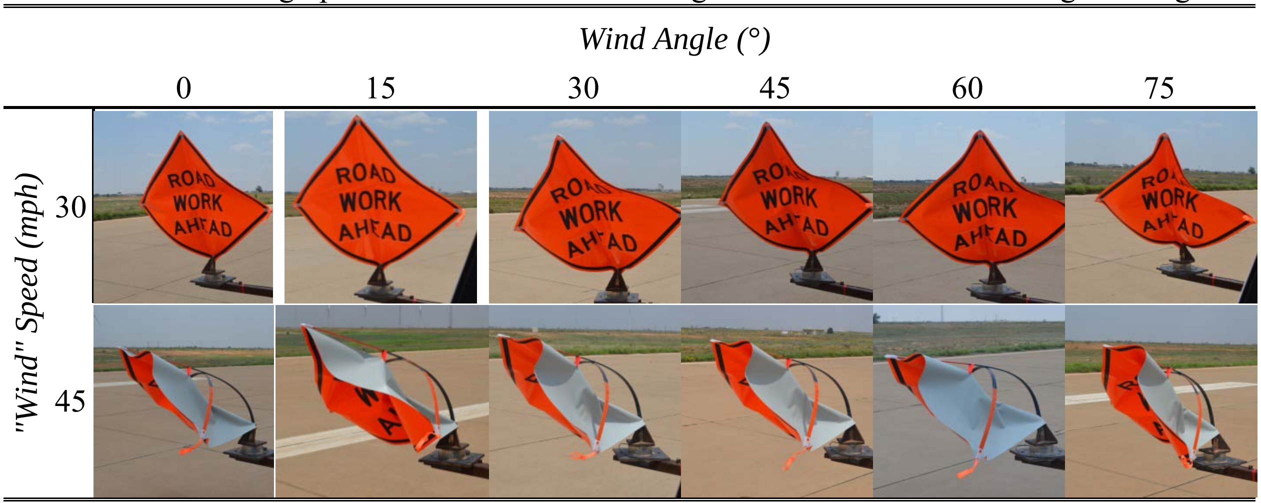


Figure 6.4 Modified Fiberglass Sign Ultimate Failures.

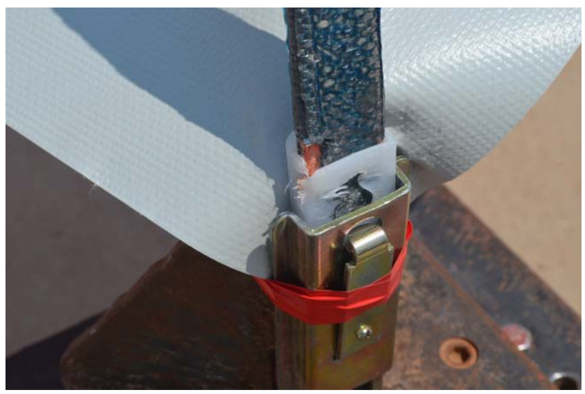


Figure 6.5 Failures of Plastic Pocket Holding the Modified Sign Frame.

### 6.3 Computer Simulation for Crashworthiness Tests

Computer simulations for vehicle crash were carried out on both 0 and 90 degree impacts as shown in Figures 6.6 and 6.7 and the crucial data from these simulations were analyzed to see if wrapping carbon fiber sheet around the vertical frame member affects the performance of portable roll-up signs during the crashworthiness test. The evaluation procedures and methods were on the basis of Manual for Assessing Safety Hardware (MASH).

According to MASH, "performance is evaluated in terms of the risk of injury to occupants of the impacting vehicle, the structural adequacy of the safety feature, the exposure to workers and pedestrians that may be behind a barrier or in the path of debris resulting from impact with a safety feature, and the post-impact behavior of the test vehicle." Three full-scale crash tests are recommended for evaluation of work-zone traffic control devices. Although these systems can be placed either on pavement or on a firm surface, such as compacted gravel or soil, it is recommended that all tests be conducted with the system placed on a paved surface in order to provide consistent comparison between tested features. If test article supports are normally secured with sand bags or other weights in field applications, they should also be utilized during crash testing.

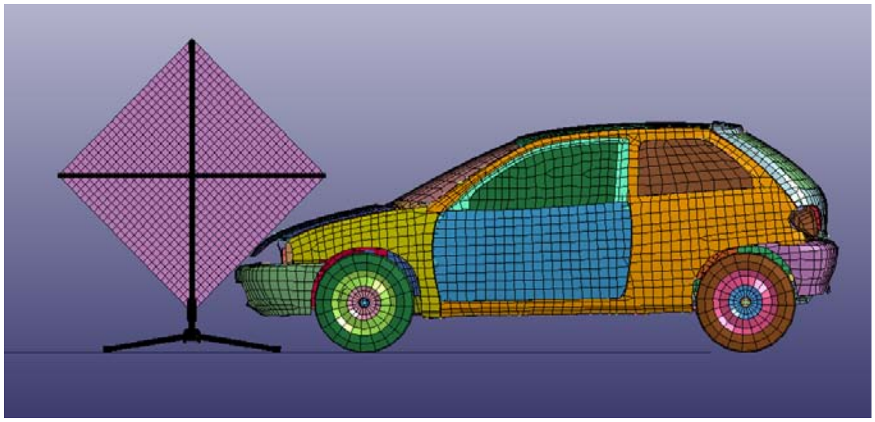


Figure 6.6 Initial State for 90 Degree Impact

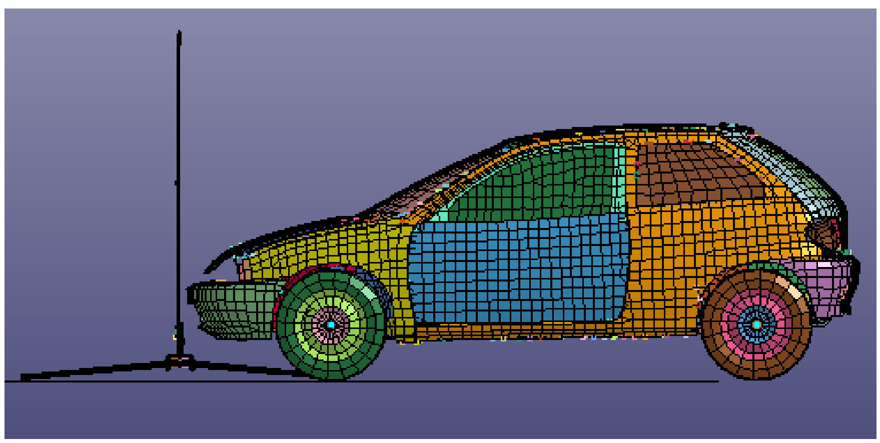


Figure 6.7 Initial State for 0 Degree Impact

A test designation of MASH 'Test 70' is designed to evaluate the ability of small vehicles to activate any breakaway, fracture, or yielding mechanism associated with the work zone feature during low-speed impacts. For free-standing, lightweight feature, velocity changes during low-speed impacts will be within acceptable limits, even when a breakaway, fracture, or yielding feature is not incorporated. Therefore, Test 70 is considered optional for work-zone traffic control devices weighing less than 220 lb.

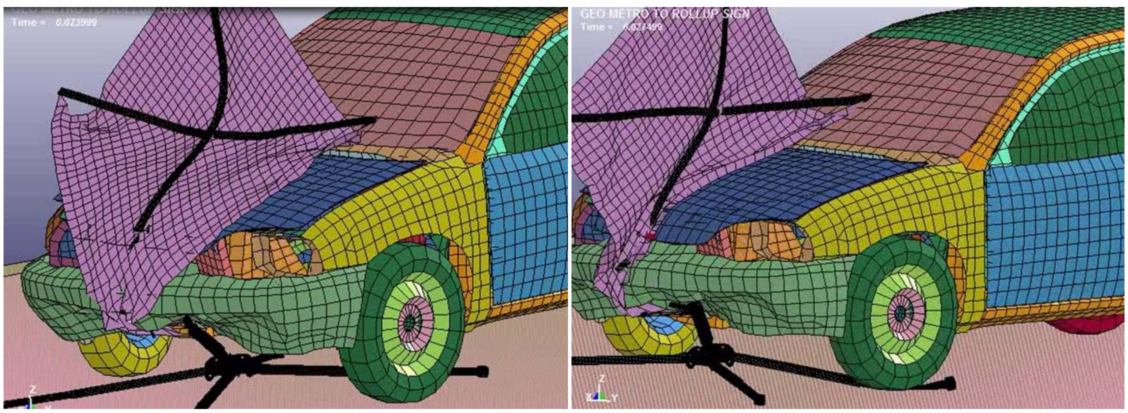
'Test 71' and 'Test 72' are intended to evaluate the behavior of features during high-speed impacts. The most common risks of failure for these tests include intrusion of structural components into the vehicle windshield, vehicle instability, and occupant risk criteria. Note, however, that lightweight free-standing features cannot cause sufficient velocity change to result in failure of the test under occupant risk criteria. Therefore, Tests 71 and 72 can be conducted without the instrumentation necessary for determining occupant risk whenever the test article has a t otal weight of 220 lb or less. In this case, vehicle intrusion, windshield damage, and vehicle stability are the primary performance evaluation factors.

Comprehensive evaluation criteria were described in MASH and are summarized in Table 6.3. Based on the evaluation criteria, the crashworthiness of portable roll-up sign should be judged in three fields: structural adequacy, occupant risk, vehicle trajectory. Considering structural adequacy and vehicle trajectory parts, evaluation of them can be readily seen through simulations as shown in Figure 6.8. In addition, Criterion H and I were evaluated; while evaluating occupant risk is not feasible through the computer simulations, especially for criterion E.

Table 6.3 Safety Evaluation Guidelines

<table>
<tr><th>Evaluation Factors</th><th>Evaluation Criteria</th><th>Applicable Tests</th></tr>
<tr><td>Structural Adequacy</td><td>B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.</td><td>60,61,62, 70,71,72</td></tr>
<tr><td rowspan="4">Occupant Risk</td><td>D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or personal in a work zone.</td><td>All</td></tr>
<tr><td>E. Detached elements, fragments, or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.</td><td>70,71,72</td></tr>
<tr><td>F. The vehicle should remain upright during and after collision. The maximum roll and pitch angels are not to exceed 75 degrees.</td><td>All except those listed in Criterion G</td></tr>
<tr><td>H. Occupant impact velocities (OIV) (see Appendix A, Section A5.3 for calculation procedure) should satisfy the following limits:
<table>
<tr><th colspan="3">Occupant Impact Velocity Limits, ft./s (m/s)</th></tr>
<tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr>
<tr><td>Longitudinal</td><td>10 ft/s (3.0 m/s)</td><td>16 ft/s (4.9 m/s)</td></tr>
</table></td><td>60,61,62, 70,71,72</td></tr>
<tr><td></td><td>I. The Occupant ridedown acceleration (see Appendix A, Section A5.3 for calculation procedure) should satisfy the following limits:
<table>
<tr><th colspan="3">Occupant Ridedown Acceleration Limits (G)</th></tr>
<tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr>
<tr><td>Longitudinal and Lateral</td><td>15.0 G</td><td>20.49 G</td></tr>
</table></td><td></td></tr>
<tr><td>Vehicle Trajectory</td><td>N. Vehicle trajectory behind the test article is acceptable.</td><td>70,71</td></tr>
</table>

In MASH, occupant impact velocity (OIV) is defined as the velocity at which a hypothetical "point mass" occupant impacts a surface of a hypothetical occupant compartment. In the light of MASH, occupant impact velocities were calculated from integrating acceleration. The results are presented in Figures 6.9 through 6.12. As shown in the figures, the maximum accelerations for 0 and 90 degree impacts were 12.04G and 12.92G, respectively. Both of them are in the range of "Occupant Ridedown Acceleration Limits" preferred 15G listed in Table 6.3. In addition, for Occupant Impact velocities, velocities for 0 and 90 degree impacts were 0.468 m/s and 0.902 m/s, respectively, which were less than "Occupant Impact Velocity Limits" preferred 3 m/s. Based on the above observations, it was concluded that the new design would have a higher chance to pass the crashworthiness test.



(a) 0 degree (b) 90 degree

Figure 6.8 Signs after Crashing

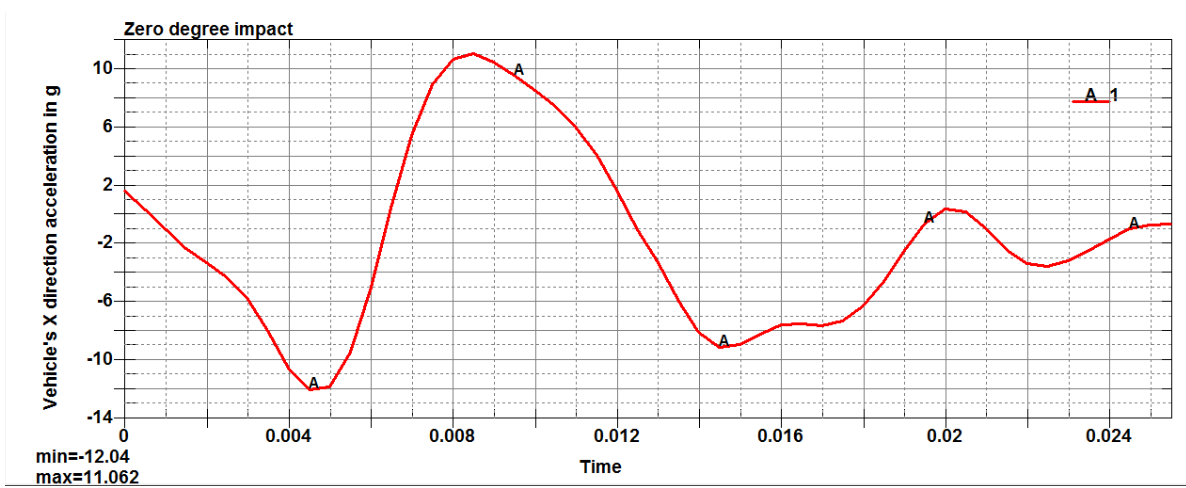



Figure 6.9 Acceleration of Accelerometer for 0 Degree Impact

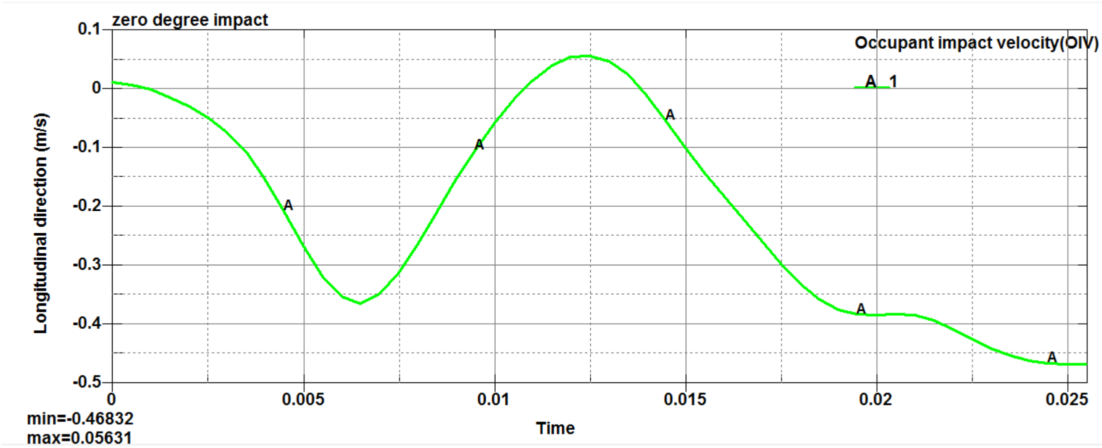



Figure 6.10 OIV for 0 Degree Impact

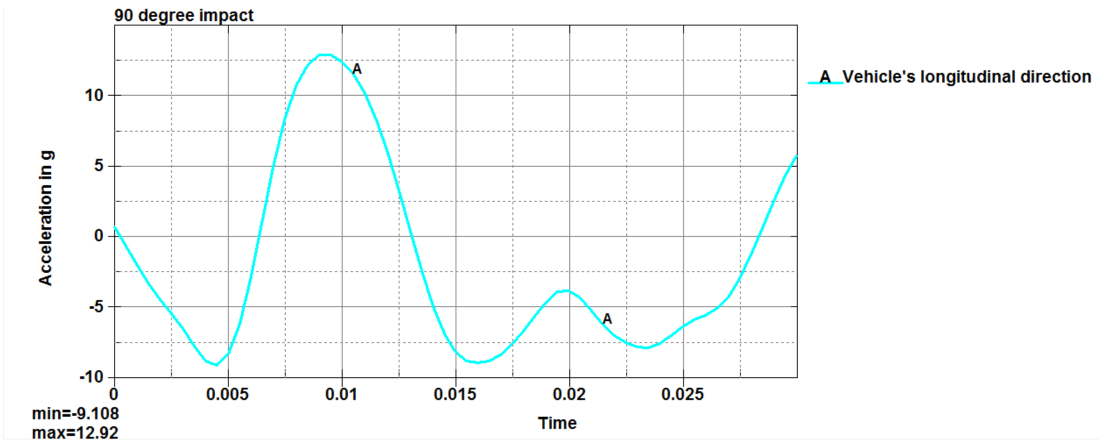



Figure 6.11 Acceleration of Accelerometer for 90 Degree Impact

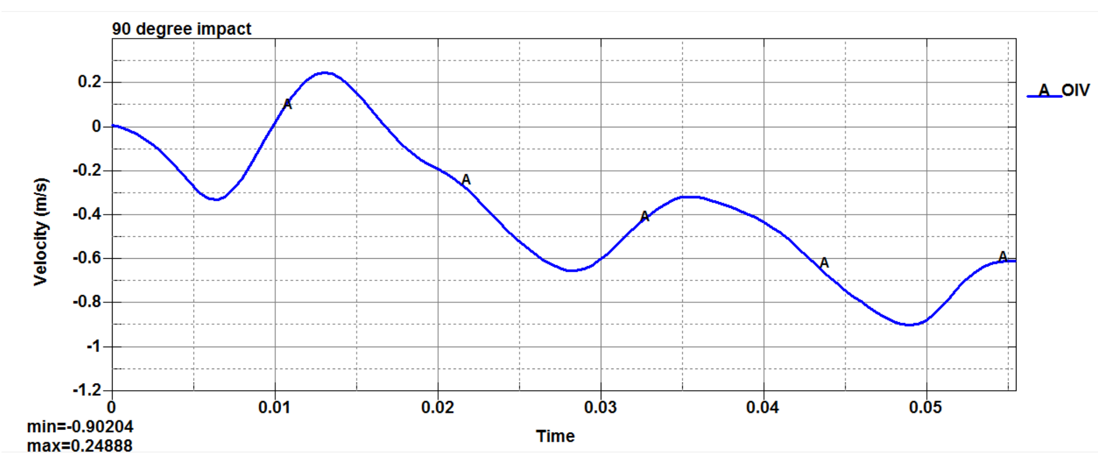



Figure 6.12 OIV for 90 Degree Impact

## 6.4 Crashworthiness Tests

Three full-scale vehicle crash tests were conducted on July 22, 2013 and August 23, 2013 at the Texas A&M Transportation Institute (TTI) Proving Ground located in Bryan, TX. A comprehensive report on the crash tests is provided by TTI as Appendix I to this report. This section summarizes the procedures and the key findings briefly.

### 6.4.1 Details of Test Signs

Two different types of sign assemblies (referred to as Type 1 and Type 2 Test Signs hereafter) were used for three different tests as shown in Table 6.3. In fact, both types were identical, except for the connection between the vertical frame members and the sign base. Figure 6.13 shows Type 1 Test Sign of which vertical member is connected to the sign base with a spring loaded universal, snap-in, pocket type bracket (referred to as spring bracket hereafter). Figure 6.14 shows Type 2 Test Sign with a through bolt bracket. It should be noted that the spring bracket is widely accepted in the current market and all signs used by TxDOT use this type of bracket; while the through-bolt bracket was proposed in this study. More details, such as dimensions of each component, can be found in Section 5.3 and Appendix I.

Table 6.4 Test Matrix for Full-Scale Vehicle Tests

| | **Sign Types** | **Vehicle Impact Angle** | **Date of Testing** | **Remarks** |
|---|---|---|---|---|
| **Test 1** (TTI Test No. 466393-1 in the TTI Report) | Type 1 with sandbags | 0 degree | July 22 2013 | One Test Sign was tested at the given angle (0 degree) by one vehicle impact |
| **Test 2** (TTI Test No. 466393-2 in the TTI Report) | Type 1 without sandbags | 0 degree | July 22 2013 | One Test Sign was tested at the given angle (0 degree) by one vehicle impact |
| **Test 3** (TTI Test No. 466393-3 in the TTI Report) | Type 2 with sandbags | 0 and 90 degrees | August 23 2013 | Two Test Signs were tested at the given angles (0 and 90 degrees by one vehicle impact |

### 6.4.2 Types of Tests Performed

Three tests have been performed and they are referred to as Tests 1, 2, and 3 in Table 6.3. In Tests 1 and 2, a vehicle hit one Type 1 Test Sign of which sign face was facing the vehicle as shown in Figures 6.15 and 6.16. The different between Test 1 and Test 2 was that Test 1 used four sandbags on the telescopic legs of the sign base while Test 2 did not as shown in Figures 6.15 and 6.16. In Test 3, a vehicle hit two Type 2 Test Signs as shown in Figures 15 and 16.

Three vehicles were used: 2009 Kia Rio for Test 1, 2008 Kia Rio for Test 2 and 2008 Kia Rio for Test 3. The speed at the time of impact was recorded: 63.4 mph for Test 1, 59.7 mph for Test 2, and 62.6 mph for Test 3. The gross static weight of test vehicles was reported as 2,622 lb for Test 1, and 2,617 lb for Tests 2 and 3.

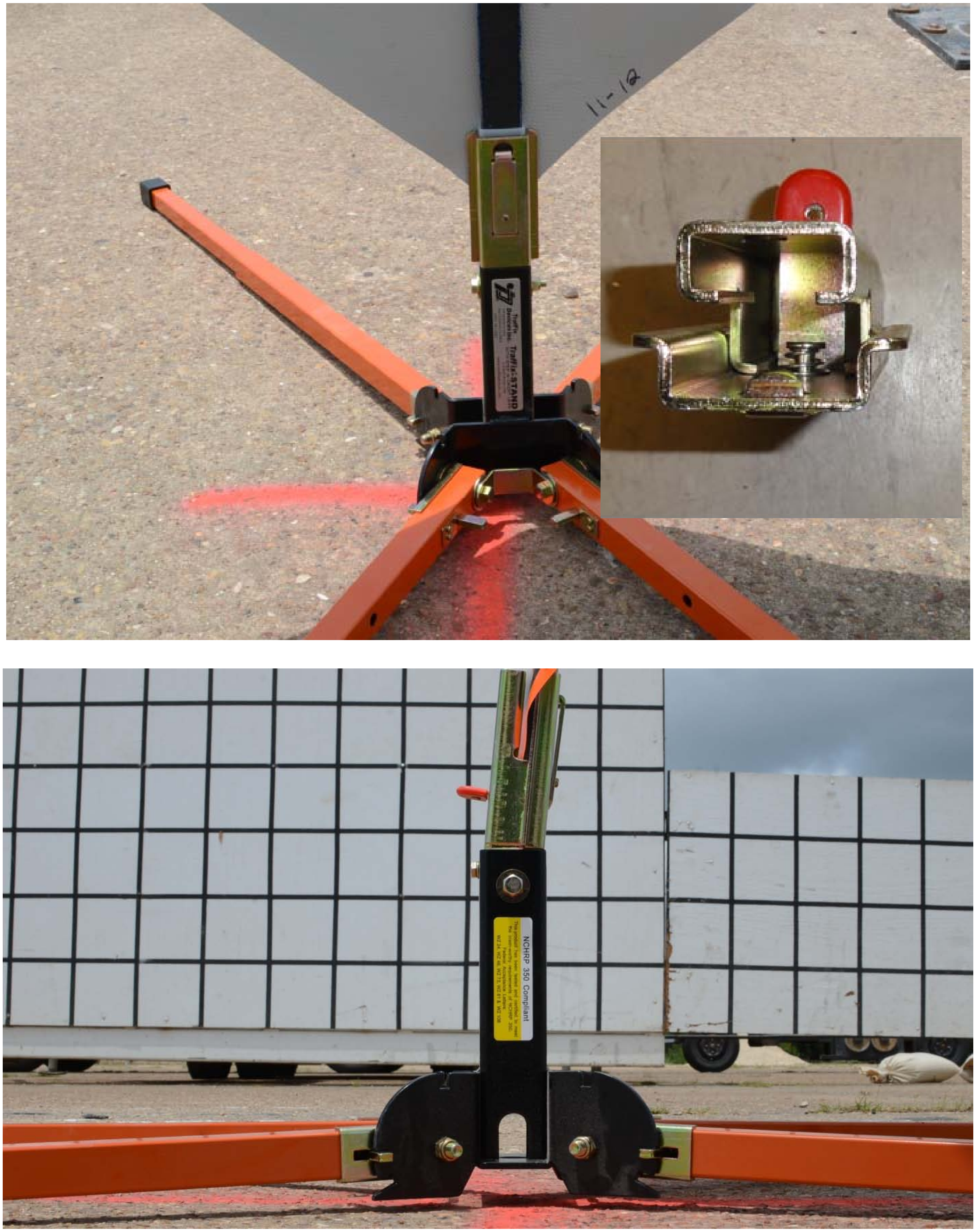



Figure 6.13 Type 1 Test Sign with a Spring Loaded Universal, Snap-in Bracket


Figure 6.14 Type 2 Test Sign with a Through-Bolt Bracket

(a) Test 1

(b) Test 2

(c) Test 3

Figure 6.15 Test Signs before Vehicle Crash


(a) Test 1 (b) Test 2


(c) Test 3

Figure 6.16 Test Set-Ups for Tests 1, 2, and 3

### 6.4.3 Results and Discussion

The performance of each portable roll-up sign was evaluated using all relevant MASH criteria for evaluation of work zone traffic control devices. Of primary concern was penetration of the parts of the test signs into the occupant compartment. In order to minimize the potential for injury during impact, penetration or intrusion into the occupant compartment is not permitted according to MASH. Any hole through the protective layer in the windshield constitutes a failure. In addition, the windshield cannot be shattered or damaged to the extent that it obstructs the vision of the driver or is deformed inward more than 3 inches. The results and discussion made in this section focus on the windshield damage, while more detailed evaluation results are presented in Appendix I.

6.4.3.1 Test 1

Figure 6.17 shows a series of photos at the time of impact during Test 1. As shown in the figure, the vertical member was released from the plastic pocket at the bottom and the top end of the vertical member hit the windshield. The windshield damage was very severe, leaving a penetration hole in it, as shown in Figure 6.18. The spring loaded bracket could hold the plastic pocket but failed to secure the vertical member at the impact as shown in Figure 6.19. Therefore, Test 1 did not pass the MASH requirements, because of the hole in the windshield caused by the impact of the vertical member.

6.4.3.2 Test 2

Figure 6.20 shows a series of photos at the time of impact during Test 2. As shown in the figure, the vertical member was released from the plastic pocket at the bottom and the top end of the vertical member hit the windshield just like Test 1. The windshield damage was also very severe, leaving a penetration hole in it, as shown in Figure 6.21. The spring loaded bracket performed exactly the same way as in Test 1 and could not secure the vertical member at the impact. Therefore, Test 2 did not pass the MASH requirements, because of the hole in the windshield caused by the impact of the vertical member. .

Considering the fact that Test 1 and Test 2 Test Signs behaved almost same way, the sandbags did not affect the damage level of windshield.

6.4.3.3 Test 3

Figure 6.22 shows a series of photos at the time of impact during Test 3. Unlike Tests 1 and 2, the vertical member was not released from the plastic pocket at the bottom as shown in Figure 6.22. As a result, the windshield damage was not as severe as those observed in Tests 1 and 2. That is, penetration or intrusion of the parts of the Test Sign was not observed in Test 3, as shown in Figures 6.23 through 6.24. The through bolt bracket could hold the plastic pocket and the vertical frame member at the impact as shown in Figure 6.25. Therefore, Test 3 satisfied the MASH requirements. However, it should be noted that the broken pieces of the plastic pocket at the top of vertical member flew into the windshield as shown in Figure 6.24 and the windshield damage shown in Figure 6.24 was due to the impact of the broken plastic pocket parts, not due to the direct impact of vertical member.

6.4.3.4 Summary and Concluding Remarks

Test 3 (through-bolt bracket and sandbags) passed the crashworthiness requirements specified in MASH. Therefore, it is recommended that the proposed sign design be used with the sign base that has a through bolt bracket.

Sandbags did not change the behavior of Test Signs and thus the damage level of windshield. The spring loaded brackets could not hold the vertical members securely at the impact. As a result, the vertical members were released from the plastic pockets at the bottom, and the top of vertical member could make an impact on the windshield, creating a penetration hole. On the other hand, the through bolt bracket could hold the vertical members securely at the impact and thus, the vertical member did not make a direct impact on the windshield. Only a couple of broken pieces of the top plastic pocket flew into the windshield and hit it, leaving significant damages, but without penetration or intrusion of the broken parts. Therefore, it is recommended to use softer material than the plastic material currently used in the portable roll-up signs approved by TxDOT. The use of softer material will reduce the damage level of windshield.

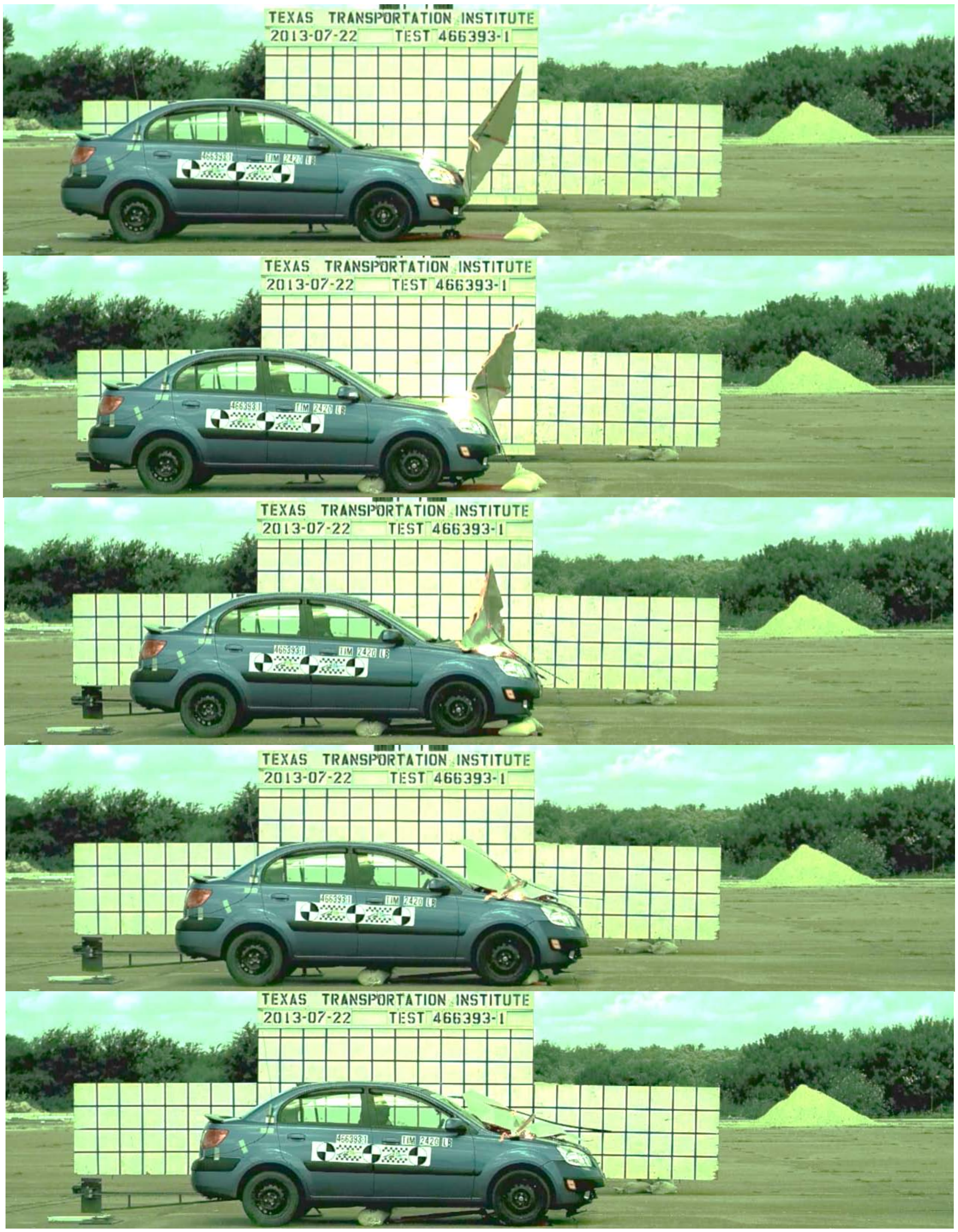



Figure 6.17 Photos at Impact for Test 1


Figure 6.18 Windshield Damage of Test 1 Vehicle

Figure 6.19 Sign Frames and Sign Surface after Impact and Sign Base Damage of Test 1

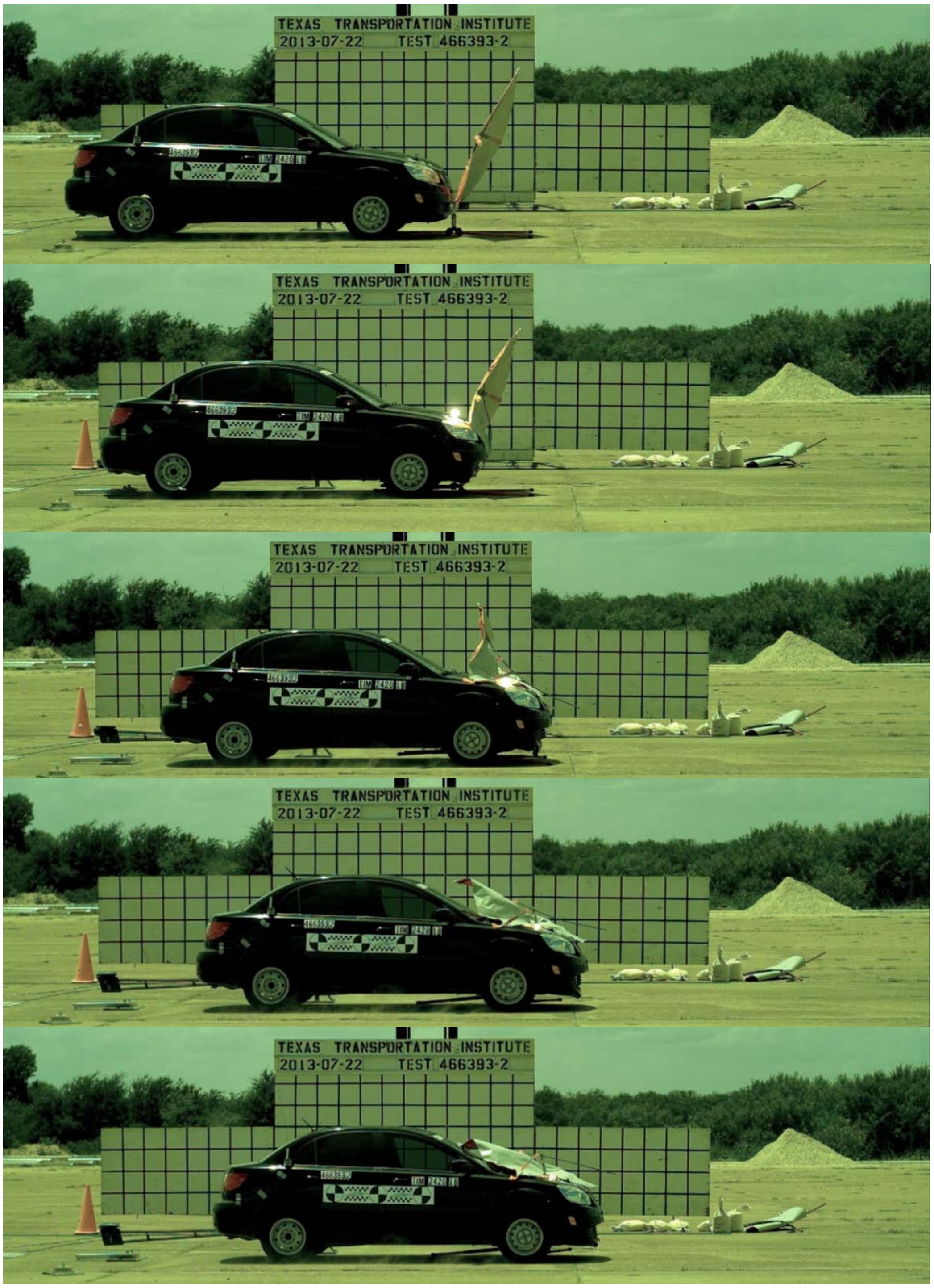



Figure 6.20 Photos at Impact for Test 2

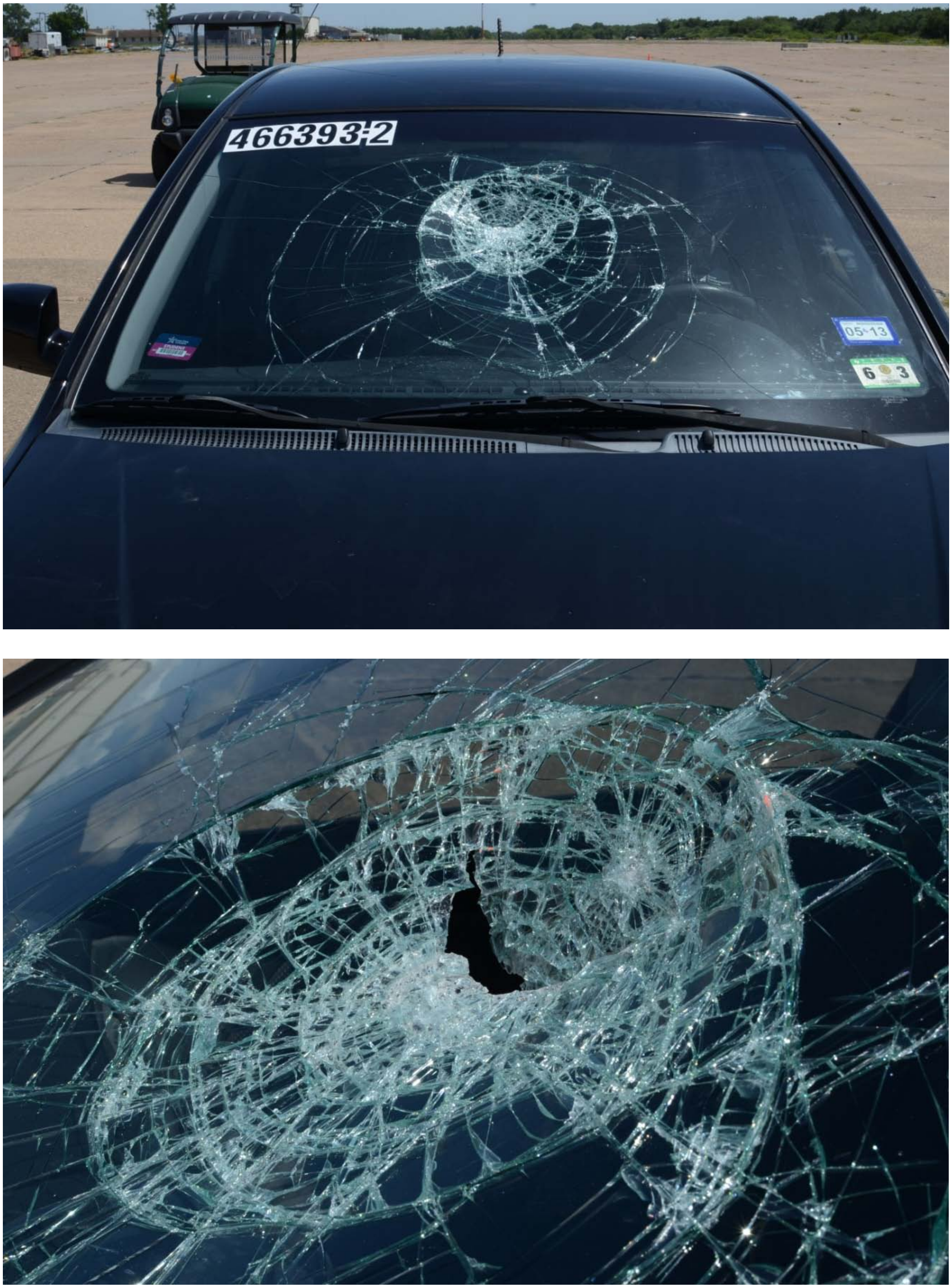



Figure 6.21 Windshield Damage of Test 2 Vehicle

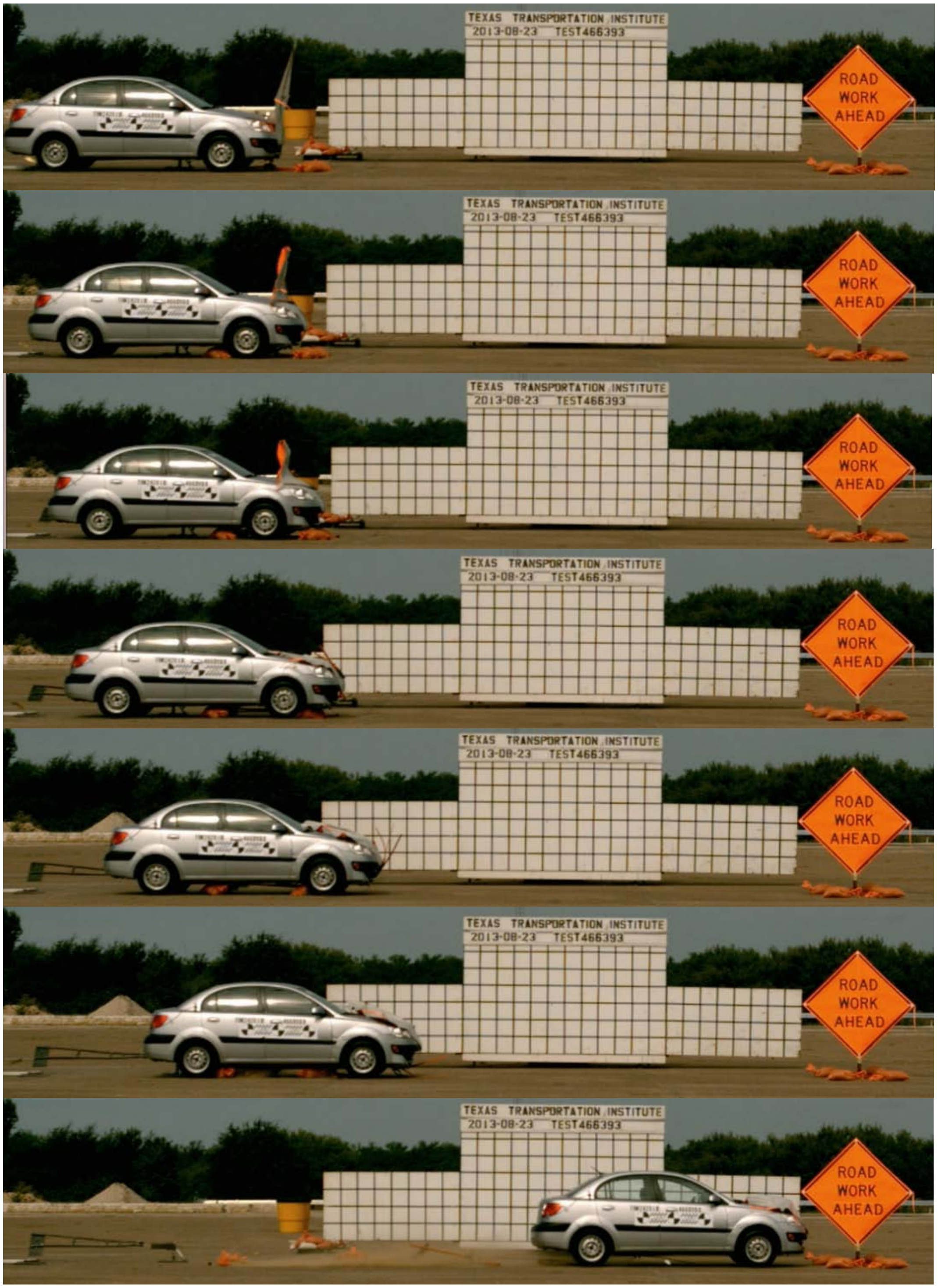



Figure 6.22 Photos at Impact for Test 3 (Continues on the Next Page)

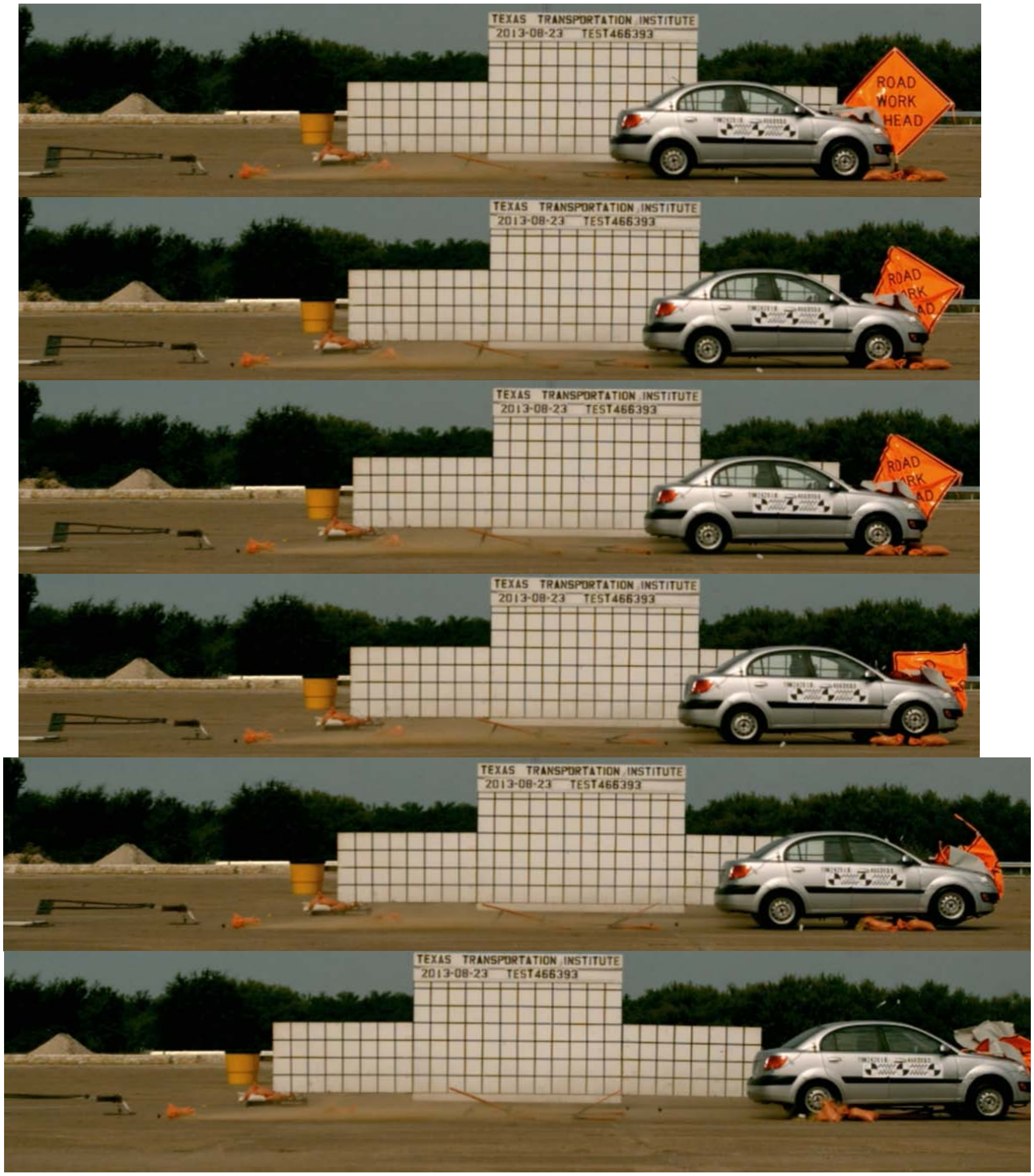



Figure 6.22 Photos at Impact for Test 3 (Continued from the Previous Page)


Figure 6.23 Windshield Damage of Test 3 Vehicle

Figure 6.24 Close-Up of Windshield Damage of Test 3 Vehicle

Figure 6.25 Sign Frames after Impact and Sign Base Damage of Test 3

# 7 PROPOSED CHANGES TO THE CURRENT TXDOT SPECIFICATIONS

Revisions were suggested based on the results of Tasks 1 through 5 for TxDOT Specifications, *801-60-66 - Sing Face, Roll-Up, Reflective, Construction and Work Zone* and *801-12-77 - Stand, Sign, Portable, for Roll-Up Signs, 1 Foot Mounting Height*.

The key revisions suggested for TxDOT Specification 801-60-66 include:

- Part II, Section 1: The following sentence was added.
  "The sign material and battens provided shall meet the requirements of the AASHTO Manual for Assessing Safety Hardware (MASH)."

- Part II, Section 5.1: the term 'fiberglass' was replaced with the term 'fiber reinforced polymer (FRP) composite materials'.

- Part II, Sections 5.3, 5.4., and 5.5 were added. These new sections define the requirements regarding the flexural and torsional resistances of vertical battens.

- Part II, Section 5.6 a nd 6.5 w ere added. These new sections define the requirements for the connection details if a through-bolt connection is used.

The key revisions suggested for TxDOT Specification 801-12-77 include:

- Part II, Section 1: 'the National Cooperative Highway Research Program (NCHRP) Report 350' was replaced with 'the AASHTO Manual for Assessing Safety Hardware (MASH)'.

- Part II, Section 3.4: A through-bolt connection was added as one of the methods to attach the vertical batten to the sign base.

The revised specifications are provided in Appendix II and III. The suggested revisions are highlighted in red and the comments corresponding to the revisions are also provided at the end of the specifications.

# 8 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Portable roll-up signs are widely used in the maintenance work zone throughout Texas. However, it was reported that the vertical frame members made of fiberglass broke due to excessive bending caused by wind loading. This required immediate attention and TxDOT initiated this research project to improve the behavior of portable roll-up signs under high wind situations. In this project, a work plan was developed to modify the current roll-up sign design or develop a new design, especially the design of vertical frame members. A work plan was proposed in this study which includes a comprehensive literature review and experimental program. Based on the work performed, the following conclusions were drawn.

## 8.1 Conclusions

1. The failure of vertical members of portable roll-up signs was due to the progressive cracking at the fiber-matrix interfaces primarily due to torsion caused by wind loads, not due to bending.

2. To avoid the observed failure, the torsional capacity of vertical members had to be increased while maintaining the bending stiffness at the same level. This was archived by applying high-strength carbon fiber sheets to the fiberglass frames in the transverse direction, i.e., perpendicular to the fiber direction of the fiberglass frames.

3. For horizontal members, failure occurred near the vertical and horizontal member joint due to bending. To prevent this type of failure, the horizontal members were reinforced with carbon fiber sheets to increase the bending capacity. However, the application of carbon fiber sheets should be limited to the region near the joint, so that the increase in bending stiffness does not increase the torsional moment applied to the bottom of the vertical members.

4. The field measurement and the vehicle-induced wind tests revealed that the torsional moments applied to vertical members can be up to 2,000 lb.-in. However, the torsional capacity of the current fiberglass without carbon fiber sheets was only around 500 lb.-in. It was, therefore, required that the application of carbon fiber sheets had to be able to increase the torsional capacity to 2,000 lb.-in.

5. The static tests conducted in the laboratory showed that the torsional capacity was increased significantly, exceeding the torsional capacity of the fiberglass frames with carbon fiber sheets. Torsional capacity was about 4 times bigger than that of the fiberglass frames without carbon fiber sheets, exceeding 2,000 lb.-in.

6. The various wind tests showed that the application of carbon fiber sheets to fiberglass frames also improved the serviceability of portable roll-up signs. The roll-up signs with the vertical members with carbon fiber sheets were readable at 45 mph while

the signs with the vertical members without carbon fiber sheets were not readable. Therefore, it can be said that the sign can be used up to 45 mph.

7. The prototype portable roll-up signs were manufactured in the laboratory at the Texas Tech University. The assembled sign with the improved designs, i.e., carbon fiber sheets with fiberglass core and the through-bolt bracket passed the MASH requirements. Thus, it can be adopted by TxDOT.

## 8.2 Recommendations for Future Research

The evaluation of the modified design for frame members was performed with focus on the short-term behavior. The long-term performance needs to be verified, particularly to determine the bond characteristics between the carbon fiber sheets and the existing fiberglass members.

## REFERENCES


3M. (2010). 3M™ Work Zone.from http://solutions.3m.com/wps/portal/3M/en_US/Traffic_Safety/TSS/Offerings/Products/Work_Zone/.

AASHTO (2009). Manual for Assessing Safety Hardware (MASH), 1st Edition, American Society of State Highway and Transportation Officials.

Atahan, A.O. (2006). "Finite-element Crash Test Simulation of New York Portable Concrte Brrier with I-Shaped Connector," Journal of Structural Engineering. Vol. 132, No. 3, pp. 430 - 440.

ASCE (2005). Minimum Design Loads for Buildings and Other Structures (ASCE7-05). Reston, VA, USA, American Society of Civil Engineers.

Alabama Department of Transportation. (2004a). Maintenance Bureau Specification 2000-01 For 48" Roll Up Signs. Montgomery, Al: Alabama DOT.

Alabama Department of Transportation. (2004b). Maintenance Bureau Specification 2000-02 For 36" Roll Up Signs. Montgomery, Al: Alabama DOT.

Barrero-Gil, A. and Sanz-Andrés, A. (2009). "Aeroelastic effects in a traffic sign panel induced by a passing vehicle." Journal of Wind Engineering and Industrial Aerodynamics, Vol. 97, No. 5-6, pp. 298-303.

Bligh, R. P. (2000). Safety Evaluation of Traffic Control Devices and Breakaway Supports: Summary Report, Project Summary Report 1792-S Project 0-1792: Roadside Safety Hardware for Traffic Control Devices, U.S. Texas Transportation Institute, Texas.

Bligh, R. P., Bullard, D. L., Menges, W. L. and Schoeneman, S. K. (2000) et al. Impact Performance Evaluation of Work Zone Traffic Control Devices, Report 0-1792-2, U.S. Texas Transportation Institute, Texas.

Bone Safety Signs. (2007-2010). "Bone Safety Signs Homepage." from http://www.bonesafety.com/.

Bryden, J.E. (1990). "Crash Tests of Work Zone Traffic Control Devices, in Transportation Research Record", Journal of the Transportation Research Board, No. 1254, T RB, National Research Council, Washington, D.C., 1990, pp. 26 – 35.

Cali, P. M. and E. E. Covert (2000). "Experimental measurements of the loads induced on an overhead highway sign structure by vehicle-induced gusts." Journal of Wind Engineering and Industrial Aerodynamics, Vol. 84, No.1, pp. 87-100.

Consolazio, G., Chung, J. and Gurly, K. (2003). Impact Simulation and Full Scale Crash Testing of a Low Profile Concrete Workzone Barrier, Comput. Struct. Vol. 81, No. 13, pp. 1359 – 1374.

Dicke Safety Products. (2009). "Dicke Safety Products Hompage." from http://dicketool.com/index.htm.

FHWA, (1998). Memorandum - Information: Crash Tested Work Zone Traffic Control Devices. Federal Highway Administration.

FHWA (2009a). The Manual on U niform Traffic Control Devices. U.S. Department of Transportation.

FHWA (2009b). Manual on U niform Traffic Control Devices. Washington D.C.: Federal Highway Administration.

Flay, R. G. J. and P. S. Jackson (1992). "Flow simulations for wind-tunnel studies of sail aerodynamics." Journal of Wind Engineering and Industrial Aerodynamics, Vol. 44, No. 1-3, pp. 2703-2714.

Florida Department of Transportation. (2009). Section 990 Temporary Traffic Control Devixes Materials. Florida DOT.

Hillstrom, D. U. and Y. M. Levin (2000). Sign Stand with Cam Release Assembly. U.S. Patent 6032908

Hosch, I. and F. Fouad (2009). "Fatigue Design of Sign Support Structures for Loading Caused by Natural Wind Loads." Transportation Research Record: Journal of the Transportation Research Board 2131(-1): 15-22.

Kacin, J., P. Rizzo, et al. (2010). "Fatigue analysis of overhead sign support structures." Engineering Structures 32(6): 1659-1670.

Kansas Department of Transportation. (2007). Section 2203 Roll-Up Sign. KDOT.

Knapp, M. (1982). Wind Deflectable Sign Holder. U.S. Patent 4309836

Knapp, M. D. (1985). Rigid Mechanical Corner Pocket For Tensioning Flexible Signs and Signal Devices. U.S. Patent 4490934

Knight, J. J., A. D. Lucey, et al. (2010). "Fluid-structure interaction of a two-dimensional membrane in a flow with a pressure gradient with application to convertible car roofs." Journal of Wind Engineering and Industrial Aerodynamics 98(2): 65-72.

Leach, F. D. (1992). Highway Sign. U.S. Patent 5152091

Letchford, C. W. (2001). "Wind loads on rectangular signboards and hoardings." Journal of Wind Engineering and Industrial Aerodynamics 89(2): 135-151.

D.G. Linzell and Z. Radó, Portable Sign Crash Test, Research Agreement No. 510401, Pennsylvania Transportation Institute, 2007.

Mak, K.K., Bligh, R.P., and Rhodes, L. (1998). "Crash Testing and Evaluation of Work Zone Traffic Control Devices," Journal of the Transportation Research Board, No. 1650, TRB, National Research Council, Washington, D.C., 1998, pp. 45 – 54.

Mak, K.K., Bligh, R.P., and Menges, W.L. (2000). Evaluation of Work Zone Barricades and Temporary Sign Supports, Research Report 5388-F1, U.S. Texas Transportation Institute, Texas, 2000.

NCHRP (1993). NCHRP Report 350 - Recommended Procedures for the Safety Performance Evaluation of Highway Features, Transportation Research Board, Washington D.C.

NCHRP (2006). NCHRP Report 553 - Crashworthy Work-Zone Traffic Control Devices, TRB, National Research Council, Washington, D.C.

Polivka, K.A., FALLER, R.K., Rohde, J. R., Sicking, D.L. (2002). "Crash Testing and Analysis of Work-Zone Sign Supports," Journal of the Transportation Research Board, No. 1797, TRB, National Research Council, Washington, D.C., 2002 pp. 96 – 104.

Quinn, A. D., C. J. Baker, et al. (2001a). "Wind and vehicle induced forces on flat plates--Part 1: wind induced force." Journal of Wind Engineering and Industrial Aerodynamics 89(9): 817-829.

Quinn, A. D., C. J. Baker, et al. (2001b). "Wind and vehicle induced forces on flat plates--Part 2: vehicle induced force." Journal of Wind Engineering and Industrial Aerodynamics 89(9): 831-847.

Rice Signs. (2009). "Rice Signs Hompage." from http://www.ricesigns.com/.

Ross, H. E., Sicking, D. L., & Zimmer, R. A. (1993). National Cooperative Highway Research Program Report 350. Washington, D.C.: National Academy Press.

Sanz-Andrés, A., J. Santiago-Prowald, et al. (2003). "Vehicle-induced loads on t raffic sign panels." Journal of Wind Engineering and Industrial Aerodynamics 91(7): 925-942.
Sarkisian, R. (1981). Adjustable Sign Mouting Bracket. U.S. Patent 4288053
Seely, J. R. (1985). Sign and Attachment Apparatus. U.S. Patent 4507887
Seely, J. R. and C. E. Ursprung (1985). Compact Sign and Stand. U.S. Patent 4548379
Sign Up Corp. (2010). "Sign Up Corp Hompage." from http://www.signupcorp.com/
TrafFix Devices Inc. (1998-2010). "TrafFix Devices Inc. Homepage." from http://www.traffixdevices.com/.
TxDOT (2007). DMS - 8310 Flexible Roll-Up Reflective Signs. Texas Department of Transportation. Austin, TX:
TxDOT (2010a). Specification No. TxDOT 801-12-77* Stand, Sign, Portable, For Roll-Up Signs, 1 Foot Mounting Height. Texas Department of Transportation. Austin, TX:
TxDOT (2010b). Specification No. TxDOT 801-12-78 Stand, Sign, Portable, For Roll-Up Signs, 7 Foot Mounting Height. Texas Department of Transportation. Austin, TX:
TxDOT (2010c). Specification No. TxDOT 801-60-66* Sign Face, Roll-up, Reflective, Construction and Work Zone. Texas Department of Transportation. Austin, TX:
Viola, I. M. and F. Fossati (2008). Downwind sails aerodynamics analysis. International Colloquium on: Bluff Bodies Aerodynamics & Applications, Milano, Italy.
USA-Sign. (2007). "USA-Sign Hompage." from http://www.usa-sign.com/

# APPENDIX I

# MASH EVALUATION OF ALTERNATIVE SUPPORT MATERIALS FOR PORTABLE ROLL-UP SIGNS

**TTI: 0-6639-13**

# *MASH* EVALUATION OF ALTERNATIVE SUPPORT MATERIALS FOR PORTABLE ROLL-UP SIGNS

ACCREDITED
ISO 17025 Laboratory
Testing Certificate # 2821.01

Crash testing performed at:
TTI Proving Ground
3100 SH 47, Building 7091
Bryan, TX 77807

**Test Report 0-6639-13-1**

**Cooperative Research Program**

**TEXAS A&M TRANSPORTATION INSTITUTE**
**COLLEGE STATION, TEXAS**

**TEXAS DEPARTMENT OF TRANSPORTATION**

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
http://tti.tamu.edu/documents/0-6639-13-1.pdf

Technical Report Documentation Page

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| FHWA/TX-13/0-6639-13-1 | | |

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|---|---|
| *MASH* EVALUATION OF ALTERNATIVE SUPPORT MATERIALS FOR PORTABLE ROLL-UP SIGNS | August 2013 |
| | 6. Performing Organization Code |

| 7. Author(s) | 8. Performing Organization Report No. |
|---|---|
| Roger P. Bligh and Wanda L. Menges | Test Report No. 0-6639-13-1 |

| 9. Performing Organization Name and Address | 10. Work Unit No. (TRAIS) |
|---|---|
| Texas Transportation Institute Proving Ground<br>The Texas A&M University System<br>College Station, Texas 77843-3135 | 11. Contract or Grant No.<br>Project 0-6639-13 |

| 12. Sponsoring Agency Name and Address | 13. Type of Report and Period Covered |
|---|---|
| Texas Department of Transportation<br>Research and Technology Implementation Office<br>P.O. Box 5080<br>Austin, Texas 78763-5080 | Test Report:<br>July 2012 – August 2013 |
| | 14. Sponsoring Agency Code |

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Testing of Alternative Support Materials for Portable Roll-Up Signs Used in Maintenance Work Zones

URL: http://tti.tamu.edu/documents/0-6639-13-1.pdf

16. Abstract


Fiberglass members are commonly used as the frame for portable roll-up fabric signs. These signs can flex in windy conditions to a point that causes them to become illegible. Under high winds, the fiberglass stays can break and render the useless. The Amarillo District has experimented with aluminum frames of the same cross-sectional dimensions as the fiberglass frame members with little success due to the aluminum frames bending in high winds. Therefore, research was undertaken by Texas Tech University to determine which materials can provide improved wind resistance and more durable and reliable service in this application than either fiberglass or aluminum.

This report documents full-scale crash testing of a modified portable roll-up sign system designed to provide improved in-field service for wind loads. The modifications included use of carbon fiber wraps to increase stiffness in preferred directions, and a bolt through the vertical stay that delays separation of the stay from the base. The modified portable sign stand met *MASH* impact performance criteria.


| 17. Key Words | 18. Distribution Statement |
|---|---|
| Work Zone, Maintenance Signing, Traffic Control Device, Roll-Up Sign, Portable Sign, Sign Support, Roadside Safety, Crash Testing. | No restrictions. This document is available to the public through NTIS:<br>National Technical Information Service<br>Springfield, Virginia 22161<br>http://www.ntis.gov |

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# MASH EVALUATION OF ALTERNATIVE SUPPORT MATERIALS FOR PORTABLE ROLL-UP SIGNS

by

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Report No. 0-6639-13-1
Project No. 0-6639-13
Project Title: Testing of Alternative Support Materials for Portable Roll-Up Signs
Used in Maintenance Work Zones

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

August 2013

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

# DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation, and its contents are not intended for construction, bidding, or permit purposes. In addition, the above listed agencies assume no liability for its contents or use thereof. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report. The engineer in charge of the project was Roger P. Bligh, P.E. (Texas, #78550).

# TTI PROVING GROUND DISCLAIMER

The results of the crash testing reported herein apply only to the article being tested.

ACCREDITED
ISO 17025 Laboratory
Testing Certificate # 2821.01

Crash testing performed at:
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## ACKNOWLEDGMENTS

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# CHAPTER 1. INTRODUCTION

## 1.1 BACKGROUND

Portable roll-up signs are currently used by the Texas Department of Transportation (TxDOT) for short-term, daytime maintenance/construction activities and emergency operations. These flexible fabric signs are supported by fiberglass frames attached to a multi-leg base. In windy conditions typical of the Texas coast and panhandle, the rollup sign panels lay back to a point that they become illegible. In more extreme conditions, the support can blow over or the fiberglass stays can break.

The cost of resetting signs and replacing those that fail involves not only direct materials and labor, but also the safety of maintenance personnel due to increased exposure and the motoring public due to lost information in the work zone. Research project 0-6399 was undertaken to understand the nature of wind loading on portable roll-up signs, and identify alternative materials to support the flexible sign substrates that will improve the performance of the sign support in windy conditions and reduce wind-induced failures without compromising crashworthiness.

## 1.2 OBJECTIVES/SCOPE OF RESEARCH

Alternate materials were identified by researchers at Texas Tech University that offer promise for improving field performance providing more durable and reliable service in windy conditions. The alternate materials were incorporated into a modified short term sign stand that is readily available in the marketplace. The crashworthiness of modified system was evaluated through a series of crash tests conducted in accordance with the American Association of State Highway Transportation Officials (AASHTO's) *Manual for Assessing Safety Hardware (MASH) (1)*. These tests were performed at the Texas A&M Transportation Institute (TTI) Proving Ground, and the results are reported herein.

# CHAPTER 2. SYSTEM DETAILS

## 2.1 TEST ARTICLE DESIGN AND CONSTRUCTION

Two prototype portable roll-up sign assemblies were provided by researchers at Texas Tech University. The roll-up fabric sign substrates were 3M™ Diamond Grade™ RS24 roll-up sign sheeting that were obtained through TrafFix Devices, Inc. The sign sheeting is listed on the TxDOT 801-60-66 Prequalified Products List (QPL) "Sign Face, Roll-Up, Reflective, Construction and Work Zone." The sign panels incorporated plastic corner pockets into which the ends of the horizontal and vertical fiberglass stays were inserted.

The fiberglass stays were obtained from TrafFix Devices, Inc. The vertical stays were 66 inches long, 1.25 inches wide, and 5/16 inches thick. The horizontal stays were 66 inches long, 1.25 inches wide, and 3/16 inches thick.

Mbrace® CF 130 carbon fiber sheets were used to strengthen and reinforce portions of the fiberglass stays. Mbrace® CF 130 is a dry fabric constructed of very high strength aerospace grade carbon fibers that is manufactured by BASF Construction Chemicals, LLC. The carbon fiber sheets were applied using epoxy based resin, namely, Mbrace® Primer and Saturant.

The carbon fiber sheets were applied to the lower 40 inches of the vertical stays and the middle 24-inch region of the horizontal stays. One layer of carbon fiber sheet was wrapped around the stays, with an overlap on one of the long side of the stays to cover the starting edge of the sheet.

The bottom corner of the roll-up fabric signs were inserted into 22000 Series TrafFix Sign Stands that were obtained through TrafFix Devices, Inc. The four telescoping, tubular steel legs of the sign stand were extended to their fully open position. The legs were positioned in the lowest height adjustment, such that the mounting height from the pavement surface to the bottom corner of the roll-up fabric sign was 12 inches. The weight of the sign stand was 20 lb.

The assembled portable sign system was placed on a concrete apron for the crash testing. The first test was performed with a 40-lb sand bag placed at the end of each of the four legs of the sign stand. This is how they are typically deployed in the coastal and western regions of Texas that frequently experience high winds. A subsequent test was conducted without sand bags to determine their effect on the impact performance of the portable sign system.

General details of the roll-up sign support system are shown in Figure 2.1 and 2.2. Additional details of the system are provided in Appendix A. Photographs of the assembled test prototypes are shown in Figure 2.3.

## 2.2 MATERIAL SPECIFICATIONS

The roll-up fabric sign substrates were manufactured from 3M™ Diamond Grade™ RS24 roll-up sign sheeting. The material specifications for the sign sheeting are provided in Appendix B. Researchers at Texas Tech University conducted laboratory tests to characterize the material properties of the fiberglass stays. The tensile strength of the fiberglass stays varied from 67 ksi to 87 ksi, and Young's Modulus ranged from 5500 ksi to 5800 ksi. Mbrace® CF 130 carbon fiber sheets were used to strengthen and reinforce portions of the fiberglass stays as described above. The engineering properties of the carbon fibers are provided in Appendix C.

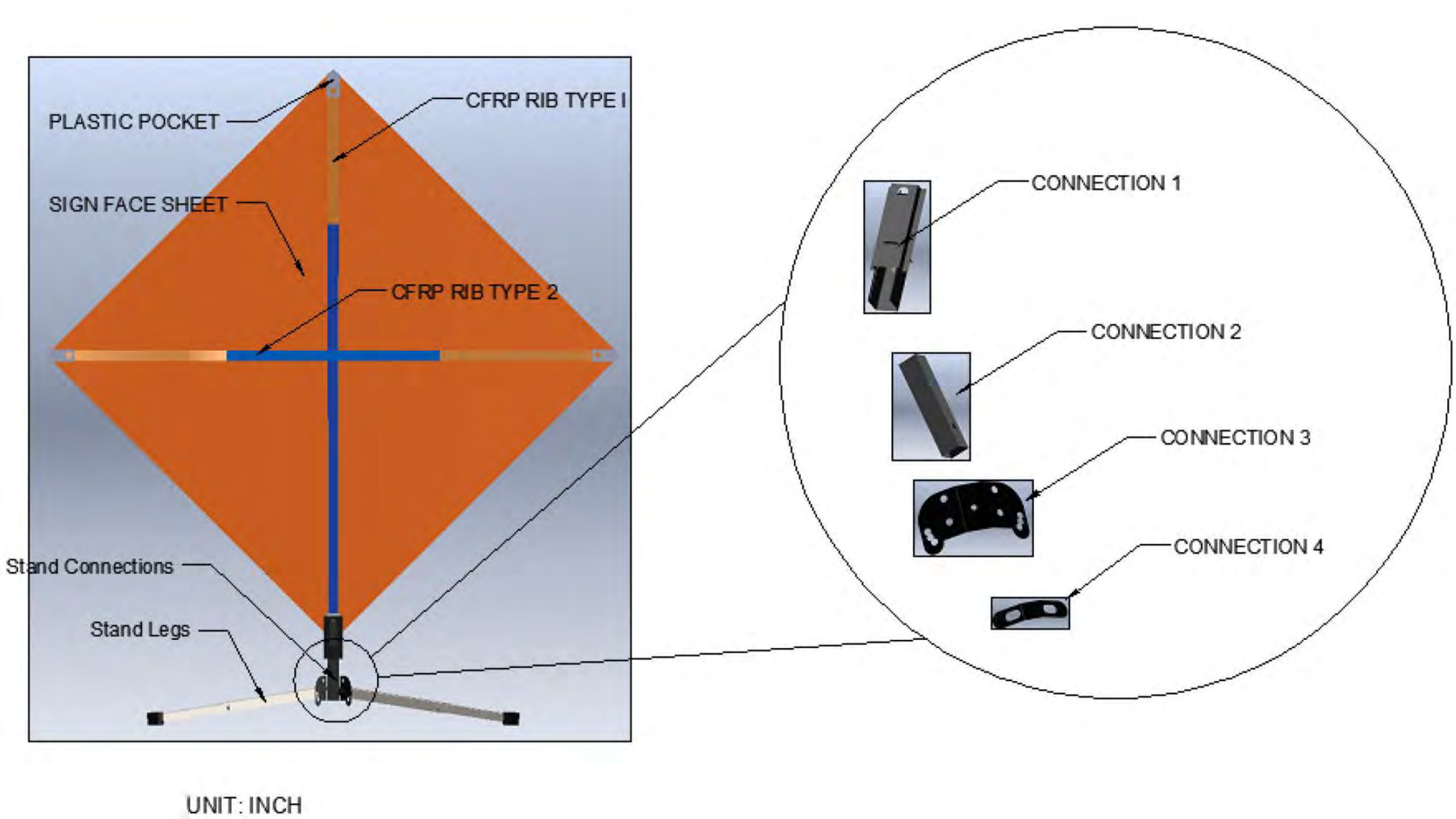



**Figure 2.1. Components of the Portable Roll-Up Sign.**

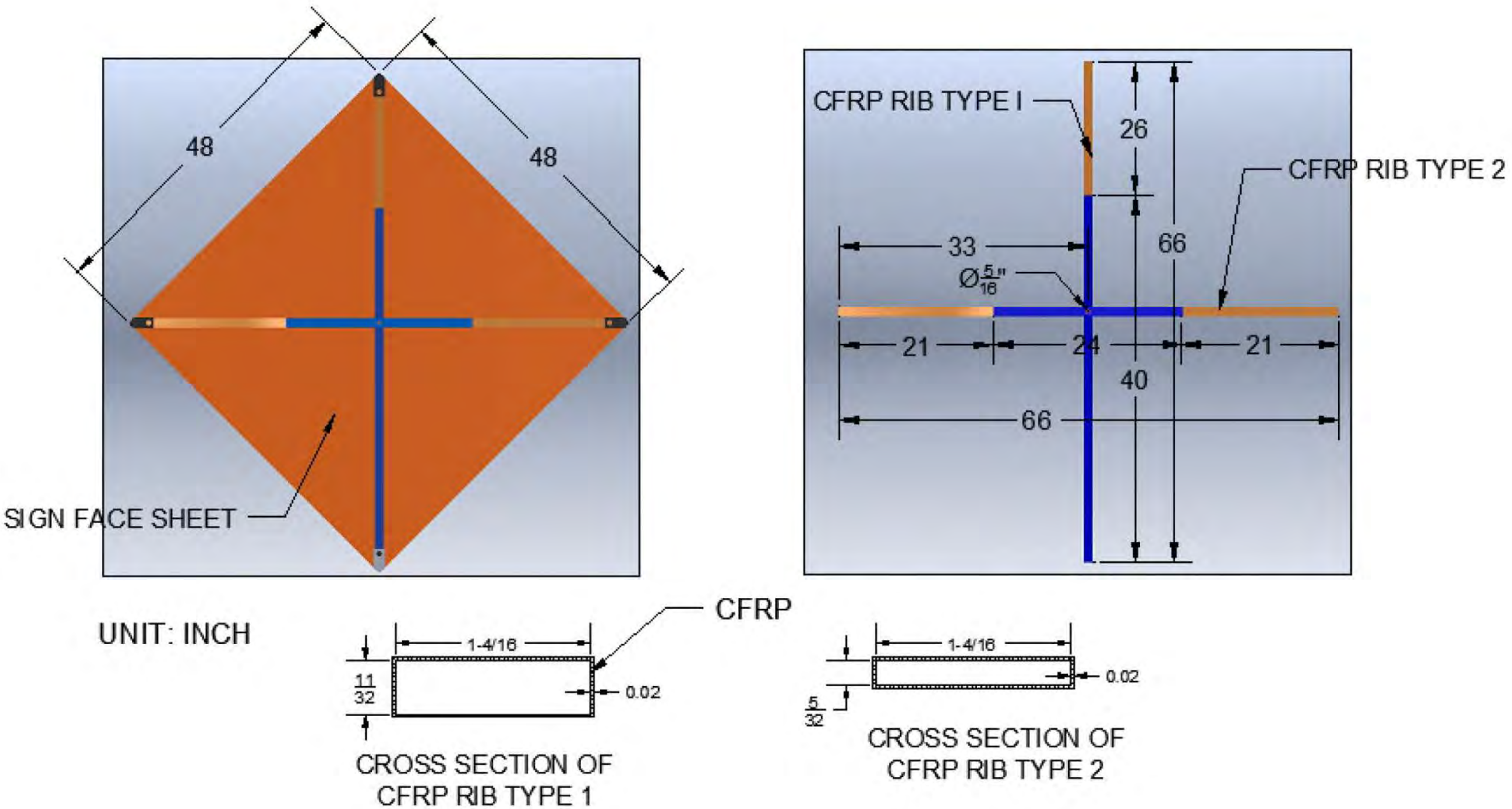
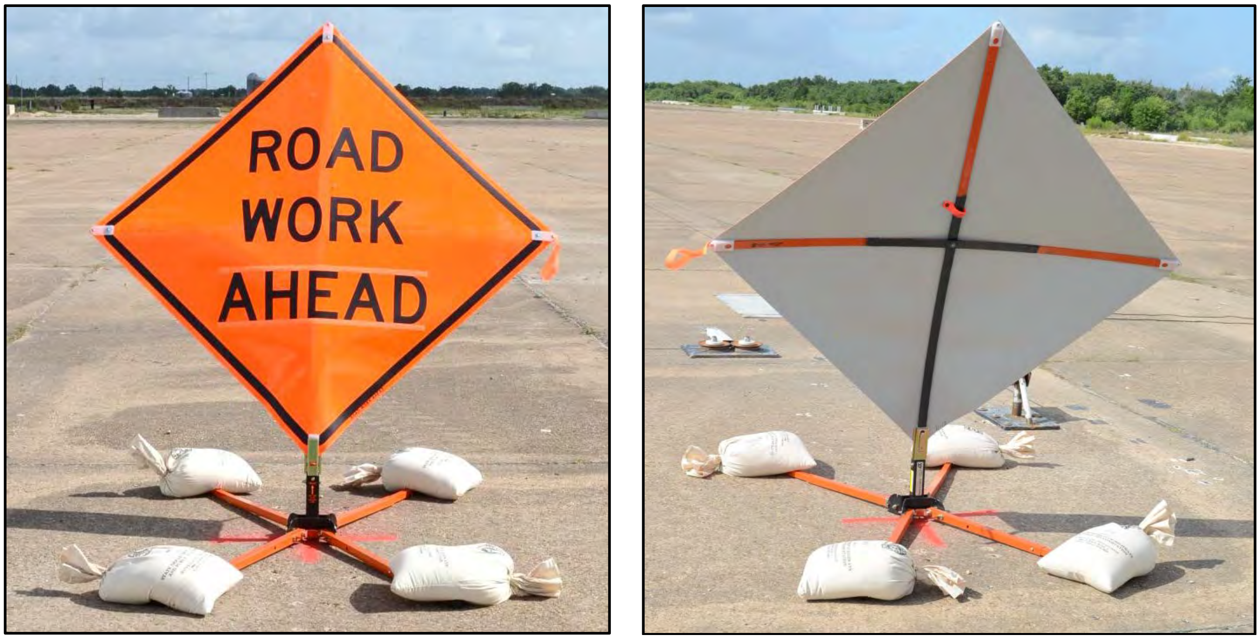



**Figure 2.2. Dimensional Details of the Portable Roll-Up Sign Panel and Supports.**




Portable Roll-Up Sign with Sandbags


Portable Roll-Up Sign without Sandbags

**Figure 2.3. Portable Roll-Up Sign before Test No. 4663963-1 and 2.**

# CHAPTER 3. TEST REQUIREMENTS AND EVALUATION CRITERIA

## 3.1 CRASH TEST MATRIX

According to *MASH*, up to three tests are recommended to evaluate work zone traffic control devices to Test Level 3 (TL-3):

- ***MASH* Test 3-70**: An 1100C (2420 lb/1100 kg) vehicle impacting the device at a nominal impact speed of 19 mi/h and critical impact angle (CIA) judged to have the greatest potential for test failure. This test evaluates a device's ability to successfully activate by breakaway, fracture, or yielding mechanism during low-speed impacts with a small vehicle.
- ***MASH* Test 3-71**: An 1100C (2420 lb/1100 kg) vehicle impacting the device at a nominal impact speed of 62 mi/h and CIA judged to have the greatest potential for test failure. This evaluates the behavior of the device during high-speed impacts with a small vehicle and the potential for intrusion of structural components into the vehicle.
- ***MASH* Test 3-72**: A 2270P (5000 lb/2270 kg) vehicle impacting the device at a nominal impact speed of 62 mi/h and CIA judged to have the greatest potential for test failure. This evaluates the behavior of the device during high-speed impacts with a pickup truck.

*MASH* test 3-71 was performed on the portable roll-up sign stands evaluated under this project. This test is considered to be the critical test for temporary work zone traffic control devices with a 1-ft mounting height due to the increased propensity for occupant compartment intrusion through the windshield of the small car at higher speeds. MASH states that Test 3-70 is considered optional for work-zone traffic control devices weighing less than 220 lb, because velocity changes during low-speed impacts with free-standing, lightweight features will be within acceptable limits. The higher hood height and longer wrap around distance from the ground to the base of the windshield makes test 3-72 with the pickup truck less critical for low-mounted signs. The 4 ft × 4ft fabric sign in a diamond configuration at a 1 ft mounting height stands approximately 6 ft-8 inches tall. The wrap around distance on a Dodge Ram 1500 pickup truck is approximately 7 ft-10 inches. Therefore, the sign would contact the hood rather than the windshield. Further, because the hood height of the pickup truck, which is approximately 3 ft-10 inches, matches the height of the center of the sign panel and exceeds the center of mass of the sign support system, it is likely that the sign panel will be carried forward by the truck even if it releases from its base.

FHWA requires the impact performance of temporary work zone sign supports to be evaluated for two different orientations. In addition to the common scenario involving the car impacting the device head-on (i.e., 0 deg.), an impact with the device turned either turned 90 degrees or laid on the ground, whichever is judged the more critical case, is also required. This test condition accounts for the common field practice of rotating or lying a device down out of view of traffic until it is needed again and/or picked up and moved to the next job site. In order to reduce testing cost, FHWA permits the evaluation of both the zero and ninety degree orientations using two separate devices impacted in sequence in a single crash test. When conducting such tests, consideration must be given to the fact that the first device impacted can potentially affect or interfere with the subsequent device. If the impact evaluation of the second device is hindered by interaction with the first device, a separate test is conducted to evaluate the second device.

In the initial testing of the portable roll-up sign system, single devices were tested headon at zero degrees. In subsequent testing of a modified sign stand, two separate devices oriented at zero and ninety degrees were impacted in a single crash test. The devices were separated by a distance of 30 ft.

The crash test and data analysis procedures followed under the project were in accordance with guidelines presented in *MASH*. Chapter 4 presents brief descriptions of these procedures.

## 3.2 EVALUATION CRITERIA

The performance of each portable roll-up sign was evaluated using all relevant *MASH* criteria for evaluation of work zone traffic control devices. Of primary concern regarding the impact behavior of a work zone traffic control device is penetration of the device or parts of the device into the occupant compartment. In order to minimize the potential for injury during impact, penetration or intrusion into the occupant compartment is not permitted. Any hole through the protective layer in the windshield constitutes a failure. In addition, the windshield cannot be shattered or damaged to the extent that it obstructs the vision of the driver or is deformed inward more than 3 inches. The appropriate safety evaluation criteria from Table 5-1 of *MASH* were used to evaluate the crash tests reported herein, and are listed in further detail under the assessment of each crash test.

# CHAPTER 4. CRASH TEST PROCEDURES

## 4.1 TEST FACILITY

The full-scale crash tests reported herein was performed at Texas A&M Transportation Institute (TTI) Proving Ground, an International Standards Organization (ISO) 17025 accredited laboratory with American Association for Laboratory Accreditation (A2LA) Mechanical Testing certificate 2821.01. The full-scale crash tests were performed according to TTI Proving Ground quality procedures and according to *MASH* guidelines and standards.

The TTI Proving Ground is a 2000-acre complex of research and training facilities located 10 miles northwest of the main campus of Texas A&M University. The site, formerly an Air Force base, has large expanses of concrete runways and parking aprons well-suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and safety evaluation of roadside safety hardware. The site selected for placement and testing of the portable roll-up signs evaluated under this project was an out-of-service concrete apron. The apron consists of an unreinforced jointed-concrete pavement in 12.5-ft × 15--ft blocks nominally 6 inches deep. The apron is over 60 years old, and the joints have some displacement, but are otherwise flat and level.

## 4.2 VEHICLE TOW AND GUIDANCE PROCEDURES

The test vehicles were towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional steel cable was connected to the test vehicle, passed around a pulley near the impact point, through a pulley on the tow vehicle, and then anchored to the ground such that the tow vehicle moved away from the test site. A two-to-one speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the test vehicle was released to be unrestrained. The vehicle remained freewheeling (i.e., no steering or braking inputs) until it cleared the immediate area of the test site, after which the brakes were activated to bring it to a safe and controlled stop.

## 4.3 DATA ACQUISITION SYSTEMS

### 4.3.1 Vehicle Instrumentation

*MASH* states “that lightweight free-standing features cannot cause sufficient velocity change to result in failure of the test under occupant risk criteria. Therefore, Tests 71 and 72 can be conducted without the instrumentation necessary for determining occupant risk whenever the test article has a total weight of 220 lb (100 kg) or less.” Consequently, the vehicles used in the testing program were uninstrumented except for a remote controlled braking package installed for safety purposes.

### 4.3.2 Anthropomorphic Dummy Instrumentation

An Alderson Research Laboratories Hybrid II, 50th percentile male anthropomorphic dummy, restrained with lap and shoulder belts, was placed in the driver's position of each 1100C vehicle. The dummy was uninstrumented.

### 4.3.3 Photographic Instrumentation and Data Processing

Photographic coverage of each test included two high-speed cameras: one placed with a field of view perpendicular to the vehicle path, and one placed behind the installation at an oblique angle. A flashbulb activated by pressure-sensitive tape switches was positioned on the impacting vehicle to indicate the instant of contact with the installation and was visible from each camera. The video from these high-speed cameras was analyzed on a computer-linked motion analyzer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A mini-DV camera and still cameras recorded and documented conditions of the test vehicle and installation before and after the test.

# CHAPTER 5. CRASH TEST RESULTS

## 5.1 CRASH TEST NO. 466393-1 (*MASH* TEST 3-71) -- WITH SANDBAGS

### 5.1.1 Test Designation and Actual Impact Conditions

*MASH* Test 3-71 involves an 1100C vehicle weighing 2420 lb ±55 lb and impacting the portable roll-up sign support at an impact speed of 62.2 mi/h ±2.5 mi/h. The centerline of the vehicle was aligned with the centerline of the roll-up sign. The 2009 Kia Rio used in the test weighed 2443 lb and the actual impact speed and angle were 63.4 mi/h and 0 degrees, respectively. The portable roll-up sign was impacted with the centerline of the vehicle aligned with the centerline of the device, with the device oriented 90 degrees to traffic flow.

### 5.1.2 Test Vehicle

The 2009 Kia Rio, shown in Figures 5.1 and 5.2, was used for the crash test. Test inertia weight of the vehicle was 2443 lb, and its gross static weight was 2622 lb. The height to the lower edge of the vehicle bumper was 6.75 inches, and the height to the upper edge of the bumper was 22.00 inches. Table D1 in Appendix D gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.

### 5.1.3 Weather Conditions

The test was performed on the morning of July 22, 2013. Weather conditions at the time of testing were as follows: (a) wind speed: 11mi/h; (b) wind direction: 205 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); (c) temperature: 86°F; (d) relative humidity: 73 percent.

### 5.1.4 Test Description

The 2009 Kia Rio, traveling at an impact speed of 63.4 mi/h, contacted the portable roll-up sign with the centerline of the vehicle aligned with the centerline of the device, with the device oriented 90 degrees to traffic flow. At approximately 0.037 s after impact, the fabric sign panel and support stays began to ride up on the hood of the vehicle, and at 0.057 s, the top of the fabric sign panel and upper supports had contacted the windshield. The plastic sleeve at the top of the fabric sign panel and the top of the vertical stay punctured the windshield at 0.063 s. The fabric sign panel and attached stays reached maximum penetration at 0.148 s and subsequently began to rotate out of the windshield. At 0.208 s, the fabric sign panel and attached stays rode up the windshield and lost contact with the vehicle. The speed of the vehicle at loss of contact was 62.6 mi/h. The lower support base came to rest 1.4 ft downstream of impact. The fabric sign panel and stays came to rest 75 ft downstream of impact, and the vehicle came to a stop 262 ft downstream of impact and 8 ft to the right (toward traffic lanes) after application of brakes. Figure E1 in Appendix E shows sequential photographs of the test period.

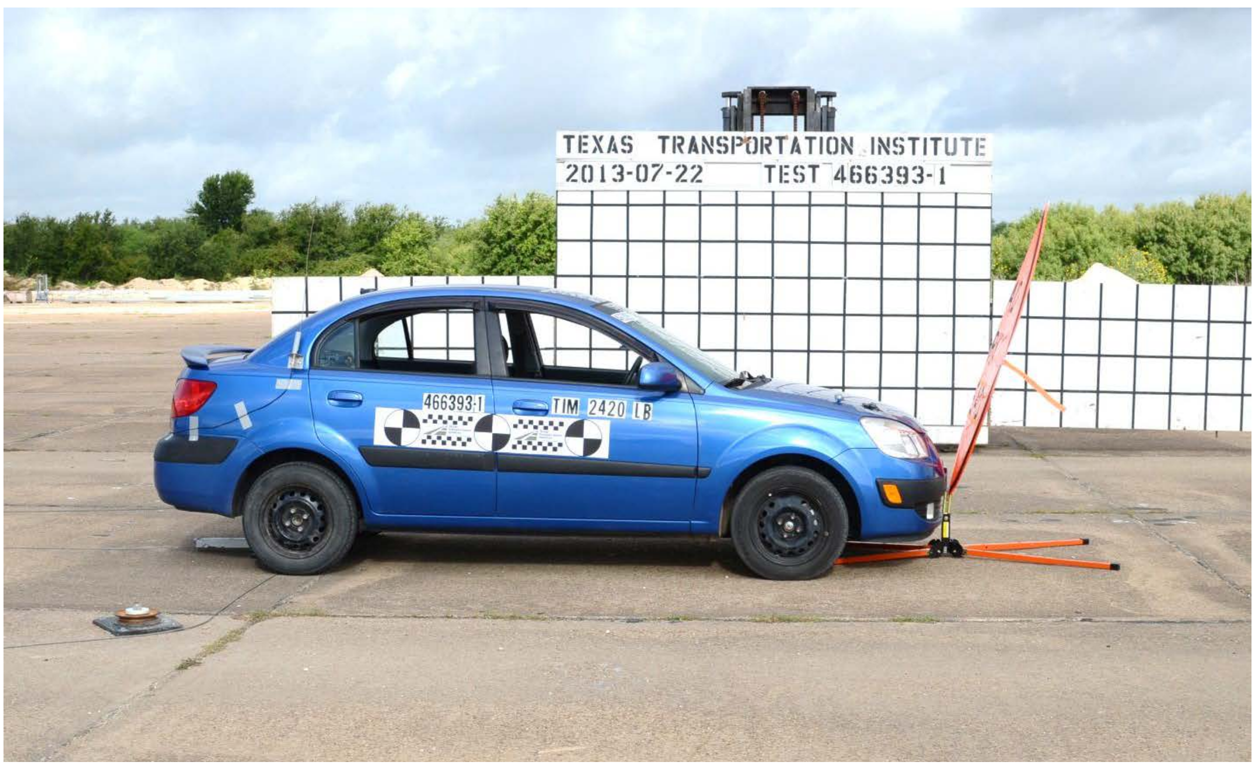



**Figure 5.1. Vehicle/Installation Geometrics for Test No. 466393-1.**


**Figure 5.2. Vehicle before Test No. 466393-1.**

### 5.1.5 Damage to Test Installation

Figures 5.3 and 5.4 show damage to the work zone traffic control device. The fabric sign panel and stays separated from the lower base, contacted and penetrated the windshield, rode up and over the vehicle, and came to rest 75 ft downstream of impact. The base of the temporary sign support came to rest 1.4 ft downstream of impact. Two of the sandbags remained intact, one was torn open and emptied of sand, and the fourth was torn and partially emptied.

### 5.1.6 Vehicle Damage

Figure 5.5 shows damage to the 1100C vehicle. The bottom of the front bumper cover was fractured, and the hood sustained scuff marks. No measureable deformation was noted to the exterior hood or bumper. The windshield was punctured/cut by the top corner of the sign panel, leaving a 2-inch × 1.5-inch hole. The area around the puncture was depressed into the occupant compartment 1.5 inches, and the total area shattered measured 20 inches × 17.25 inches. Figure 5.6 shows the windshield damage from inside the occupant compartment. Table D2 and D3 in Appendix D provides exterior crush and occupant compartment measurements.

### 5.1.7 Occupant Risk Factors

Previous full-scale crash tests have shown that the acceleration levels experienced by the vehicle during impact with lightweight, free-standing work zone traffic control devices weighing less than 220 lb were not significant. Consequently, MASH does not require instrumentation of the vehicle, and the occupant risk factors were not calculated for this test. Figure 5.7 summarizes pertinent information from the test.

### 5.1.8 Assessment of Test Results

An assessment of the test based on the applicable *MASH* safety evaluation criteria is provided below.

*5.1.8.1 Structural Adequacy*

*B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.*

Results: The portable roll-up sign yielded to the vehicle by breaking away from its base. (PASS)


**Figure 5.3. After Impact Locations for Test No. 466393-1.**

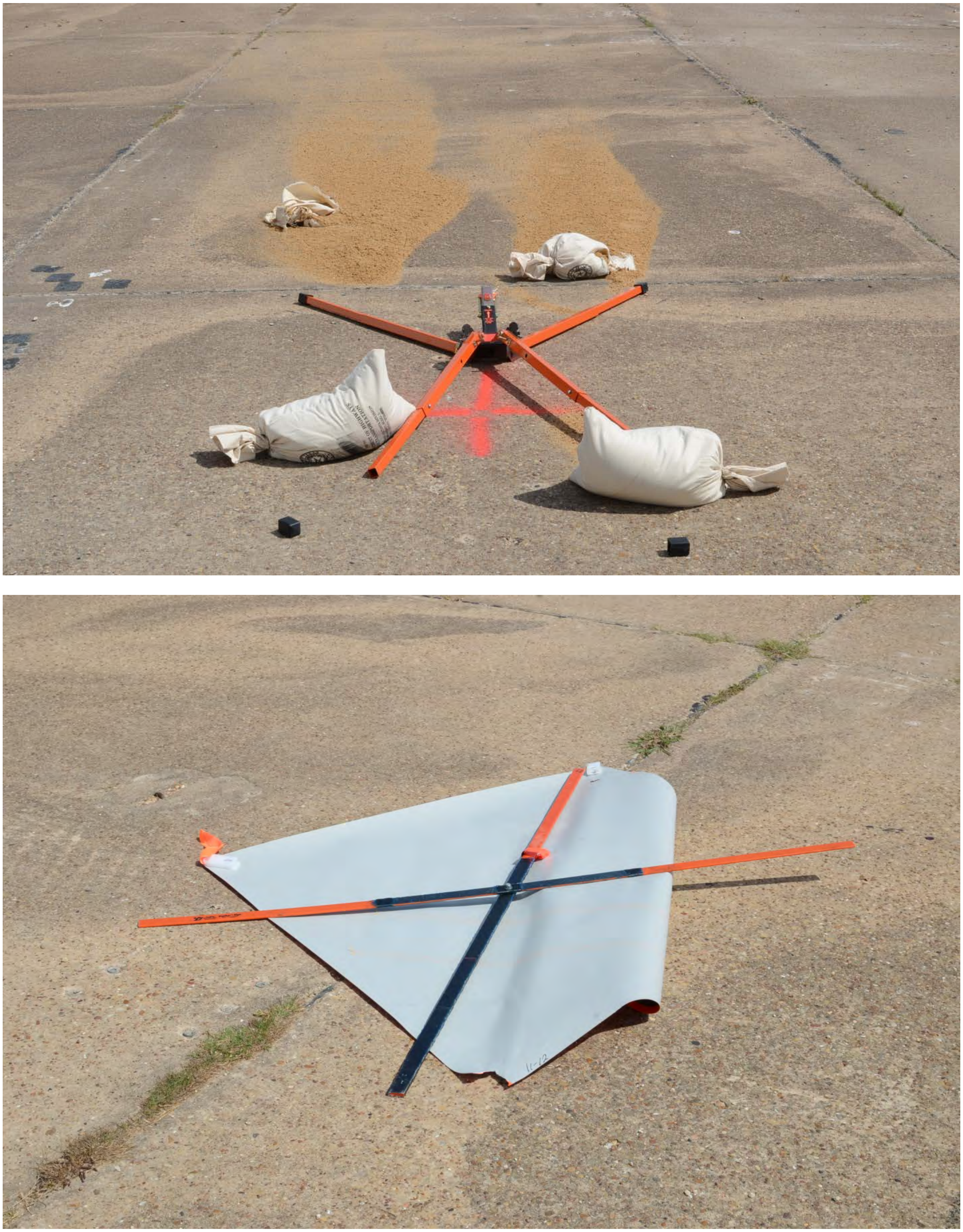
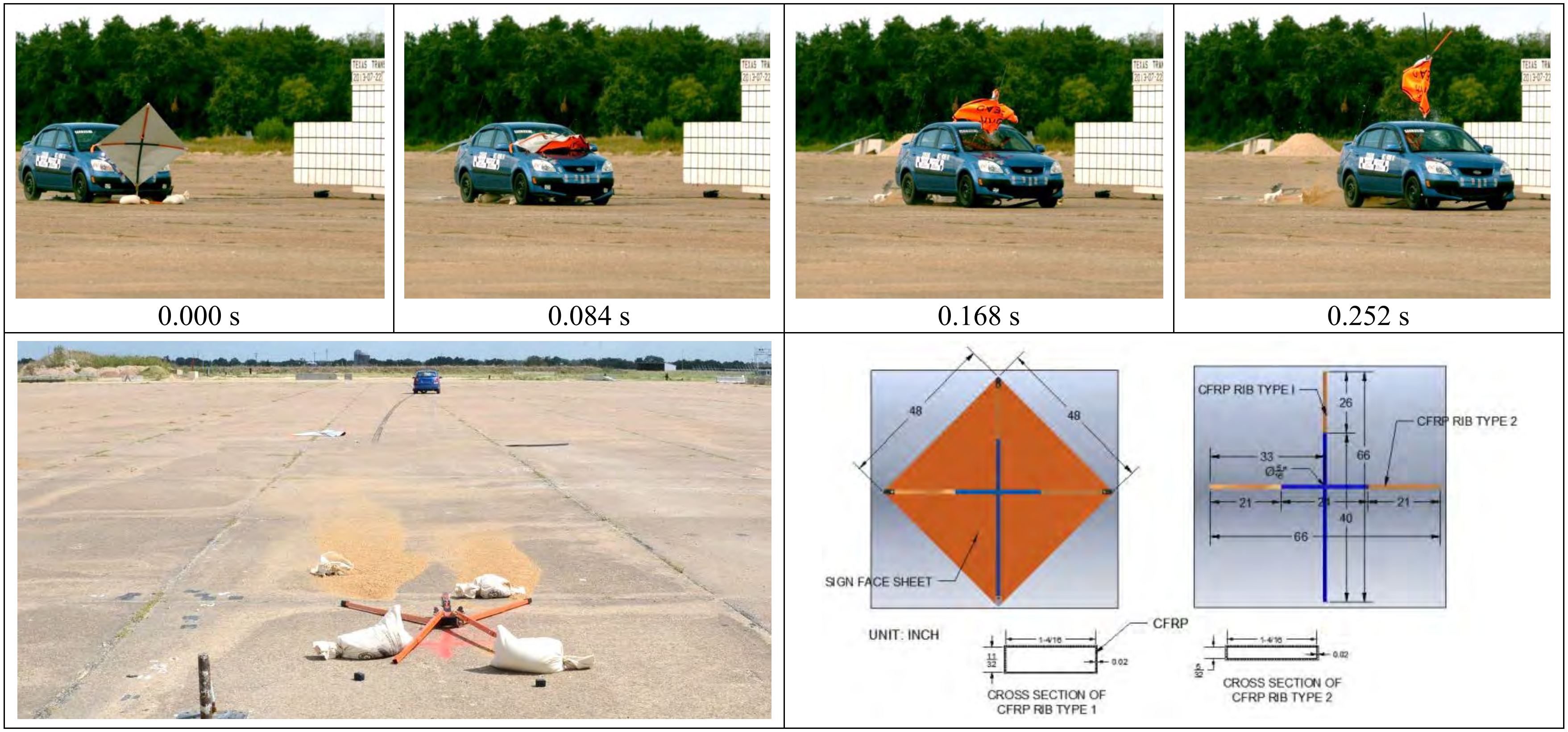


**Figure 5.4. Installation after Test No. 466393-1.**


**Figure 5.5. Vehicle after Test No. 466393-1.**

**Figure 5.6. Interior of Vehicle for Test No. 466393-1.**




**General Information**
- Test Agency ............ Texas Transportation Institute (TTI)
- Test Standard Test No. ......... MASH Test 3-71
- TTI Test No. ............ 466393-1
- Test Date ............ 2013-07-22

**Test Article**
- Type ............ Work Zone Traffic Control Device
- Name ............ Portable Roll-Up Sign with sandbags
- Installation Height ............ 1-ft mounting height
- Material or Key Elements ...... Fabric sign substrate with carbon wrapped fiberglass stays and metal base ballasted with four 40-lb sandbags

**Soil Type and Condition** ......... Placed on concrete surface, dry

**Test Vehicle**
- Type/Designation ......... 1100C
- Make and Model ......... 2009 Kia Rio
- Curb ............ 2459 lb
- Test Inertial ............ 2443 lb
- Dummy ............ 179 lb
- Gross Static ............ 2622 lb

**Impact Conditions**
- Speed ............ 63.4 mi/h
- Angle ............ 0 degrees
- Location/Orientation ... 90 degrees to traffic

**Exit Conditions**
- Speed ............ 62.6 mi/h
- Angle ............ 0 degrees

**Post-Impact Trajectory**
- Stopping Distance ............ 262 ft downstream
  8 ft toward traffic

**Test Article Deflections**
- Fabric Sign & Upper Supports .... 75 ft downstream
- Lower Support/Base ............ 1.4 ft downstream

**Vehicle Damage**
- VDS ............ 12FC1
- CDC ............ 12FCGN6
- Max. Exterior Deformation .......... 1.5 inches (windshield)
- OCDI ............ FS0000000
- Max. Occupant Compartment Deformation ............ 1.5 inches (windshield)
- Windshield Damage ............ Punctured

**Figure 5.7. Summary of Results for *MASH* Test 3-71 on the Portable Roll-Up Sign with Sandbags.**

*5.1.8.2 Occupant Risk*

*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH. (roof ≤4.0 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 inches; forward of A-pillar ≤12.0 inches; front side door area above seat ≤9.0 inches; front side door below seat ≤12.0 inches; floor pan/transmission tunnel area ≤12.0 inches).*

Results: The detached fabric sign panel and attached stays rotated into and penetrated the windshield into the occupant compartment. (FAIL)

*E. Detached element, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.*

Results: The detached fabric sign panel momentarily blocked the driver's vision, but for less than 0.1 seconds. This short time frame would not affect the driver's ability to control the vehicle. (PASS)

*F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*

Results: The 1100C vehicle remained upright during and after the collision event. (PASS)

*H. Occupant impact velocities should satisfy the following:*

*Longitudinal and Lateral Occupant Impact Velocity*

| *Preferred* | *Maximum* |
|---|---|
| *10 ft/s* | *16.4 ft/s* |

Results: The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. (N/A)

*I. Occupant ridedown accelerations should satisfy the following:*

*Longitudinal and Lateral Occupant Ridedown Accelerations*

| *Preferred* | *Maximum* |
|---|---|
| *15.0 Gs* | *20.49 Gs* |

Results: The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. (N/A)

*5.1.8.3 Vehicle Trajectory*

*N. Vehicle trajectory behind the test article is acceptable.*

Result: The 1100C vehicle came to rest 262 ft downstream of the impact position of the portable roll-up sign. (PASS)

## 5.2 CRASH TEST NO. 466393-2 (*MASH* TEST 3-71) -- WITHOUT SANDBAGS

After failure of the initial design with sand bags, the same system was retested without sand bags. The objective was to determine if the sand bags affect the interaction of the portable roll-up sign system with the vehicle. It was hypothesized that the lighter weight sign stand (i.e., without the sand bags) could be accelerated more quickly and might delay release of the sign panel from the sign stand.

### 5.2.1 Test Designation and Actual Impact Conditions

*MASH* Test 3-71 involves an 1100C vehicle weighing 2420 lb ±55 lb and impacting the portable roll-up sign stand at an impact speed of 62.2 mi/h ±2.5 mi/h. The centerline of the vehicle was aligned with the centerline of the roll-up sign. The 2008 Kia Rio used in the test weighed 2437 lb and the actual impact speed and angle were 59.7 mi/h and 0 degrees, respectively. The portable roll-up sign was impacted with the centerline of the vehicle aligned with the centerline of the device, with the device oriented 90 degrees to traffic flow.

### 5.2.2 Test Vehicle

The 2008 Kia Rio, shown in Figures 5.8 and 5.9, was used for the crash test. Test inertia weight of the vehicle was 2437 lb, and its gross static weight was 2617 lb. The height to the lower edge of the vehicle bumper was 6.75 inches, and the height to the upper edge of the bumper was 22.00 inches. Table D4 in Appendix D gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.

### 5.2.3 Weather Conditions

The test was performed on the afternoon of July 22, 2013. Weather conditions at the time of testing were as follows: (a) wind speed: 11mi/h; (b) wind direction: 179 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); (c) temperature: 94°F; (d) relative humidity: 55 percent.

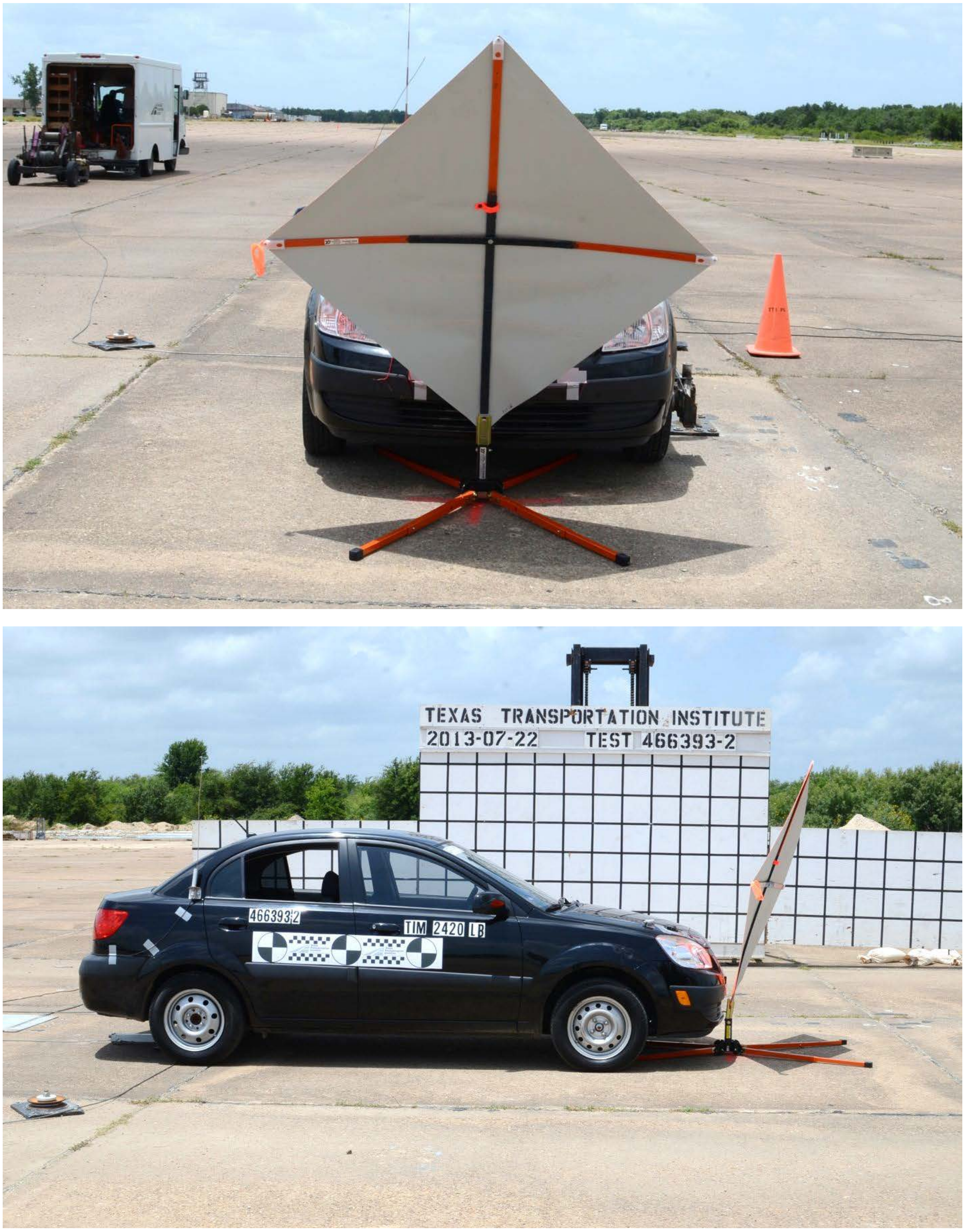



**Figure 5.8. Vehicle/Installation Geometrics for Test No. 466393-2.**


**Figure 5.9. Vehicle before Test No. 466393-2.**

### 5.2.4 Test Description

The 2008 Kia Rio, traveling at an impact speed of 59.7 mi/h, contacted the portable roll-up sign with the centerline of the vehicle aligned with the centerline of the device, and with the device oriented 90 degrees to traffic flow. At approximately 0.051 s after impact, the fabric sign panel and stays began to ride up on the hood of the vehicle, and at 0.059 s, the top of the fabric sign panel and upper supports had contacted the windshield. The top corner of the fabric sign, along with the plastic pockets and stays punctured the windshield at 0.068 s. The fabric sign panel and attached stays reached maximum penetration at 0.146 s, and subsequently began to rotate out of the windshield. At 0.250 s, the fabric sign panel and stays rode up the windshield and lost contact with the vehicle. The lower support base rode under the vehicle for a time and came to rest 158 ft downstream of impact and 6 ft to the left. The fabric sign panel and attached stays came to rest 65 ft downstream of impact and 18 ft to the right. After application of the brakes, the vehicle came to a stop 210 ft downstream of impact and 3 ft to the right. Figure E2 in Appendix E shows sequential photographs of the test period.

### 5.2.5 Damage to Test Installation

Figures 5.10 and 5.11 show damage to the roll-up sign stand. The fabric sign panel and stays separated from the lower base, contacted and penetrated the windshield, rode up and over the vehicle and came to rest 65 ft downstream of impact. The base of the sign came to rest 158 ft downstream of impact.

### 5.2.6 Vehicle Damage

Figure 5.12 shows damage to the 1100C vehicle. The hood sustained scuff marks. No measureable deformation was noted to the exterior hood or bumper. The windshield had a 4-inch × 1.5-inch hole. The area around the hole was depressed into the occupant compartment 1.5 inches, and the total shattered area on the windshield measured 15 inches × 13 inches. Figure 5.13 shows the windshield damage from inside the occupant compartment. Table D5 and D6 in Appendix D provides exterior crush and occupant compartment measurements.

### 5.2.7 Occupant Risk Factors

Previous full-scale crash tests have shown that the acceleration levels experienced by the vehicle during impact with lightweight, free-standing work zone traffic control devices weighing less than 220 lb were not significant. Consequently, *MASH* does not require instrumentation of the vehicle, and the occupant risk factors were not calculated for this test. Figure 5.14 summarizes pertinent information from the test.

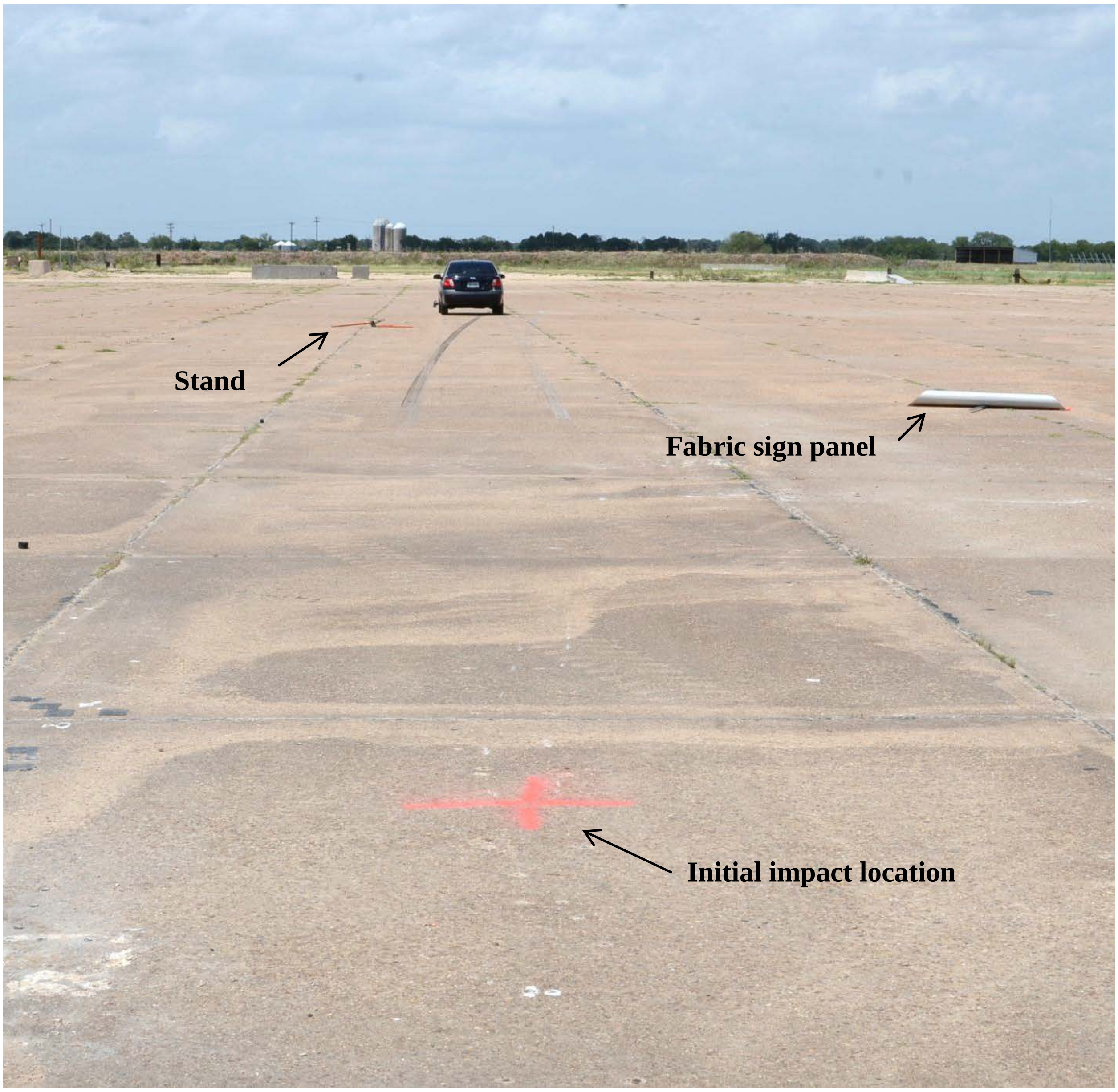
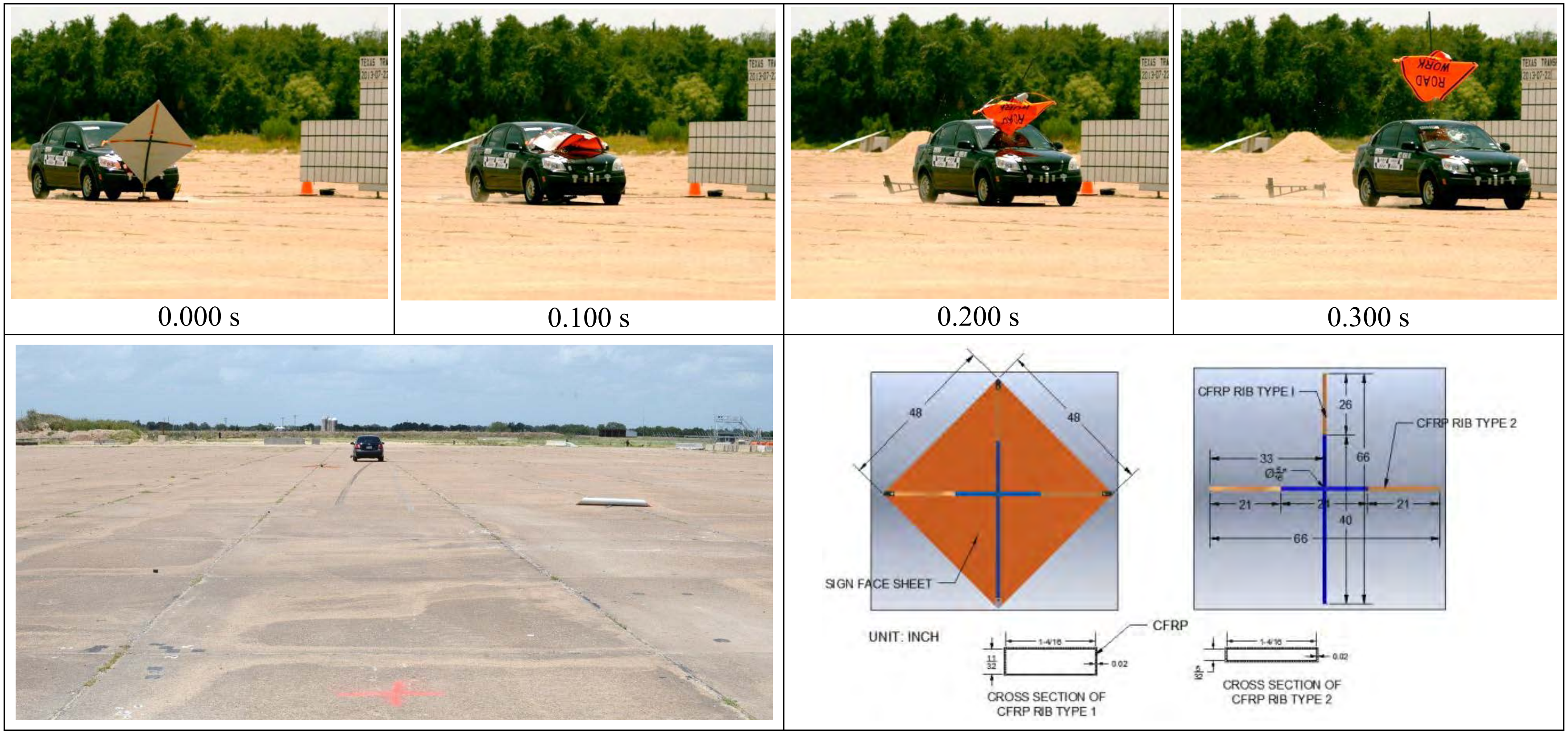



**Figure 5.10. After Impact Locations for Test No. 466393-2.**

**Figure 5.11. Installation after Test No. 466393-2.**


**Figure 5.12. Vehicle after Test No. 466393-2.**

**Figure 5.13. Interior of Vehicle for Test No. 466393-2.**




**General Information**
- Test Agency ......................... Texas Transportation Institute (TTI)
- Test Standard Test No. ......... MASH Test 3-71
- TTI Test No. ......................... 466393-2
- Test Date ............................. 2013-07-22

**Test Article**
- Type..................................... Work Zone Traffic Control Device
- Name ................................... Portable Roll-Up Sign without sandbags
- Installation Height.................. 1-ft mounting height
- Material or Key Elements ...... Fabric sign substrate with carbon wrapped fiberglass stays and metal base ballasted with four 40-lb sandbags

**Soil Type and Condition**......... Placed on concrete surface, dry

**Test Vehicle**
- Type/Designation.........1100C
- Make and Model.........2008 Kia Rio
- Curb ...........................2301 lb
- Test Inertial.................2437 lb
- Dummy........................ 180 lb
- Gross Static.................2617 lb

**Impact Conditions**
- Speed.........................59.7 mi/h
- Angle..........................0 degrees
- Location/Orientation ...90 degrees to traffic

**Exit Conditions**
- Speed.........................58.9 mi/h
- Angle..........................0 degrees

**Post-Impact Trajectory**
- Stopping Distance .................... 210 ft downstream; 3 ft toward traffic

**Test Article Deflections**
- Fabric Sign & Upper Supports .. 65 ft downstream
- Lower Support/Base ................ 158 ft downstream

**Vehicle Damage**
- VDS.......................................... 12FC1
- CDC ......................................... 12FCGN6
- Max. Exterior Deformation ........ 1.5 inches (windshield)
- OCDI ........................................ FS0000000
- Max. Occupant Compartment Deformation........................ 1.5 inches (windshield)
- Windshield Damage ................. Punctured

**Figure 5.14. Summary of Results for *MASH* Test 3-71 on the Portable Roll-Up Sign without Sandbags.**

### 5.2.8 Assessment of Test Results

An assessment of the test based on the applicable *MASH* safety evaluation criteria is provided below.

*5.2.8.1 Structural Adequacy*

*B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.*

Results: The portable roll-up sign yielded to the vehicle by breaking away from the base. (PASS)

*5.2.8.2 Occupant Risk*

*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH. (roof ≤4.0 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 inches; forward of A-pillar ≤12.0 inches; front side door area above seat ≤9.0 inches; front side door below seat ≤12.0 inches; floor pan/transmission tunnel area ≤12.0 inches).*

Results: The detached fabric sign panel and attached stays rotated into and penetrated the windshield into the occupant compartment. (FAIL)

*E. Detached element, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.*

Results: The detached fabric sign panel momentarily blocked the driver's vision, but for less than 0.1 seconds. This short time frame would not affect the driver's ability to control the vehicle. (PASS)

*F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*

Results: The 1100C vehicle remained upright during and after the collision event. (PASS)

*I. Occupant impact velocities should satisfy the following:*

*Longitudinal and Lateral Occupant Impact Velocity*

| *Preferred* | *Maximum* |
|---|---|
| *10 ft/s* | *16.4 ft/s* |

Results: The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. (N/A)

*I. Occupant ridedown accelerations should satisfy the following:*
*Longitudinal and Lateral Occupant Ridedown Accelerations*

| *Preferred* | *Maximum* |
|---|---|
| *15.0 Gs* | *20.49 Gs* |

Results: The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. (N/A)

*5.2.8.3 Vehicle Trajectory*

*N. Vehicle trajectory behind the test article is acceptable.*

Result: The 1100C vehicle came to rest 210 ft downstream of the impact position of the portable roll-up sign.

## 5.3 CRASH TEST NO. 466393-3 (*MASH* TEST 3-71) – MODIFIED WITH SANDBAGS

After failure of the initial design, the portable roll-up sign system was modified. A ⅜-inch diameter bolt passed through the sign stand bracket and vertical fiberglass stay as shown in Figure 5.15. The objective of the modification was to delay or prevent release of the sign and, thereby, reduce or eliminate its interaction with the windshield.

### 5.3.1 Test Designation and Actual Impact Conditions

*MASH* Test 3-71 involves an 1100C vehicle weighing 2420 lb ±55 lb and impacting the portable roll-up sign support at an impact speed of 62.2 mi/h ±2.5 mi/h. In this test, two separate devices were impacted. The first sign was oriented perpendicular to the path of the vehicle and the second was placed 30 ft downstream and oriented parallel to the path of the vehicle. The centerline of the vehicle was aligned with the centerline of each roll-up sign. The 2008 Kia Rio used in the test weighed 2442 lb. The actual impact speed and angle were 62.6 mi/h and 0 degrees for the first sign, 61.1 mi/h and 0 degrees for the second sign, respectively. The portable roll-up signs were sequentially impacted with the centerline of the vehicle aligned with the centerline of the signs.


**Figure 5.15. Bolt Added Through Stand Bracket and Vertical Stay.**

### 5.3.2 Test Vehicle

The 2008 Kia Rio, shown in Figures 5.16 and 5.17, was used for the crash test. Test inertia weight of the vehicle was 2442 lb, and its gross static weight was 2617 lb. The height to the lower edge of the vehicle bumper was 6.75 inches, and the height to the upper edge of the bumper was 21.25 inches. Table D7 in Appendix D gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.

### 5.3.3 Weather Conditions

The test was performed on the morning of August 23, 2013. Weather conditions at the time of testing were as follows: (a) wind speed: 5 mi/h; (b) wind direction: 168 degrees with respect to the vehicle (vehicle was traveling in a northerly direction); (c) temperature: 96°F; (d) relative humidity: 52 percent.

### 5.3.4 Test Description

The 2008 Kia Rio, traveling at an impact speed of 62.6 mi/h, contacted the first portable roll-up sign with the centerline of the vehicle aligned with the centerline of the device, with the device oriented perpendicular to the path of the vehicle. Shortly after impact, the fabric sign panel and fiberglass stays wrapped around the hood of the vehicle. As the vehicle proceeded to ride over the sign stand, the connection bolt through the sign bracket and vertical fiberglass stay kept the fiberglass stays from releasing. The stays pulled out of the fabric roll-up sign substrate, and the plastic pocket at the top corner of the roll-up sign struck the bottom of the windshield. The prolonged contact with the stays caused the stand to rotate as the vehicle was passing over it. As the sign stand rotated, one of the legs of the stand punctured the gas tank of the vehicle. The sign stand rode under the vehicle for a time and came to rest 35 ft downstream of impact. The fabric sign panel remained draped across the hood of the vehicle as the vehicle approached and impacted the second portable roll-up sign support system.

The 2008 Kia Rio, traveling at an impact speed of 61.1 mi/h, contacted the second portable roll-up sign with the centerline of the vehicle aligned with the centerline of the device, with the device oriented parallel to the path of the vehicle. The fabric roll-up sign from the first sign system contacted the bottom edge of the fabric roll-up sign of the second sign support system just before impact. Immediately thereafter, the second fabric sign wrapped around the bumper and hood of the vehicle. Upon review of high-speed film, researchers concluded that the first fabric roll-up sign did not interfere with or influence the behavior or trajectory of the send sign system. As the vehicle progressed over the sign stand, the stays remained attached to the stand and were pulled out of the fabric roll-up sign. The plastic corner pocket at the top corner of the sign panel released from the fabric sign and struck the middle of the windshield. There was not direct contact between the fabric sign panel and the windshield of the vehicle.

Brakes were applied, and the vehicle came to a stop at 238 ft downstream of impact of the initial impact point with the first portable sign support system.


**Figure 5.16. Vehicle/Installation Geometrics for Test No. 466393-3.**


**Figure 5.17. Vehicle before Test No. 466393-3.**

### 5.3.5 Damage to Test Installation

Figures 5.18 and 5.19 show damage to the work zone traffic control device. The fabric sign panels separated from each of the lower bases. The plastic corner pocket at the top corner of the sign panel released from the fabric sign and struck the middle of the windshield. The fabric sign panels then rode up and over the vehicle. The base of the first work zone traffic control device came to rest 35 ft downstream of impact, and the second base came to rest 75 ft downstream of impact.

### 5.3.6 Vehicle Damage

Figure 5.20 shows damage to the 1100C vehicle. The hood sustained scuff marks. No measureable deformation was noted to the exterior hood or bumper. Contact with the top corner of the first fabric roll-up sign panel caused the windshield to shatter over an area measuring 3 inches × 3.5 inches. This area was deformed toward the occupant compartment 0.75 inches, but there was no penetration or tear of the plastic liner. Contact of the plastic corner pocket from the second roll-up sign caused cracking of the windshield in two other small areas measuring 2.5-inch × 2-inch and 1.5-inch × 1-inch. There was no deformation of these areas into the occupant compartment. The gas tank had a puncture measuring 1.85 inches × 0.26 inch. Figure 5.21 shows the damage to the gas tank. Table D8 and D9 in Appendix D provides exterior crush and occupant compartment measurements.

### 5.3.7 Occupant Risk Factors

Previous full-scale crash tests have shown that the acceleration levels experienced by the vehicle during impact with lightweight, free-standing work zone traffic control devices weighing less than 220 lb were not significant. Consequently, MASH does not require instrumentation of the vehicle, and the occupant risk factors were not calculated for this test. Figure 5.22 summarizes pertinent information from the test.

### 5.3.8 Assessment of Test Results – Sign Perpendicular to Path of Vehicle (First Impact)

An assessment of the test based on the applicable *MASH* safety evaluation criteria is provided below.

*5.3.8.1 Structural Adequacy*

> *B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.*
>
> Results: The portable roll-up sign yielded to the vehicle. (PASS)

**Figure 5.18. After Impact Locations for Test No. 466393-3.**


**Figure 5.19. Installation after Test No. 466393-3.**

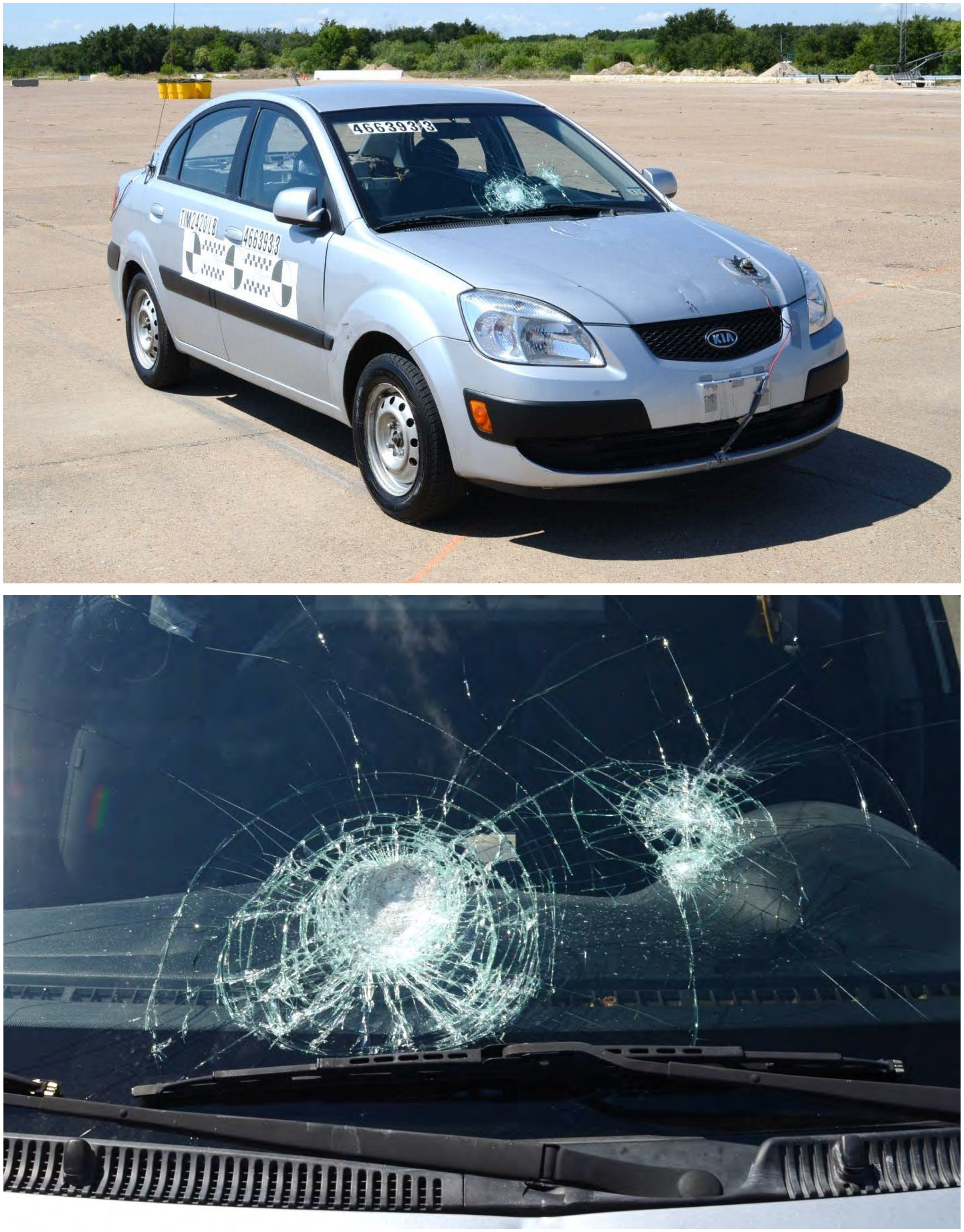



**Figure 5.20. Vehicle after Test No. 466393-3.**

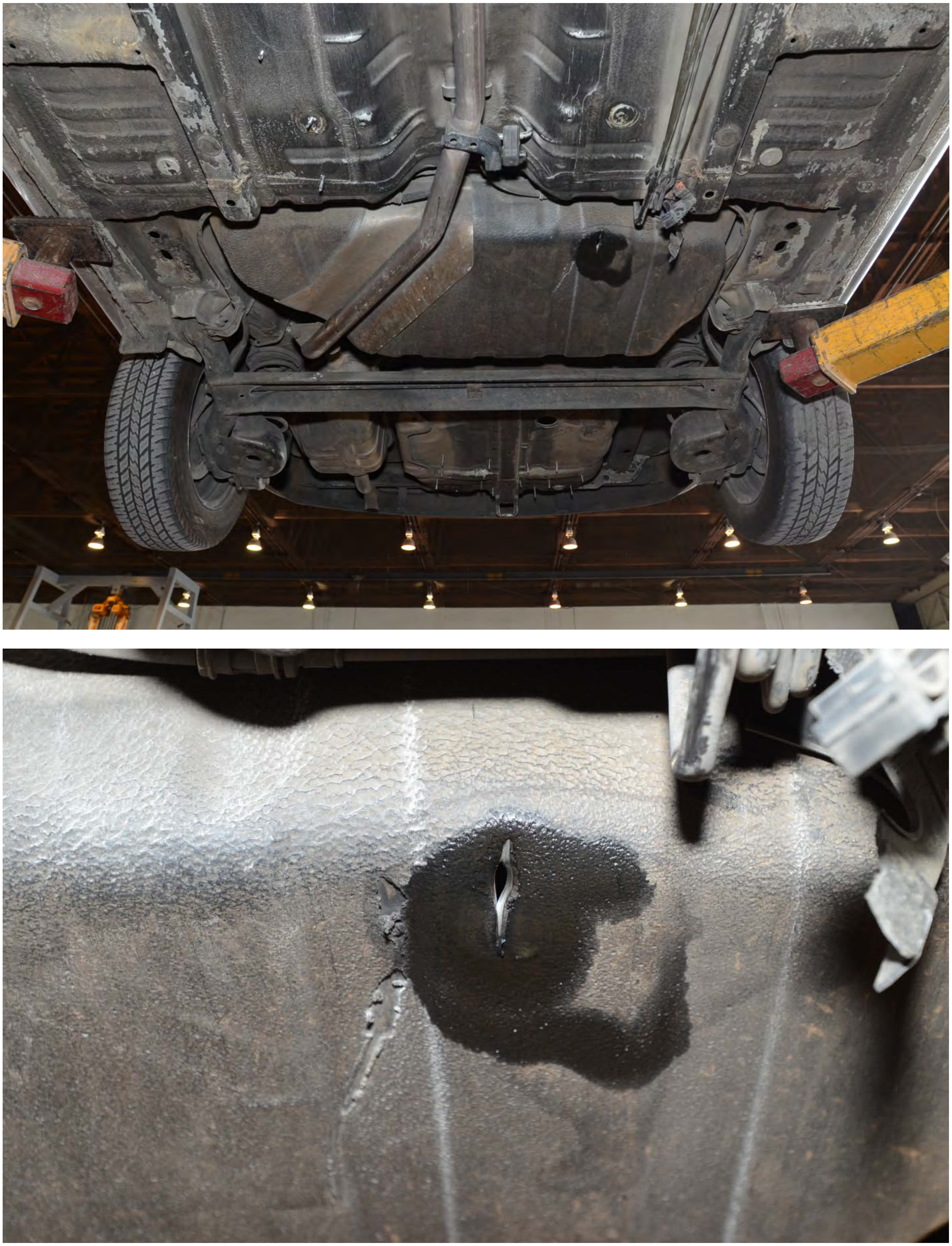
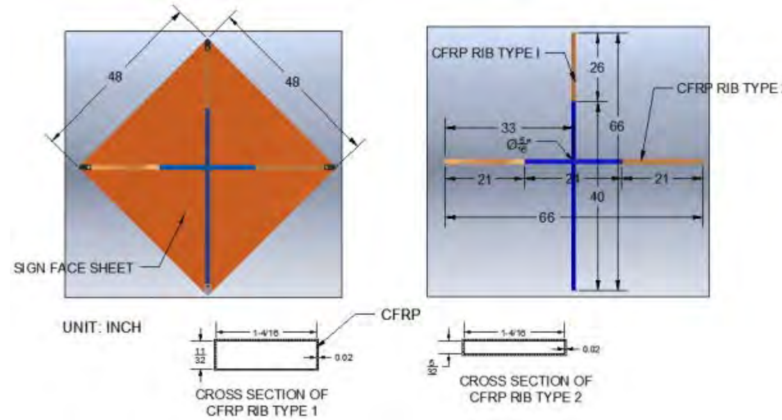


**Figure 5.21. Vehicle Gas Tank after Test No. 466393-3.**






**General Information**
- Test Agency .......................... Texas Transportation Institute (TTI)
- Test Standard Test No. ......... MASH Test 3-71
- TTI Test No. ......................... 466393-3
- Test Date ............................. 2013-08-23

**Test Article**
- Type..................................... Work Zone Traffic Control Device
- Name ................................... Modified Portable Roll-Up Sign with sandbags
- Installation Height.................. 1-ft mounting height
- Material or Key Elements ...... Fabric sign substrate with carbon wrapped fiberglass stays bolted to metal base ballasted with four 40-lb sandbags

**Soil Type and Condition**......... Placed on concrete surface, dry

**Test Vehicle**
- Type/Designation ........1100C
- Make and Model.........2008 Kia Rio
- Curb ...........................2427 lb
- Test Inertial ................2442 lb
- Dummy........................ 175 lb
- Gross Static................2617 lb

**Impact Conditions**
- Speed (first sign) .........62.6 mi/h
- Speed (second sign)....61.6 mi/h
- Angle..........................0 degrees
- Location/Orientation ....90 degrees to traffic

**Exit Conditions**
- Speed..........................
- Angle..........................2 degrees

**Post-Impact Trajectory**
- Stopping Distance .................... 238 ft downstream

**Test Article Deflections**
- Fabric Sign & Upper Supports .. 75 ft downstream
- Lower Support/Base ................ 35 ft downstream

**Vehicle Damage**
- VDS......................................... 12FC1
- CDC ........................................ 12FCGN6
- Max. Exterior Deformation ........ 0.75 inches (windshield)
- OCDI ....................................... FS0000000
- Max. Occupant Compartment Deformation........................ 0.75 inches (windshield)
- Windshield Damage ................. Shattered 0.75 inch inward
- Damage to Gas Tank ............... Punctured 1.8x0.26 inches

**Figure 5.22. Summary of Results for *MASH* Test 3-71 on the Modified Portable Roll-Up Sign with Sandbags.**

*5.3.8.2 Occupant Risk*

*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH. (roof ≤4.0 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 inches; forward of A-pillar ≤12.0 inches; front side door area above seat ≤9.0 inches; front side door below seat ≤12.0 inches; floor pan/transmission tunnel area ≤12.0 inches).*

Results: The fiberglass stays pulled out of the fabric roll-up sign panel and the top corner of the fabric sign and its plastic pocket contacted the windshield. The windshield was depressed toward the occupant compartment 0.75 inches and there was no penetration of the plastic liner. (PASS)

*E. Detached element, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.*

Results: The detached fabric sign panel did not block the driver's vision nor affect the driver's ability to control the vehicle. (PASS)

*F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*

Results: The 1100C vehicle remained upright during and after the collision event. (PASS)

*J. Occupant impact velocities should satisfy the following:*

*Longitudinal and Lateral Occupant Impact Velocity*

| *Preferred* | *Maximum* |
|---|---|
| *10 ft/s* | *16.4 ft/s* |

Results: The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. (N/A)

*I. Occupant ridedown accelerations should satisfy the following:*

*Longitudinal and Lateral Occupant Ridedown Accelerations*

| *Preferred* | *Maximum* |
|---|---|
| *15.0 Gs* | *20.49 Gs* |

Results: The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. (N/A)

*5.3.8.3 Vehicle Trajectory*

*N. Vehicle trajectory behind the test article is acceptable.*

Result: The 1100C vehicle came to rest 238 ft downstream of the impact point with the first portable roll-up sign.

### 5.3.9 Assessment of Test Results – Sign Parallel to Path of Vehicle (Second Impact)

An assessment of the test based on the applicable *MASH* safety evaluation criteria is provided below.

*5.3.9.1 Structural Adequacy*

*B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.*

Results: The portable roll-up sign yielded to the vehicle. (PASS)

*5.3.9.2 Occupant Risk*

*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH. (roof ≤4.0 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 inches; forward of A-pillar ≤12.0 inches; front side door area above seat ≤9.0 inches; front side door below seat ≤12.0 inches; floor pan/transmission tunnel area ≤12.0 inches).*

Results: The sign panel never contacted the windshield. The plastic pocket at the top corner of the sign panel released and contacted the windshield causing some cracking over a small area. There was no deformation of the windshield toward the occupant compartment and no penetration of the plastic liner. (PASS)

*E. Detached element, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.*

Results: The detached fabric sign panel did not block the driver's vision nor affect the driver's ability to control the vehicle. (PASS)

*F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*

Results: The 1100C vehicle remained upright during and after the collision event. (PASS)

*K. Occupant impact velocities should satisfy the following:*

*Longitudinal and Lateral Occupant Impact Velocity*

| *Preferred* | *Maximum* |
|---|---|
| *10 ft/s* | *16.4 ft/s* |

Results: The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. (N/A)

*I. Occupant ridedown accelerations should satisfy the following:*

*Longitudinal and Lateral Occupant Ridedown Accelerations*

| *Preferred* | *Maximum* |
|---|---|
| *15.0 Gs* | *20.49 Gs* |

Results: The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. (N/A)

*5.3.9.3 Vehicle Trajectory*

*N. Vehicle trajectory behind the test article is acceptable.*

Result: The 1100C vehicle came to rest 238 ft downstream of the impact point with the first portable roll-up sign.

# CHAPTER 6. SUMMARY AND CONCLUSIONS

Current portable roll-up signs have experienced field problems when subjected to high winds. In windy conditions typical of the Texas coast and panhandle, the rollup sign panels lay back to a point that they become illegible. In more extreme conditions, the support can blow over or the fiberglass stays can break. Under project 0-6399, research was performed by Texas Tech University to identify alternative materials to support flexible, roll-up sign substrates that will improve their performance in windy conditions.

The new design incorporates carbon fiber wraps around selected portions of the fiberglass support stays to increase their torsional stiffness without appreciably changing their bending stiffness. A prototype portable sign support system was submitted to TTI for full-scale crash testing and evaluation in accordance with *MASH* guidelines.

## 6.1 INITIAL PORTABLE ROLL-UP SIGN STAND SYSTEM

The portable roll-up sign yielded was initially tested with sand bags placed on each of the four legs of the sign stand as ballast. This is how these devices are typically deployed in areas such as the Texas panhandle that are subject to high winds. The test involved a small passenger car impacting the portable sign support head-on with the sign oriented perpendicular to the path of the impacting vehicle. The roll-up sign pulled out of the sign stand and contacted the windshield of the vehicle. The top corner of the sign panel penetrated the windshield, causing the system to fail Evaluation Criterion D of *MASH*. A summary of the test results in presented in Table 6.1.

After failure of the initial crash test, the same system was retested without sand bags to determine if the presence of sand bags affects the interaction of the portable roll-up sign system with the vehicle. Many portable sign systems have been tested without additional ballast. Testing without ballast might permit the sign stand to be accelerated more quickly and, thereby, delay release of the sign panel from the sign stand. The test involved a small passenger car impacting the portable sign support head-on with the sign oriented perpendicular to the path of the impacting vehicle. The behavior of the sign support system was very similar to that observed in the test with sand bags. The roll-up sign pulled out of the sign stand and contacted the windshield of the vehicle. The top corner of the sign panel penetrated the windshield, causing the system to fail Evaluation Criterion D of *MASH*. A summary of the test results in presented in Table 6.2.

## 6.2 MODIFIED PORTABLE ROLL-UP SIGN STAND SYSTEM

After failure of the initial design, the portable roll-up sign system was modified. A 3/8-inch diameter bolt was inserted through the sign stand bracket and vertical fiberglass stay. The purpose of the modification was to delay or prevent release of the sign panel from the sign stand and, thereby, reduce or eliminate interaction of the sign panel with the windshield.

In this test, two separate modified portable roll-up sign systems were impacted. The first sign was oriented perpendicular to the path of the vehicle and the second was placed 30 ft downstream and oriented parallel to the path of the vehicle. The test involved a small passenger car impacting the signs sequentially. As the vehicle proceeded to ride over the sign stand, the connection bolt through the sign bracket and vertical fiberglass stay kept the fiberglass stays from releasing. The stays pulled out of the fabric roll-up sign substrate, and the plastic pocket at the top corner of the roll-up sign struck the bottom of the windshield. The windshield was shattered and deformed inward toward the occupant compartment 0.75 inches. However, there was no penetration of the plastic liner, and the modified portable roll-up sign support orientated perpendicular to the path of the vehicle satisfied *MASH* evaluation criteria as summarized in Table 6.3.

It should be noted that the added connection bolt resulted in prolonged contact of the vehicle with the vertical fiberglass stay. As the sign stand rotated as a result of this interaction, one of the legs of the stand punctured a hole in the gas tank of the vehicle. MASH states:

> "Although not a specific factor in assessing test results, integrity of the test vehicle's fuel tank is a potential concern. It is preferable that the fuel tank remains intact and not be punctured. Damage to, or rupture of, the fuel tank, oil pan, or other features that might serve as a surrogate of a fuel tank should be reported."

The fabric roll-up sign from the first sign system was carried along on the hood of the vehicle and it contacted the bottom edge of the fabric roll-up sign of the second sign support system just before impact. However, upon review of high-speed film, researchers concluded that the first fabric roll-up sign did not interfere with or influence the behavior or trajectory of the second sign system. As the vehicle progressed over the sign stand, the stays remained attached to the stand and were pulled out of the fabric roll-up sign. The plastic corner pocket at the top corner of the sign panel released from the fabric sign and struck the middle of the windshield. Although there was some cracking, there was no deformation of the windshield toward the occupant compartment and no penetration of the plastic liner. As summarized in Table 6.4, the modified portable roll-up sign support orientated parallel to the path of the vehicle satisfied *MASH* evaluation criteria.

**Table 6.1. Performance Evaluation Summary for *MASH* Test 3-71 on the Portable Roll-Up Sign with Sandbags.**

Test Agency: Texas Transportation Institute | Test No.: 466393-1 | Test Date: 2013-07-22

| ***MASH* Test 3-71 Evaluation Criteria** | **Test Results** | **Assessment** |
|---|---|---|
| <u>Structural Adequacy</u><br>*B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.* | The portable roll-up sign yielded to the vehicle by breaking away from the base. | Pass |
| <u>Occupant Risk</u><br>*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.* | The detached fabric sign panel and attached stays rotated into and penetrated the windshield into the occupant compartment. | Fail |
| *E. Detached elements, fragments, or other debris from the test article, of vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.* | The detached fabric sign panel momentarily blocked the driver's vision, but for less than 0.1 seconds. This short time frame would not affect the driver's ability to control the vehicle. | Pass |
| *F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.* | The 1100C vehicle remained upright during and after the collision event. | Pass |
| *H. Longitudinal and lateral occupant impact velocities should fall below the preferred value of 10 ft/s, or at least below the maximum allowable value of 16.4 ft/s.* | The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. | N/A |
| *I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15.0 Gs, or at least below the maximum allowable value of 20.49 Gs.* | | N/A |
| <u>Vehicle Trajectory</u><br>*N. Vehicle trajectory behind the test article is acceptable.* | The 1100C vehicle came to rest 262 ft downstream of the impact position of the portable roll-up sign. | Pass |

**Table 6.2. Performance Evaluation Summary for *MASH* Test 3-71 on the Portable Roll-Up Sign without Sandbags.**

Test Agency: Texas Transportation Institute | Test No.: 466393-2 | Test Date: 2013-07-22

| ***MASH* Test 3-71 Evaluation Criteria** | **Test Results** | **Assessment** |
|---|---|---|
| Structural Adequacy<br>*B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.* | The portable roll-up sign yielded to the vehicle by breaking away from the base. | Pass |
| Occupant Risk<br>*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.* | The detached fabric sign panel and attached stays rotated into and penetrated the windshield into the occupant compartment. | Fail |
| *E. Detached elements, fragments, or other debris from the test article, of vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.* | The detached fabric sign panel momentarily blocked the driver's vision, but for less than 0.1 seconds. This short time frame would not affect the driver's ability to control the vehicle. | Pass |
| *F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.* | The 1100C vehicle remained upright during and after the collision event. | Pass |
| *H. Longitudinal and lateral occupant impact velocities should fall below the preferred value of 10 ft/s, or at least below the maximum allowable value of 16.4 ft/s.* | The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. | N/A |
| *I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15.0 Gs, or at least below the maximum allowable value of 20.49 Gs.* | | N/A |
| Vehicle Trajectory<br>*N. Vehicle trajectory behind the test article is acceptable.* | The 1100C vehicle came to rest 210 ft downstream of the impact position of the portable roll-up sign. | Pass |

**Table 6.3. Performance Evaluation Summary for *MASH* Test 3-71 on Modified Portable Roll-Up Sign with Sandbags – Sign Perpendicular to Path of Vehicle (First Impact).**

Test Agency: Texas Transportation Institute | Test No.: 466393-3 | Test Date: 2013-08-23

| ***MASH* Test 3-71 Evaluation Criteria** | **Test Results** | **Assessment** |
|---|---|---|
| <u>Structural Adequacy</u><br>*B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.* | The portable roll-up sign yielded to the vehicle. | Pass |
| <u>Occupant Risk</u><br>*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.* | The fiberglass stays pulled out of the fabric roll-up sign panel and the top corner of the fabric sign and its plastic pocket contacted the windshield. | Pass |
| *Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.* | The windshield was depressed toward the occupant compartment 0.75 inches and there was no penetration of the plastic liner. | Pass |
| *E. Detached elements, fragments, or other debris from the test article, of vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.* | The detached fabric sign panel did not block the driver's vision nor affect the driver's ability to control the vehicle. | Pass |
| *F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.* | The 1100C vehicle remained upright during and after the collision event. | Pass |
| *H. Longitudinal and lateral occupant impact velocities should fall below the preferred value of 10 ft/s, or at least below the maximum allowable value of 16.4 ft/s.* | The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. | Pass |
| *I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15.0 Gs, or at least below the maximum allowable value of 20.49 Gs.* | | Pass |
| <u>Vehicle Trajectory</u><br>*N. Vehicle trajectory behind the test article is acceptable.* | The 1100C vehicle came to rest 238 ft downstream of the impact position of the portable roll-up sign. | Pass |

## Table 6.4. Performance Evaluation Summary for *MASH* Test 3-71 on Modified Portable Roll-Up Sign with Sandbags – Sign Parallel to Path of Vehicle (Second Impact).

Test Agency: Texas Transportation Institute — Test No.: 466393-3 — Test Date: 2013-08-23

| ***MASH* Test 3-71 Evaluation Criteria** | **Test Results** | **Assessment** |
|---|---|---|
| Structural Adequacy | | |
| *B. The test article should readily activate in a predictable manner by breaking away, fracturing, or yielding.* | The portable roll-up sign yielded to the vehicle. | Pass |
| Occupant Risk | | |
| *D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.* | The plastic pocket at the top corner of the sign panel released and contacted the windshield causing some cracking over a small area. | Pass |
| *Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.* | There was no deformation of the windshield toward the occupant compartment and no penetration of the plastic liner. | Pass |
| *E. Detached elements, fragments, or other debris from the test article, of vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle.* | The detached fabric sign panel did not block the driver's vision nor affect the driver's ability to control the vehicle. | Pass |
| *F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.* | The 1100C vehicle remained upright during and after the collision event. | Pass |
| *H. Longitudinal and lateral occupant impact velocities should fall below the preferred value of 10 ft/s, or at least below the maximum allowable value of 16.4 ft/s.* | The test vehicle was not instrumented based on the total weight of the test article being less than 220 lb. | Pass |
| *I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15.0 Gs, or at least below the maximum allowable value of 20.49 Gs.* | | Pass |
| Vehicle Trajectory | | |
| *N. Vehicle trajectory behind the test article is acceptable.* | The 1100C vehicle came to rest 238 ft downstream of the impact position of the portable roll-up sign. | Pass |

# CHAPTER 7. IMPLEMENTATION STATEMENT

Portable roll-up signs are routinely used by TxDOT for short-term, daytime maintenance/construction activities and emergency operations. These flexible fabric signs are supported by fiberglass frames attached to a multi-leg base. In windy conditions typical of the Texas coast and panhandle, the rollup sign panels can lay back to a point that they become illegible. In more extreme conditions, the support can blow over or the fiberglass stays can break.

There is a direct cost associated with having to reset signs that blow down and replace those that fail. Additionally, these activities increase exposure for the maintenance personnel performing the work, and temporary loss of a sign and the information it is intended to convey could potentially pose a safety concern for both work zone personnel and the motoring public.

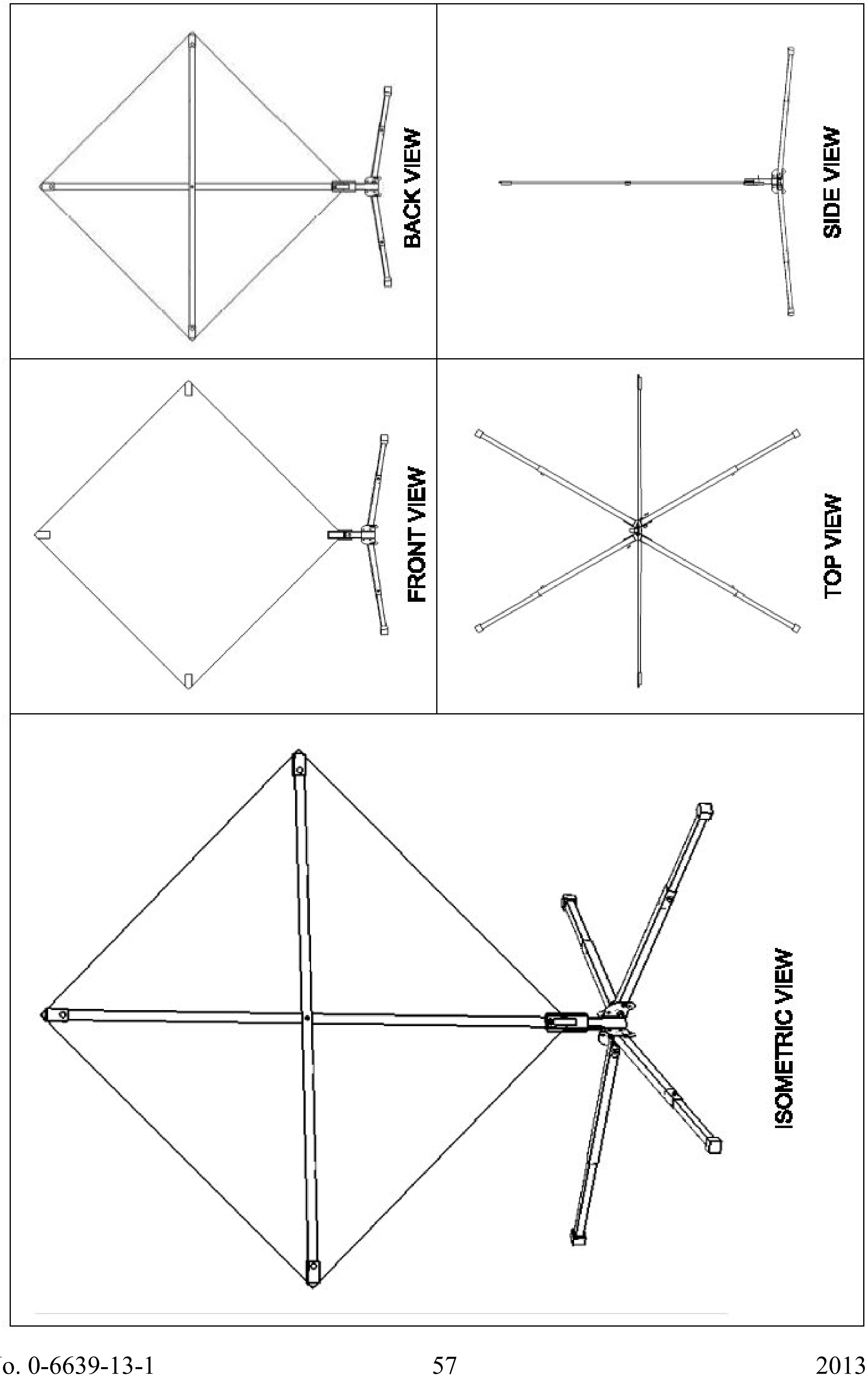
Under research project 0-6399, design modifications were developed to improve the performance of the sign support in windy conditions and reduce wind-induced failures. The crashworthiness of the modified portable roll-up sign support system was evaluated through a series of full-scale crash tests.

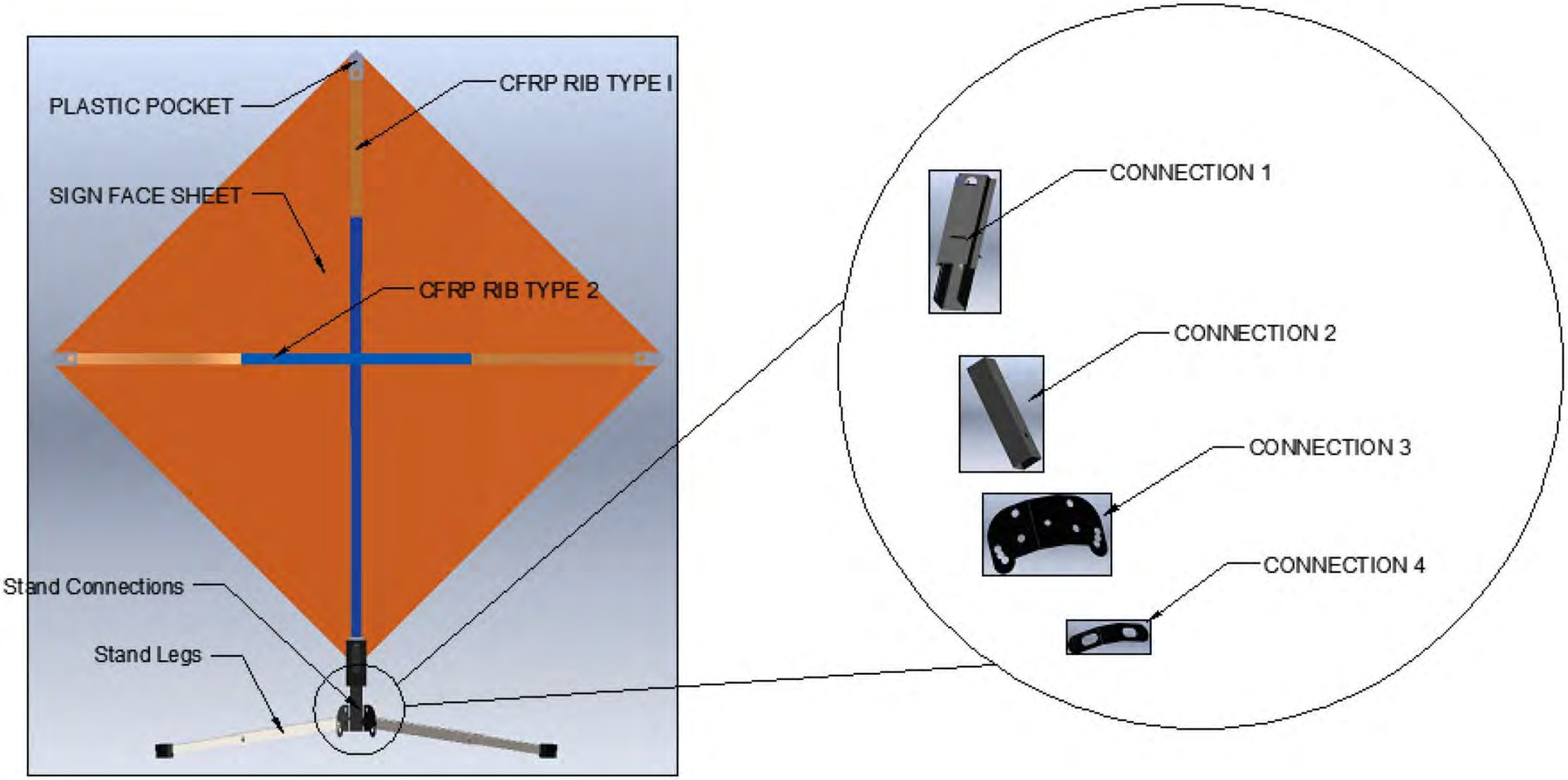
When a 3/8-inch diameter bolt was used to retain the vertical fiberglass stay and prevent it from separating from the sign stand, the modified design satisfied *MASH* evaluation criteria. Therefore, the portable sign support system with carbon wrapped fiberglass stays and a retaining bolt as tested and described herein, is considered suitable for implementation and further field evaluation. It should be noted that the use of the retaining bolt caused rotation of the sign stand during impact and resulted in one of the legs of the sign stand puncturing a hole in the gas tank of the impacting vehicle. Although this is not a specific factor in assessing test results, *MASH* states that it is preferable that the fuel tank remains intact and not be punctured. Any field implementation of this design should be done with knowledge and consideration of this behavior.

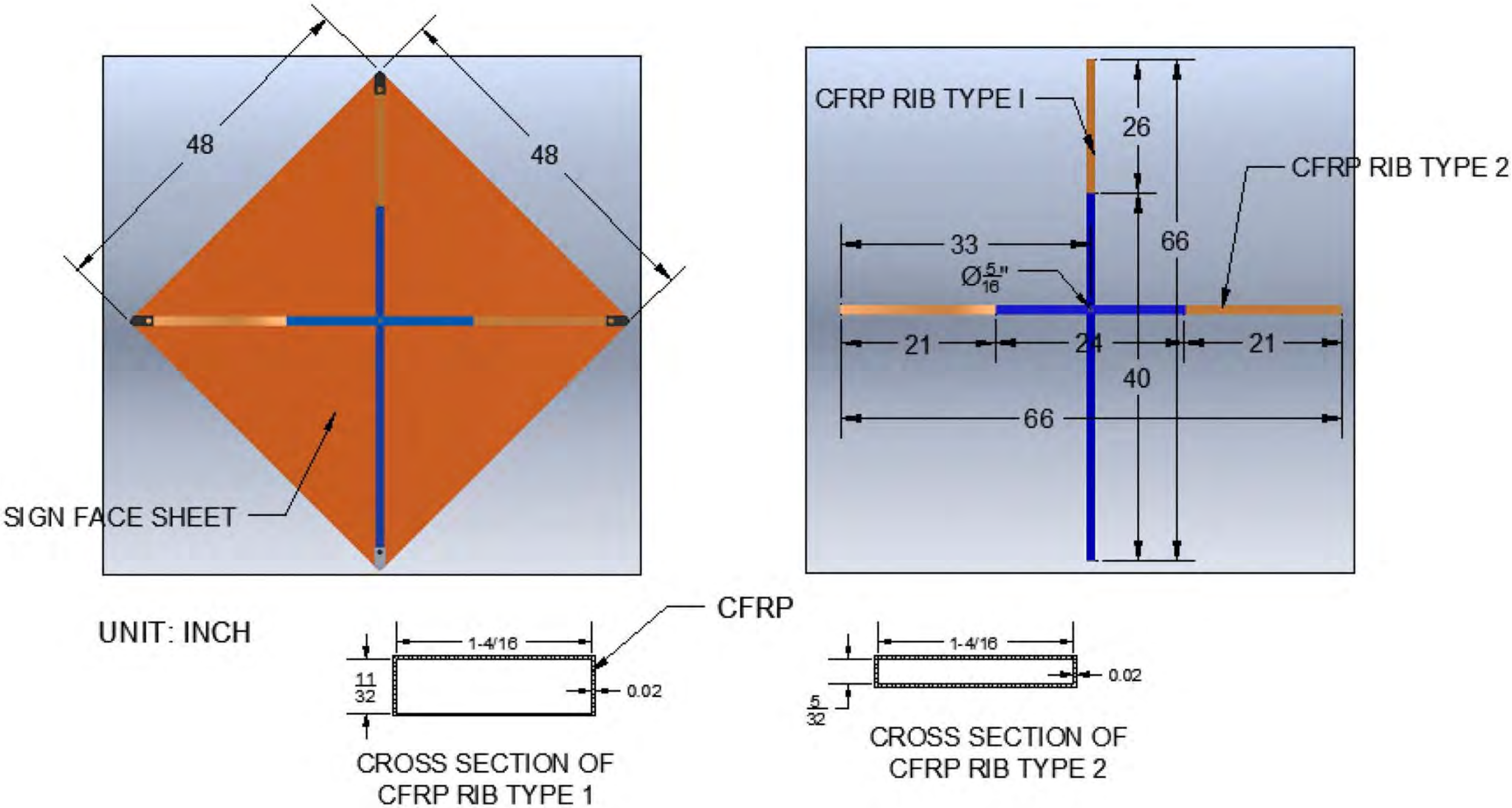
# REFERENCES

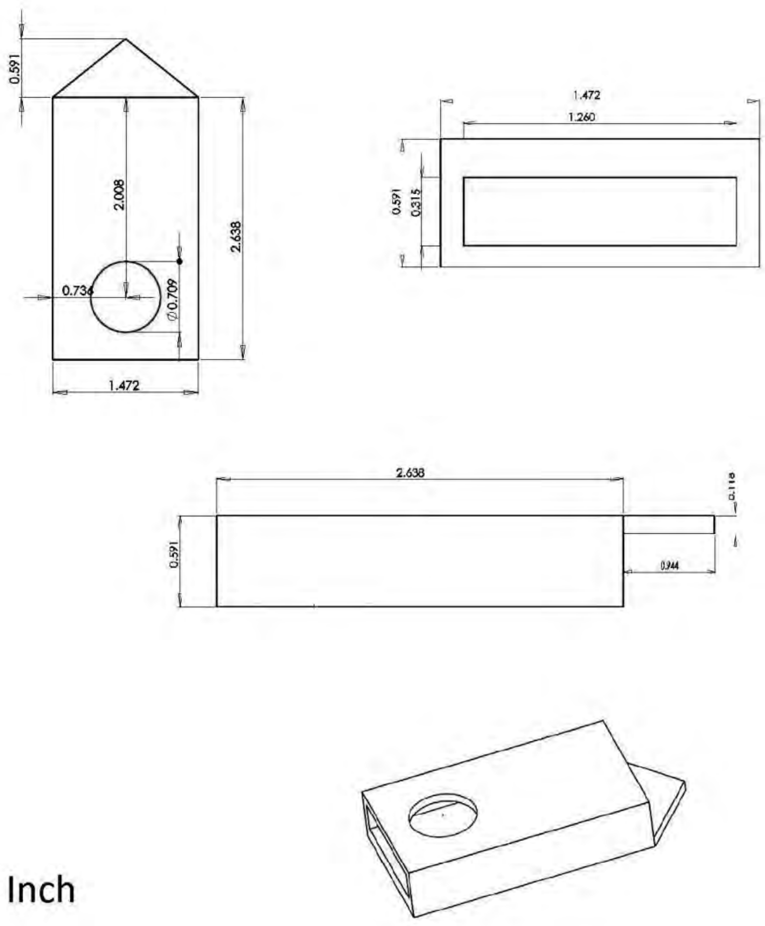

1. AASHTO, *Manual for Assessing Safety Hardware*, American Association of State Highway and Transportation Officials, Washington, D.C., 2009.

# APPENDIX A. DETAILS OF THE PORTABLE ROLL-UP SIGN



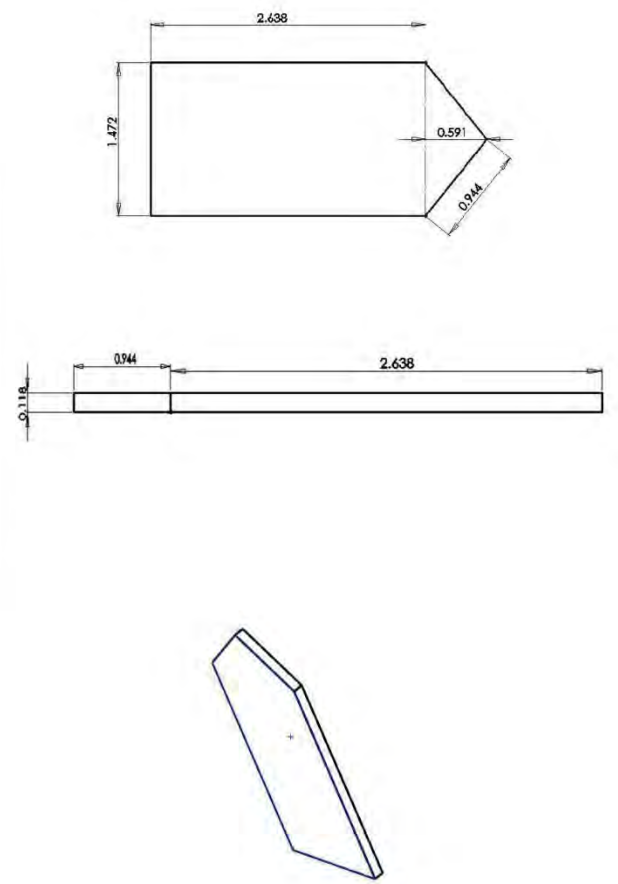

PLASTIC POCKET
CFRP RIB TYPE I
SIGN FACE SHEET
CFRP RIB TYPE 2
Stand Connections
Stand Legs
CONNECTION 1
CONNECTION 2
CONNECTION 3
CONNECTION 4


48
48
SIGN FACE SHEET
CFRP RIB TYPE I
26
CFRP RIB TYPE 2
33
66
Ø5/16"
21
24
21
40
66
UNIT: INCH
CFRP
1-4/16
11/32
0.02
CROSS SECTION OF CFRP RIB TYPE 1
1-4/16
0.02
5/32
CROSS SECTION OF CFRP RIB TYPE 2



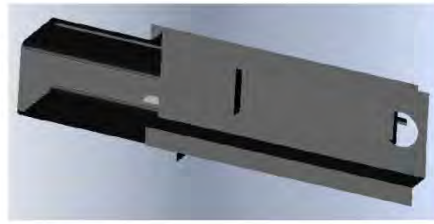

Unit: Inch

Plastic Pocket-Part 1

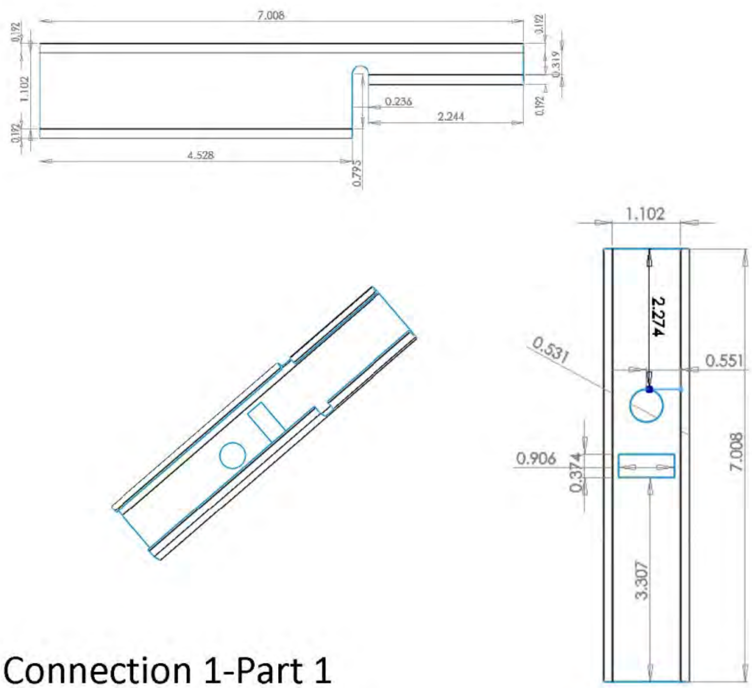



Plastic Pocket-Part 2

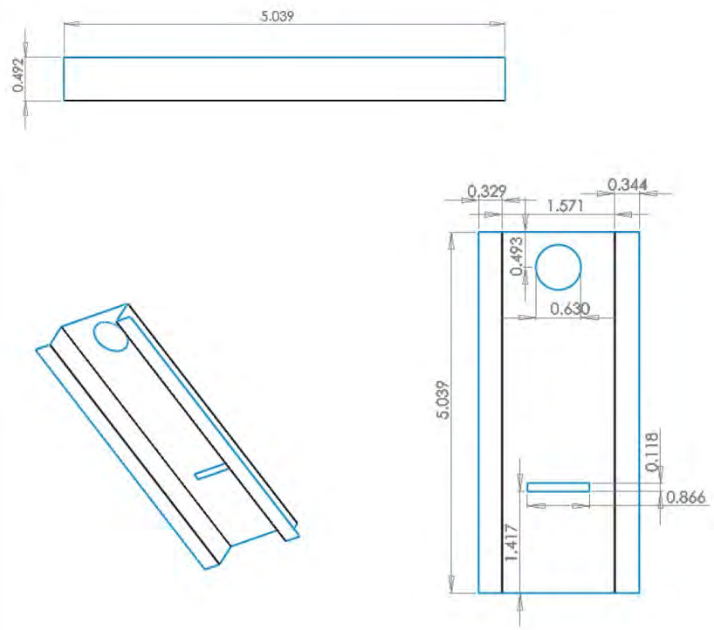
Connection 1



Unit: Inch

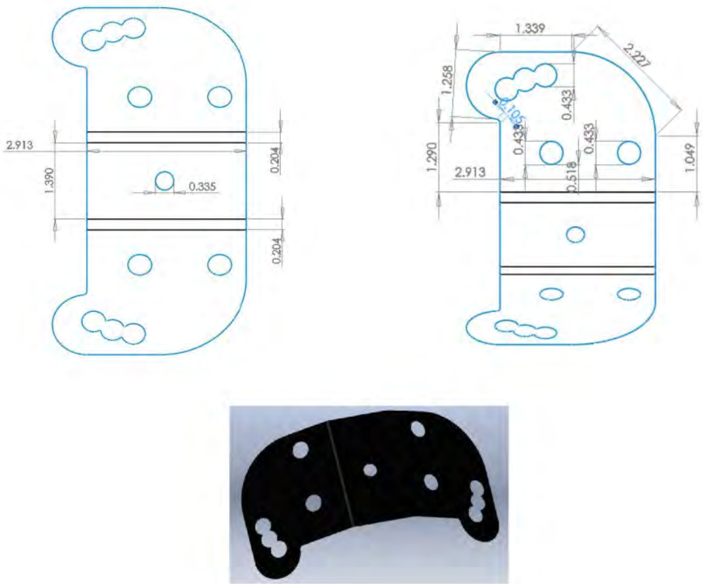



Connection 1-Part 1

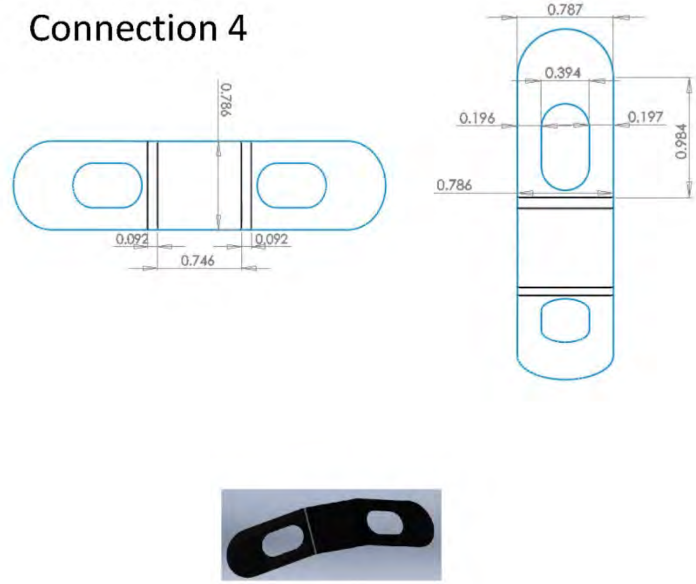



Connection 1-Part 2

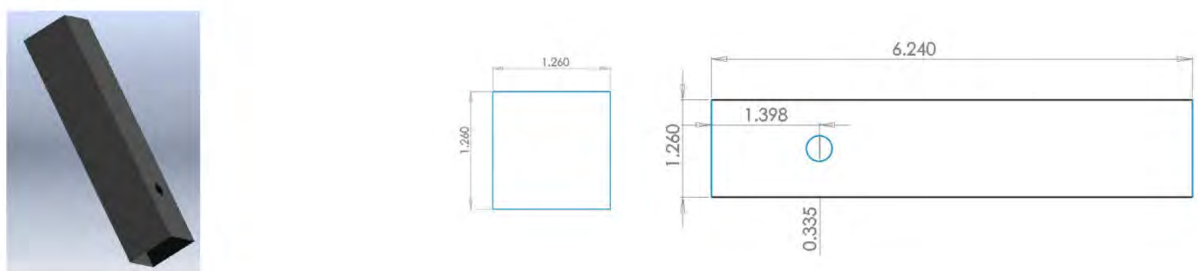
## Connection 3



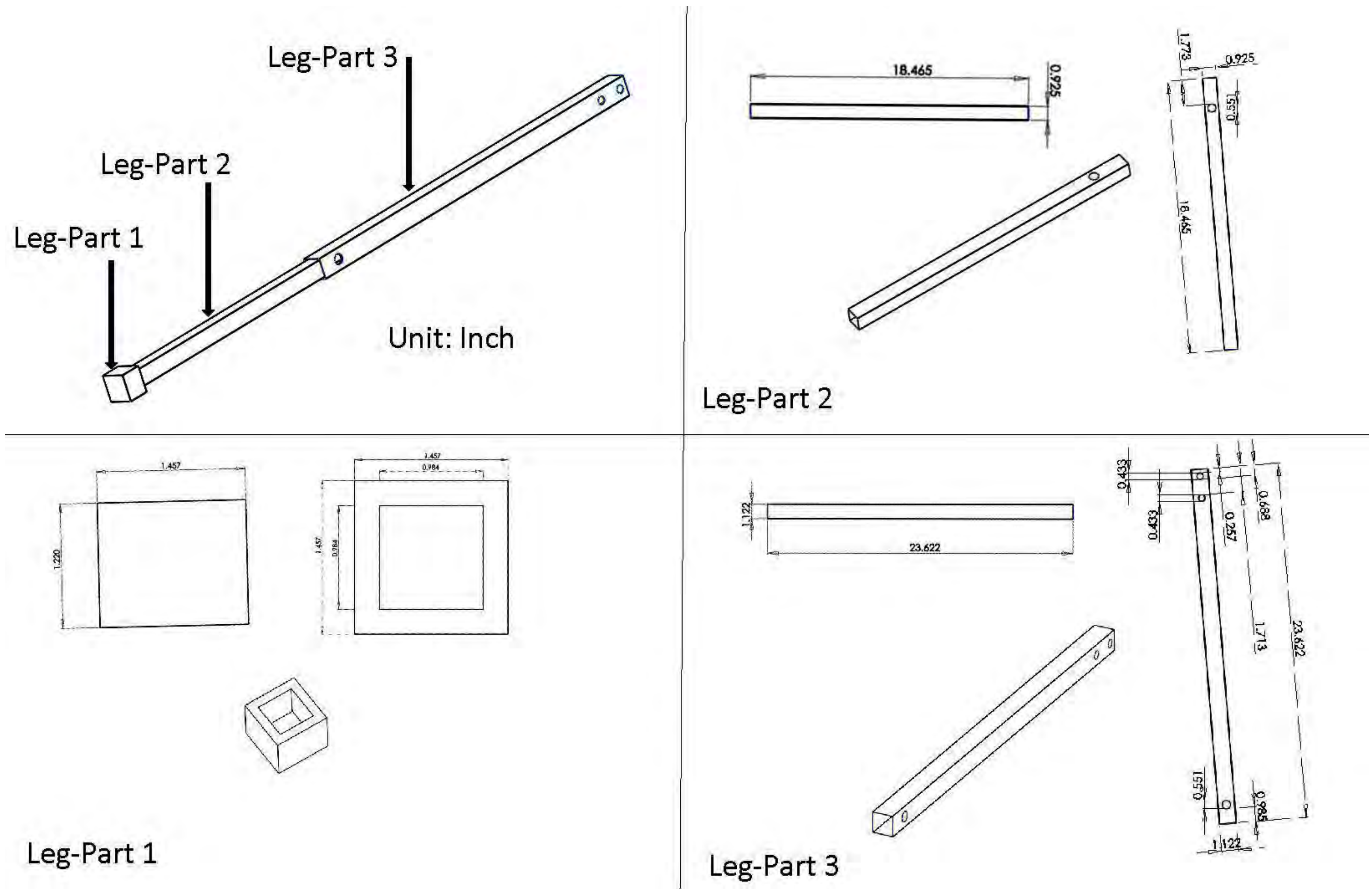

## Connection 4




## Connection 2




Unit: Inch



Leg-Part 3
Leg-Part 2
Leg-Part 1
Unit: Inch
18.465
0.925
1.773
0.925
0.551
18.465
Leg-Part 2
1.457
1.220
1.457
0.984
1.457
0.984
Leg-Part 1
1.122
23.622
0.433
0.433
0.688
0.257
1.713
23.622
0.551
0.985
1.122
Leg-Part 3

# APPENDIX B. MATERIAL SPECIFICATIONS FOR SIGN SHEETING

3M

## Diamond Grade™ Roll Up Sign Sheeting

Series RS20/RS24

**Product Bulletin RS20/RS24** **December 2007**

Replaces PB RS24 dated July 1998

### Description

3M™ Diamond Grade™ Roll Up Sign Sheeting Series RS20/RS24 is a visible light-activated fluorescent wide angle prismatic lens reflective sheeting designed for the production of roll up traffic control signs used in construction work zones. This sign sheeting is designed to provide higher nighttime sign brightness than sheetings that use glass bead lenses. RS24 sheeting has higher daytime brightness than ordinary (non-fluorescent) colored sheeting.

Series RS20/RS24 sheeting is backed with a strong, flexible, gray-coated fabric.

| Color | Product Code |
|---|---|
| White | RS20 |
| Fluorescent Orange | RS24 |

### Photometrics

**Daytime Color (x,y,Y)**

The chromaticity coordinates and total luminance factor of the retroreflective sheeting conform to Table A.

**Color Test – Fluorescent Sheetings**

Conformance to standard chromaticity (x, y) and luminance factor (Y %) requirements shall be determined by instrumental method in accordance with ASTM E 991 on sheeting applied to smooth aluminum test panels cut from Alloy 6061-T6 or 5052-H38. The values shall be determined on a HunterLab ColorFlex 45/0 spectrophotometer. Computations shall be done for CIE Illuminant D65 and the 2° standard observer.[2]

**Color Test – Ordinary Colored Sheeting**

Conformance to standard chromaticity (x,y) and luminance factor (Y %) requirements shall be determined by instrumental method in accordance with ASTM E 1164 on sheeting applied to smooth aluminum test panels cut from Alloy 6061-T6 or 5052-H38. The values shall be determined on a HunterLab ColorFlex 45/0 spectrophotometer. Computations shall be done for CIE Illuminant D65 and the 2° standard observer.[2]

**Table A - CIE Daytime Chromaticity Coordinate Limits[1] and Luminance Factor Minimum**

| Color | 1 | | 2 | | 3 | | 4 | | Luminance Factor Y (%) |
|---|---|---|---|---|---|---|---|---|---|
| | x | y | x | y | x | y | x | y | Min. |
| White | .303 | .300 | .368 | .366 | .340 | .393 | .274 | .329 | 40 |
| Fluorescent Orange | .583 | .416 | .535 | .400 | .595 | .351 | .645 | .355 | 30 |

[1]The four pairs of chromaticity coordinates define the acceptable color limits for CIE D65 illumination in terms of the CIE 1931 Standard Colorimetric System.

[2]The instrumentally determined color values of retroreflective sheeting can vary significantly depending on the make and model of colorimetric spectrophotometer as well as the color and retroreflective optics of the sheeting (David M. Burns and Timothy J. Donahue, Measurement Issues in the Color Specification of Fluorescent Retroreflective Materials for High Visibility Traffic Signing and Personal Safety Applications, Proceedings of SPIE: Fourth Oxford Conference on Spectroscopy, 4826, pp. 39-49, 2003). For the purposes of this document, the HunterLab ColorFlex 45/0 spectrophotometer shall be the referee instrument.

**Coefficients of Retroreflection ($R_A$)**
The values in Table C are minimum coefficients of retroreflection expressed in candelas per lux per square meter (cd/lux/m²).

**Test for Coefficients of Retroreflection**
Conformance to coefficient of retroreflection requirements shall be determined by instrumental method in accordance with ASTM E-810 "Test Method for Coefficient of Retroreflection of Retroreflective Sheeting," and per E-810 the values of 0° and 90° rotation are averaged to determine the $R_A$ in Table C.

**Table C**
**Minimum Coefficient of Retroreflection**
**$R_A$ for New Sheeting**
**(cd/lux/m²)**

**White**

| Observation[1] Angle | Entrance Angle[2] | | |
|---|---|---|---|
| | -4° | 30° | 45° |
| 0.2° | 300 | 180 | 100 |
| 0.5° | 200 | 75 | 60 |
| 1.0° | 15 | 15 | 15 |

**Fluorescent Orange**

| Observation[1] Angle | Entrance Angle[2] | | |
|---|---|---|---|
| | -4° | 30° | 45° |
| 0.2° | 200 | 120 | 60 |
| 0.5° | 120 | 50 | 30 |
| 1.0° | 10 | 10 | 10 |

[1] Observation (Divergence) Angle - The angle between the illumination axis and the observation axis.

[2] Entrance (Incidence) Angle - The angle from the illumination axis to the retroreflector axis. The retroreflector axis is an axis perpendicular to the retroreflective surface.

## Orientation

3M™ Diamond Grade™ Roll Up Sign Sheeting Series RS20/RS24 is designed to be an effective wide angle reflective sheeting regardless of its orientation on the substrate or ultimate orientation after installation. However, because the efficiency of light return from cube corner reflectors is not equal at all rotation angles, it is possible to get the widest entrance angle light return when the sheeting is oriented in a particular way.

For purposes of test measurement of RS24 sheeting, it is important for the material to have a datum mark (the orientation arrow) so that the sample can be properly oriented in the test machinery. In those situations where extra wide entrance angle performance is required, this arrow can be used to assure the preferred orientation.

## Resistance to Accelerated Weathering

The retroreflective surface of the sheeting is weather resistant and shows no appreciable cracking, blistering, crazing, edge lifting or curling, or dimensional change of more than 1/32m (0.08cm) after one year's unprotected outdoor exposure in Florida, south facing and inclined 45° from the vertical, or after 1500 hours' exposure in xenon arc weatherometer in accordance with ASTM G26, Type B, Method A. Wash panels following exposure in a 5% HCL solution for 45 seconds, rinsed thoroughly with clean water, blotted with a soft clean cloth and brought to equilibrium at standard conditions. After cleaning, the coefficient of retroreflection is expected to be not less than 50% of Table C values when measured according to ASTM E-810. The color is expected to conform to the requirements of Table B. Where more than one panel is measured, the coefficient of retroreflection will be the average of all determinations.

## Interlocking Diamond Seal Pattern

Diamond Grade sheeting is differentiated from other prismatic or encapsulated lens sheeting by the distinctive seal pattern in the sheeting. Under normal light, this seal pattern will appear lighter in color than the reflective portion (see Figure 1).

## Orientation Marks (Arrows)

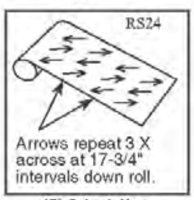
RS24 sheeting is made with small orientation (↖) arrows in the surface. These arrows point at a 45° angle. See Figure 2. The arrows assist in proper orientation of the sheeting for maximum angularity of signs (arrows point up and down). The arrows are the same color as the seal pattern and are repeated three times across a 48 inch roll and downweb at 17-3/4 inch intervals (see Figure 2). RS20 does not have orientation arrows.

## Tooling Lines

The manufacturing of a prismatic sheeting results in tooling lines being present in the product. In Diamond Grade RS20/RS24 sheeting these lines (slightly thicker than the seal pattern legs) occur across the web every 54 inches. Tooling lines are noticeable in shop light but are not observable on the road either in daylight or at night under typical use conditions (Figure 3).

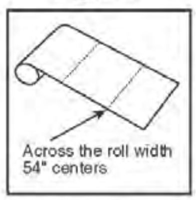

**Figure 1** - Sheeting is positioned at 90° rotation angle.

Figure 2




45° Orientation
Full Head Arrow

Figure 3




Tooling Lines

**Note: RS20 does not have orientation arrows.**

## Test Methods of Film Properties

### A. Conditioning

1. Shrinkage, flexibility and gloss measurements are performed on new test specimens which have been conditioned for 24 hours at 73°F ± 3°F (23°C ± 1°C) and 50% ± 5% relative humidity before testing. This condition is maintained during the test.

### B. Standard Test Panel and Application

Unless otherwise specified, apply the reflective sheeting according to the manufacturer's recommendations to smooth 0.040 inch (0.10 cm) minimum thickness 6061-T6 or equivalent aluminum panels that have been degreased and lightly etched. Lack of contamination of test panels must be confirmed by passing water break test and tape snap test as described in Information Folder 3.4.

## Properties

### 1. Impact Resistance

Test Method
Apply Scotch™ Double Coated Tape 665 to an etched aluminum panel of Alloy 6061-T6 0.04 inch x 3 inch x 5 inch. Apply RS20/RS24 to the taped surface grey side down and condition as in A1 above. Subject sheeting to 50 inch-pounds (5.7 Nm) impact in accordance with ASTM D-2794.

Requirement
No separation from panel or cracking outside the immediate impact area.

### 2. Shrinkage

Test Method
Following conditioning of 9 inch x 9 inch samples, place specimen on flat surface with gray side up.

Requirement
Shrinkage not greater than 1/32 inch (0.8 mm) in 10 minutes, or more than 1/8 inch (3.2 mm) in 24 hours in any dimension.

### 3. Flexibility

Test Method
Condition a 1 inch x 6 inch sample. At standard conditions, bend in one second around 1/8 inch (3.2 mm) mandrel with gray side facing mandrel.

Requirement
No cracking.

### 4. Gloss

Test Method
Test in accordance with ASTM D523 using an 85° glossmeter.

Requirement
Rating not less than 50

### 5. Tensile Strength

Test Method
Test in accordance with Federal Standard 191 Method 5100 except using a 2 inch jaw gap and a cross head speed of 6 inches/minute.

Requirement
Typical force values of:
- Warp Direction – 130 pounds force
- Fill Direction – 150 pounds force

**6. Tear Resistance**

Test Method

Test in accordance with ASTM D1044 except use a cross head of 12 inches/minute.

Requirement

Typical tear values of:

- Warp Direction – 50 pounds force
- Fill Direction – 60 pounds force

## Use

**A.** RS20/RS24 sheeting is designed for sewing or riveting corner pockets or snaps. Cross brace supports can then be used in conjunction with portable sign stands. Cross braces should not bow more than 1/2 inch when inserted. All corner pockets should be fabric, plastic or rubber. Plastic or rubber molded pockets should have rounded edges. Washers should be rubber or plastic. Metal washers should be backed with rubber or plastic washers.

**B. Process Colors**

Screening Method/Thinning/Conditioning for Processing

An off contact screen process method is the preferred screening method for 3M™ Diamond Grade™ Roll Up Sign Sheeting Series RS20/RS24. The screening table must be perfectly flat. When screening Diamond Grade roll up sheets, hold the sheets in place using a vacuum table or if a vacuum table is not available, sheets can be held in place on a non-porous table surface using a thin, uniform layer of low tack pressure sensitive adhesive. The screen mesh size should be in the (PE157 -PE 230) range of monofilament fabric. Stenciling the process colors or use of other screen fabric mesh sizes may not produce satisfactory color or durability and are not recommended.

3M™ Process Color Series 1805 (black) is the only recommended ink color for Diamond Grade roll up sheeting Series RS24. For thinning Series 1805, use only CGS 50 or CGS 80 thinner. Series 1805 colors must dry for 24 hours (on drying rack) before rolling up. See Product Bulletin 1800 or call 3M Technical Services at 1-800-553-1380 extension 4-1.

3M™ Process Color Series 990 is the only recommended ink for Diamond Grade Series RS20. Series 990 ink must be used with 4430R clear ink that protects the colors from rewetting. Series 990 colors must dry a minimum of three hours before the 4430R clear coat is applied.

**D. Storage**

Diamond Grade roll up sheeting should be stored in a cool, dry area, preferably at 65° to 75°F (18° to 24°C) and 30 to 50% relative humidity, and should be used within one year after purchase.

**Unprocessed sheets should be stored flat.**

See Information folder 1.11 for details of storage and packaging. Finished roll up signs should be stored dry and rolled up properly per OEM specifications.

## Health and Safety Information

Read all health hazard, precautionary and first aid statements found in the Material Safety Data Sheet (MSDS), and/or product label of chemicals prior to handling or use.

## General Performance Considerations

The durability of Series RS20/RS24 roll up sign sheeting will depend upon preparation, compliance with recommended application procedures, geographic area, exposure conditions, and maintenance.

## Warranty

3M warrants that 3M™ Diamond Grade™ Roll Up Sign Sheeting Series RS20/RS24 sold by 3M to be used as components for roll up traffic control signs used in work zones in the United States and Canada will remain effective for its intended use and meet the stated minimum values for coefficient of retroreflection for three years, subject to the following provisions:

**Minimum Coefficient of Retroreflection**

Candelas per Footcandle per Square Foot or Candelas per Lux per Square Meter

| Sheeting Color | Minimum Coefficient of Retroreflection (Three Years) |
|---|---|
| White | 50% of stated values of Table C |
| Fluorescent Orange | 50% of stated values of Table C |

*All measurements shall be made after sign cleaning according to 3M recommendations and in accordance with ASTM E810 "Standard Test Method for Coefficient of Retroreflection of Retroreflective Sheeting."

If Series RS20/RS24 roll up sign surface is processed in accordance with all 3M application and fabrication procedures provided in 3M's product bulletins, information folders and technical memos (which will be furnished to the agency upon request), including the exclusive use of 3M matched component systems, process colors, and recommended application equipment; and

If the sign deteriorates due to natural causes to the extent that: 1) the sign is ineffective for its intended purpose when viewed from a moving vehicle under normal day and night driving conditions by drivers with normal vision, or 2) the coefficient of retroreflection is less than the minimum herein specified 3) RS24 fluorescent sheeting color retention does not meet requirement (weathered) in Table C, 3M's sole responsibility and purchaser's and user's exclusive remedy shall be that 3M will provide pro-rata replacement of the 3M materials.

## Conditions

Such failure must be solely the result of design or manufacturing defects in the Series RS20/RS24 roll up sign sheeting and not of outside causes such as: improper fabrication, handling, maintenance or installation; process colors, thinner, coatings, or overlay films and sheetings not made by 3M; use of equipment not recommended by 3M; failure of sign hardware; exposure to chemicals, abrasion and other mechanical damage from fasteners used to mount the sign; collisions, vandalism or malicious mischief.

3M reserves the right to determine the method of replacement.

Replacement sheeting will carry the unexpired warranty of the sheeting it replaces.

Claims made under this warranty will be honored only if the signs have been dated at the time of sheeting application, which constitutes the start of the warranty period.

Claims made under this warranty will be honored only if 3M is notified of a failure within a reasonable time, reasonable information requested by 3M is provided, and 3M is permitted to verify the cause of the failure.

## Limitation of Liability

3M's liability under this warranty is limited to replacement as stated herein, and 3M assumes no liability for any incidental or consequential damages, such as lost profits, business or revenues in any way related to the product regardless of the legal theory on which the claim is based. THIS WARRANTY IS MADE IN LIEU OF ALL OTHER WARRANTIES, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE IMPLIED WARRANTIES OF MERCHANTABILITY, OF FITNESS FOR A PARTICULAR PURPOSE, AND ANY IMPLIED WARRANTY ARISING OUT OF A COURSE OF DEALING OR OF PERFORMANCE, CUSTOM OR USAGE OF TRADE.

## Literature Reference (Available from 3M)

**Screen Processing**

| | |
|---|---|
| PB1805 | 3M™ Process Colors |

**Application**

| | |
|---|---|
| IF 1.10 | Cutting, Matching, Premasking & Prespacing Instructions |
| IF 1.11 | Storage Maintenance and Removal Instructions |

**FOR INFORMATION OR ASSISTANCE**
**CALL:**
**1-800-553-1380**

**IN CANADA CALL:**
**1-800-265-1840**

**Fax-on-Demand in the U.S. and Canada:**
**1-800-887-3238**

**Internet:**
**www.3M.com/tss**



**Traffic Safety Systems Division**
3M Center, Building 0225-05-S-08
St. Paul, MN 55144-1000
1-800-553-1380
www.3M.com/tss

**3M Canada Company**
P.O. Box 5757
London, Ontario N6A 4T1
1-800-3MHELPS

**3M México, S.A. de C.V.**
Av. Santa Fe No. 55
Col. Santa Fe, Del. Alvaro Obregón
México, D.F. 01210

# APPENDIX C. ENGINEERING PROPERTIES OF THE CARBON FIBER STAYS

BASF
The Chemical Company

PRODUCT DATA

3 03 01 00 **Maintenance of Concrete**

# MBRACE® CF 130

## Unidirectional high strength carbon fiber fabric for the MBrace® Composite Strengthening System

### Description

MBrace® CF 130 is a dry fabric constructed of very high strength, aerospace grade carbon fibers. These fabrics are applied onto the surface of existing structural members in buildings, bridges, and other structures using the MBrace® family of performance polymers. The result is an externally bonded FRP (fiber reinforced polymer) reinforcement system that is engineered to increase the strength and structural performance of these members. Once installed, the MBrace® System delivers externally bonded reinforcement with outstanding long-term physical and mechanical properties.

### Yield

269 ft² (25 m²) per roll

### Packaging

Available in rolls 20 in (500 mm) wide, 162 ft (50 m) long

| ROLL | WIDTH | LENGTH |
|---|---|---|
| 269 ft² (25 m²) | 20 in (508 mm) | 162 ft (50 m) |

### Color

Black

| Features | Benefits |
|---|---|
| • High strength to weight ratio | Can add significant strength to a structure without adding significant dead load |
| • Excellent resistance to creep and fatigue | Withstands sustained and cyclic load conditions |
| • Extremely durable | Extremely resistant to a wide range of environmental conditions |
| • Easy installation | Can be installed quickly, even in areas of limited access |
| • Low aesthetic impact | Easy to conceal, will not significantly change existing member dimensions, will form around complex surfaces |

### Shelf Life

3 years in unopened containers

### Storage

Store in a cool, dry place (50 to 90 °F [10 to 32 °C]) away from direct sunlight, flame, or other hazards.

### Where to Use

APPLICATION

- Increase load bearing capacity of concrete beams, slabs, walls and columns
- Improve the seismic ductility of concrete columns
- Improve the seismic response of concrete beam column connections, shear walls and collector elements
- Improve the seismic performance of masonry shear walls and in-fill walls
- Restore structural capacity to damaged or deteriorated concrete structures
- Increase the strength of concrete pipes, silos, tanks, chimneys and tunnels
- Substitute reinforcing steel mistakenly omitted in the construction of concrete and masonry structures
- Improve the blast resistance of concrete and masonry structures
- Strengthening of some steel and timber structures

LOCATION

- Vertical
- Horizontal
- Exterior
- Interior

SUBSTRATE

- Concrete
- Masonry
- Timber
- Steel

## Technical Data

### Composition

MBrace® CF 130 is composed of a dense network of high strength carbon fibers held in a unidirectional alignment with a light thermoplastic glass fiber cross weave yarn

### Physical Properties

| PROPERTY | REQUIREMENT |
|---|---|
| **Fiber Material** | High Strength Carbon |
| **Fiber Tensile Strength** | 720 ksi (4950 MPa) |
| **Areal Weight** | 0.062 lb/ft² [300 g/m²] |
| **Fabric Width** | 20 inch [500 mm] |
| **Nominal Thickness, $t_f$ (1)** | 0.0065 in/ply [0.165 mm/ply] |

### Functional Properties

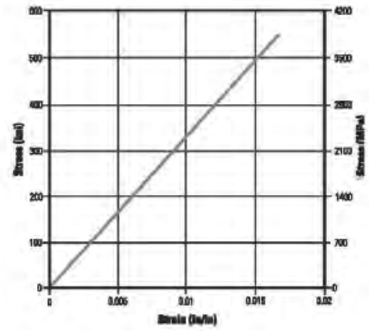
| PROPERTY | REQUIREMENT |
|---|---|
| **CTE** | $-0.21{\cdot}10^{-6}$/F ($-0.38{\cdot}10^{-6}$/C) |
| **Thermal Conductivity** | 65.1 Btu·in/hr·ft²·F (9.38 W/m·K) |
| **Electrical Resistivity** | $1.6{\cdot}10^{-3}\Omega{\cdot}$cm |

### 0° Tensile Properties (2,3)

| PROPERTY | REQUIREMENT |
|---|---|
| **Ultimate Tensile Strength, $f^*_{fu}$** | 550 ksi [3800 MPa] |
| **Tensile Modulus, $E_f$** | 33000 ksi [227 GPa] |
| **Ultimate Tensile Strength per Unit Width, $f^*_{fu}\,t_f$** | 3.57 kips/in/ply [0.625 kN/mm/ply] |
| **Tensile Modulus per Unit Width, $E_f\,t_f$** | 215 kips/in/ply [38 kN/mm/ply] |
| **Ultimate Rupture Strain, $\varepsilon^*_{fu}$** | 1.67% |

### 90° Tensile Properties (2,4)

| PROPERTY | REQUIREMENT |
|---|---|
| **Ultimate Tensile Strength** | 0 |
| **Tensile Modulus** | 0 |
| **Ultimate Rupture Strain** | n/a |




NOTES:

(1) The nominal fabric thickness is based on the total area of fibers (only) in a unit width. From experience, the actual cured thickness of a single ply laminate (fibers plus saturating resins) is 0.020 to 0.040 in (0.6 to 1.0 mm).

(2) The tensile properties given are those to be used for design. These values are derived by testing cured laminates (per ASTM D3039) and dividing the resulting strength and modulus per unit width by the nominal fabric thickness.

(3) The 0° direction denotes the direction along the length of the fabric.

(4) The 90° direction denotes the direction along the width of the fabric.

## How to Apply

### Surface Preparation

1. MBrace® CF 130 is applied to surfaces treated with MBrace® Primer, MBrace® Putty and MBrace® Saturant. Consult the data sheets for these materials for additional details.

### Application

MBrace® CF 130 is only applied as a component of the MBrace® System.

1. The MBrace® CF 130 material should be cut to the proper dimensions (dimensions will vary based on project requirements) using heavy duty shears or a utility knife.

2. Cut sections of MBrace® CF 130 can be temporarily stored by carefully rolling fabric into a 12 inch (600 mm) (approximate) roll. Do not fold or crease the fabric. Fabric shoul dbe kept free of dust, oils, moisture and other contaminants at all times.

3. Apply the MBrace® CF 130 fabric directly into uncured MBrace® Saturant applied on the substrate. There is no need to "pre-wet" the MBrace® CF 130 fabric with MBrace® Saturant prior to applying the fabric against the substrate.

4. Using a rib roller or squeegee, press the fabric against the substrate until visual signs of MBrace® Saturant are observed bleeding through the fabric. The rib roller or squeegee should only be run along the direction of the primary fibers in the fabric.

5. Apply a layer of MBrace® Saturant over the top of the MBrace® CF 130 fabric to completely encapsulate the fabric. Consult with the MBrace® Saturant data sheet on details for applying MBrace® Saturant.

### Maintenance

Periodically inspect the applied material and repair localized areas as needed. Consult an BASF representative for additional information. Visit us on the web for the most current product information and news: www.BuildingSystems.BASF.com

## For Best Performance

- Use caution when applying MBrace® CF 130 around sensitize electrical equipment. Carbon fiber filaments can become airborne, infiltrate electrical equipment and cause electrical shorts.
- Make certain the most current versions of product data sheet and MSDS are being used; call Customer Service (1-800-433-9517) to verify the most current version.
- Proper application is the responsibility of the user. Field visits by BASF personnel are for the purpose of making technical recommendations only and are not for supervising or providing quality control on the jobsite.

## Health and Safety

MBRACE® CF 130

### Warning

MBrace® Fiber Reinforcements contain carbon, glass, and/or aramid fibers, MBrace® CF 130 contains carbon and glass fibers. While handling MBrace® Fiber Reinforcements CF 130, wear appropriate work clothing to minimize contact. Product Material Safety Data Sheets (MSDS) are available and should be consulted and on hand whenever handling these products. These products are for professional and industrial use only and are only installed by trained and qualified applicators. Trained applicators must follow installation instructions.

**BASF Construction Chemicals, LLC – Building Systems**

889 Valley Park Drive
Shakopee, MN, 55379

www.BuildingSystems.BASF.com

**Customer Service** 800-433-9517
**Technical Service** 800-243-6739



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## APPENDIX D. TEST VEHICLE PROPERTIES AND INFORMATION

### Table D1. Vehicle Properties for Test No. 466393-1.

Date: 2013-07-22 Test No.: 466393-1 VIN No.: KNADE223996535907

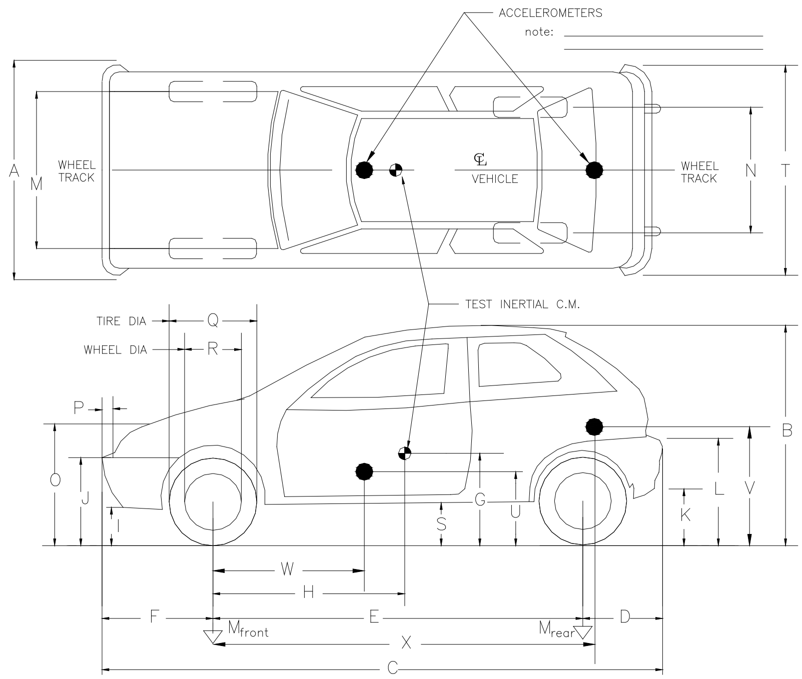
Year: 2009 Make: Kia Model: Rio

Tire Inflation Pressure: 32 psi Odometer: 96956 Tire Size: 165/65R14

Describe any damage to the vehicle prior to test: ______

● Denotes accelerometer location.

NOTES: ______




Engine Type: 4 cylinder
Engine CID: 4.6 liter
Transmission Type:
x Auto or ____ Manual
x FWD ____ RWD ____ 4WD
Optional Equipment: ______

Dummy Data:
Type: 50th percentile male
Mass: 179 lb
Seat Position: Driver

**Geometry:** inches

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A | 66.38 | F | 33.00 | K | 11.75 | P | 4.12 | U | ---- |
| B | 57.75 | G | ---- | L | 25.25 | Q | 22.18 | V | ---- |
| C | 165.75 | H | 34.44 | M | 57.75 | R | 15.38 | W | ---- |
| D | 34.00 | I | 6.75 | N | 57.12 | S | 8.00 | X | ---- |
| E | 98.75 | J | 22.00 | O | 31.25 | T | 66.12 | | |

Wheel Center Ht Front 11.00 Wheel Center Ht Rear 11.00

| **GVWR Ratings:** | | **Mass:** lb | Curb | Test Inertial | Gross Static |
|---|---|---|---|---|---|
| Front | 1918 | $M_{front}$ | 1603 | 1591 | 1675 |
| Back | 1874 | $M_{rear}$ | 856 | 852 | 947 |
| Total | 3638 | $M_{Total}$ | 2459 | 2443 | 2622 |

**Mass Distribution:**
lb LF: 798 RF: 793 LR: 421 RR: 431

## Table D2. Exterior Crush Measurements for Test No. 466393-1.

Date: 2013-07-22 Test No.: 466393-1 VIN No.: KNADE223996535907

Year: 2009 Make: Kia Model: Rio

VEHICLE CRUSH MEASUREMENT SHEET[1]

| Complete When Applicable | |
|---|---|
| **End Damage** | **Side Damage** |
| Undeformed end width ________<br>Corner shift: A1 ________<br>A2 ________<br>End shift at frame (CDC)<br>(check one)<br>< 4 inches ________<br>≥ 4 inches ________ | Bowing: B1 _____ X1 _____<br>B2 _____ X2 _____<br>Bowing constant<br>$\frac{X1+X2}{2}$ = _______ |

Note: Measure $C_1$ to $C_6$ from Driver to Passenger Side in Front or Rear impacts – Rear to Front in Side Impacts.

| Specific Impact Number | Plane* of C-Measurements | Direct Damage Width** (CDC) | Direct Damage Max*** Crush | Field L** | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | ±D |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Front plane at bumper ht | Slight scuff marks up the hood | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | Measurements recorded | | | | | | | | | | |
| | **in inches** | | | | | | | | | | |
| | | | | | | | | | | | |

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

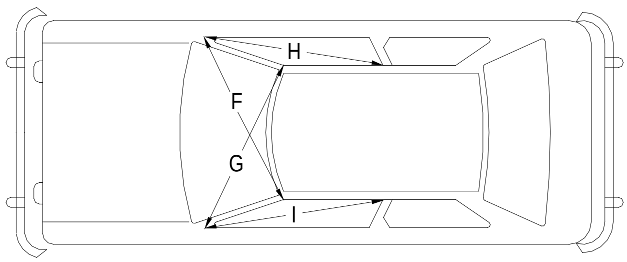
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

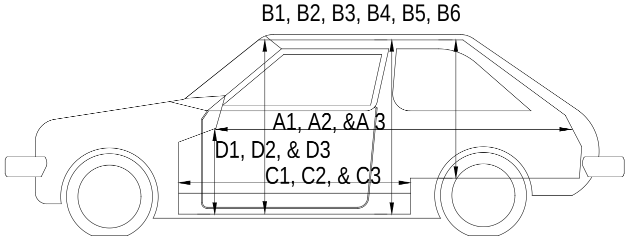
***Measure and document on the vehicle diagram the location of the maximum crush.

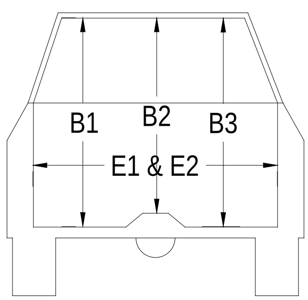
Note: Use as many lines/columns as necessary to describe each damage profile.

**Table D3. Occupant Compartment Measurements for Test No. 466393-1.**

| | | | | | |
|---|---|---|---|---|---|
| Date: | 2013-07-22 | Test No.: | 466393-1 | VIN No.: | KNADE223996535907 |
| Year: | 2009 | Make: | Kia | Model: | Rio |




**OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT**

| | **Before** (inches) | **After** (inches) |
|---|---|---|
| A1 | 67.75 | 67.75 |
| A2 | 67.25 | 67.25 |
| A3 | 67.50 | 67.50 |
| B1 | 40.50 | 40.50 |
| B2 | 36.50 | 36.50 |
| B3 | 40.50 | 40.50 |
| B4 | 36.25 | 36.25 |
| B5 | 37.25 | 37.25 |
| B6 | 36.25 | 36.25 |
| C1 | 27.00 | 27.00 |
| C2 | ---- | ---- |
| C3 | 27.50 | 27.50 |
| D1 | 9.75 | 9.75 |
| D2 | ---- | ---- |
| D3 | 9.75 | 9.75 |
| E1 | 48.25 | 48.25 |
| E2 | 51.00 | 51.00 |
| F | 50.00 | 50.00 |
| G | 50.00 | 50.00 |
| H | 36.50 | 36.50 |
| I | 36.50 | 36.50 |
| J* | 51.00 | 51.00 |

*Lateral area across the cab from driver's side kick panel to passenger's side kick panel.

## Table D4. Vehicle Properties for Test No. 466393-2.

Date: 2013-07-22 Test No.: 466393-2 VIN No.: KNADE123786431909

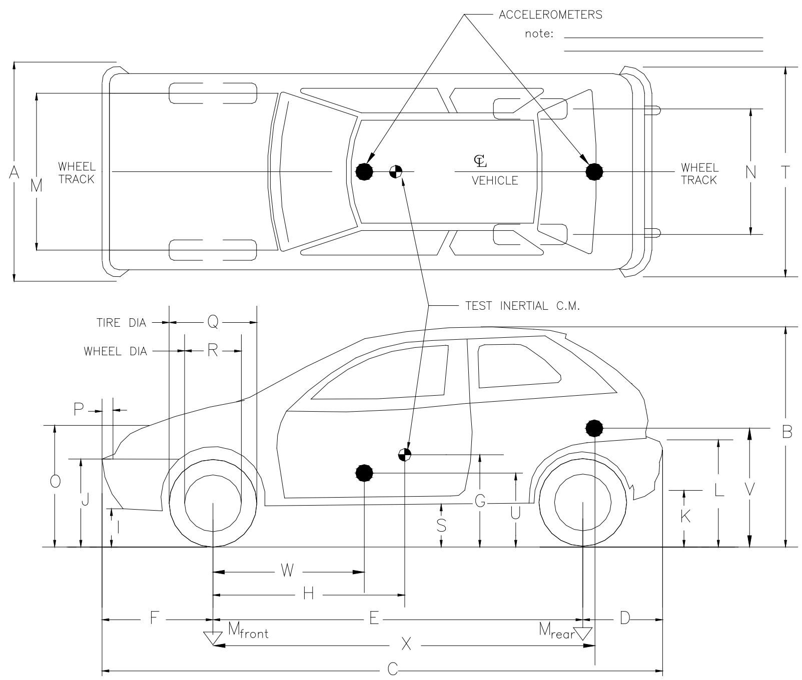
Year: 2008 Make: Kia Model: Rio

Tire Inflation Pressure: 32 psi Odometer: 64862 Tire Size: 165/65R14

Describe any damage to the vehicle prior to test: ______

● Denotes accelerometer location.

NOTES: ______




Engine Type: 4 cylinder
Engine CID: 1.6 liter
Transmission Type:
x Auto or ____ Manual
x FWD ____ RWD ____ 4WD
Optional Equipment: ______

Dummy Data:
Type: 50th percentile male
Mass: 180 lb
Seat Position: Driver

**Geometry:** inches

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A | 66.38 | F | 33.00 | K | 11.75 | P | 4.12 | U | ---- |
| B | 57.75 | G | ---- | L | 25.25 | Q | 22.18 | V | ---- |
| C | 165.75 | H | 40.16 | M | 57.75 | R | 15.38 | W | ---- |
| D | 34.00 | I | 6.75 | N | 52.12 | S | 8.00 | X | ---- |
| E | 98.75 | J | 22.00 | O | 31.35 | T | 66.12 | | ---- |

Wheel Center Ht Front ______ Wheel Center Ht Rear ______

| **GVWR Ratings:** | | **Mass:** lb | Curb | Test Inertial | Gross Static |
|---|---|---|---|---|---|
| Front | 1918 | $M_{front}$ | 1440 | 1446 | 1541 |
| Back | 1874 | $M_{rear}$ | 861 | 991 | 1076 |
| Total | 3638 | $M_{Total}$ | 2301 | 2437 | 2617 |

**Mass Distribution:**
lb LF: 732 RF: 714 LR: 493 RR: 498

## Table D5. Exterior Crush Measurements for Test No. 466393-2.

| | | | | | |
|---|---|---|---|---|---|
| Date: | 2013-07-22 | Test No.: | 466393-2 | VIN No.: | KNADE123786431909 |
| Year: | 2008 | Make: | Kia | Model: | Rio |

VEHICLE CRUSH MEASUREMENT SHEET[1]

| Complete When Applicable | |
|---|---|
| End Damage | Side Damage |
| Undeformed end width ________<br>Corner shift: A1 ________<br>A2 ________<br>End shift at frame (CDC)<br>(check one)<br>< 4 inches ________<br>≥ 4 inches ________ | Bowing: B1 _____ X1 _____<br>B2 _____ X2 _____<br>Bowing constant<br>$\frac{X1+X2}{2}$ = ______ |

Note: Measure $C_1$ to $C_6$ from Driver to Passenger Side in Front or Rear impacts – Rear to Front in Side Impacts.

| Specific Impact Number | Plane* of C-Measurements | Direct Damage Width** (CDC) | Direct Damage Max*** Crush | Field L** | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | ±D |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Front plane at bumper ht | Slight scuff marks up the hood | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | Measurements recorded | | | | | | | | | | |
| | **in inches** | | | | | | | | | | |
| | | | | | | | | | | | |

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

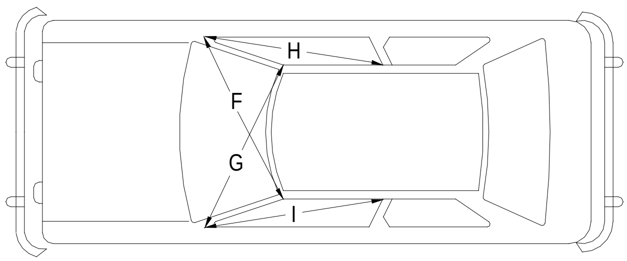
***Measure and document on the vehicle diagram the location of the maximum crush.

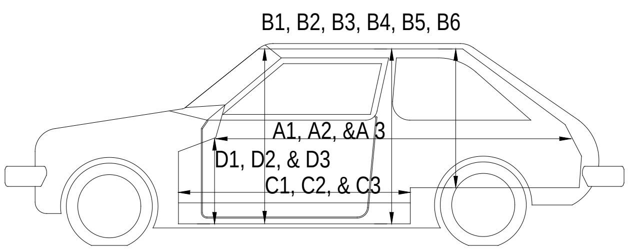
Note: Use as many lines/columns as necessary to describe each damage profile.

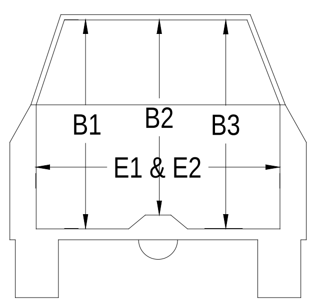
**Table D6. Occupant Compartment Measurements for Test No. 466393-2.**

Date: 2013-07-22 Test No.: 466393-2 VIN No.: KNADE123786431909

Year: 2008 Make: Kia Model: Rio




**OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT**

| | **Before** (inches) | **After** (inches) |
|---|---|---|
| A1 | 67.75 | 67.75 |
| A2 | 67.25 | 67.25 |
| A3 | 67.50 | 67.50 |
| B1 | 40.50 | 40.50 |
| B2 | 36.50 | 36.50 |
| B3 | 40.50 | 40.50 |
| B4 | 36.25 | 36.25 |
| B5 | 37.25 | 37.25 |
| B6 | 36.25 | 36.25 |
| C1 | 27.00 | 27.00 |
| C2 | ---- | ---- |
| C3 | 27.50 | 27.50 |
| D1 | 9.75 | 9.75 |
| D2 | ---- | ---- |
| D3 | 9.75 | 9.75 |
| E1 | 48.25 | 48.25 |
| E2 | 51.00 | 51.00 |
| F | 50.00 | 50.00 |
| G | 50.00 | 50.00 |
| H | 36.50 | 36.50 |
| I | 36.50 | 36.50 |
| J* | 51.00 | 51.00 |

*Lateral area across the cab from driver's side kick panel to passenger's side kick panel.

## Table D7. Vehicle Properties for Test No. 466393-3.

Date: 2013-08-23 Test No.: 466393-2 VIN No.: KNADE123286429839

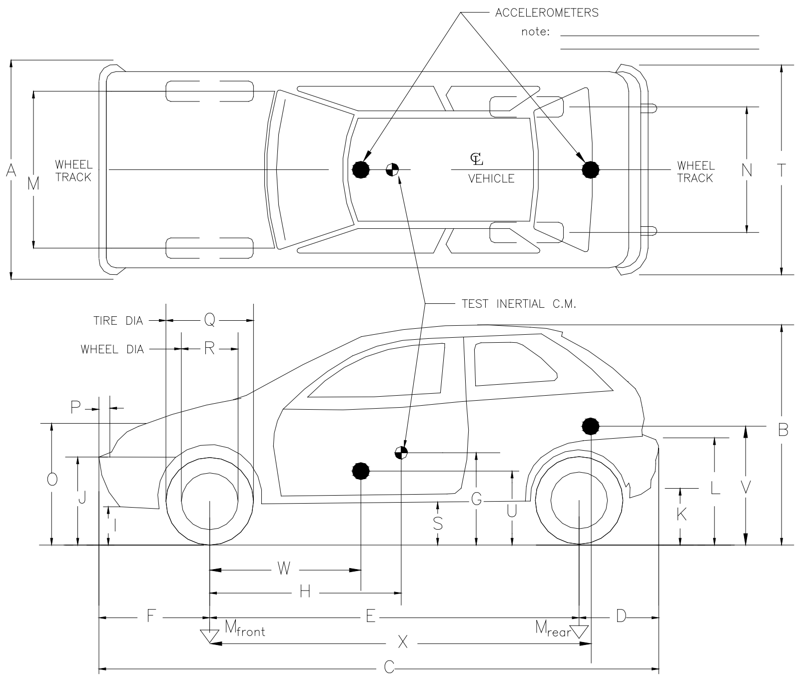
Year: 2008 Make: Kia Model: Rio

Tire Inflation Pressure: 32 psi Odometer: 257961 Tire Size: 165/65R14

Describe any damage to the vehicle prior to test:

● Denotes accelerometer location.

NOTES:




Engine Type: 4 cylinder
Engine CID: 1.6 liter
Transmission Type:
x Auto or ____ Manual
x FWD ____ RWD ____ 4WD
Optional Equipment:

Dummy Data:
Type: 50th percentile male
Mass: 175 lb
Seat Position: Driver

**Geometry:** inches

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A | 66.38 | F | 33.00 | K | 11.00 | P | 4.12 | U | ---- |
| B | 58.00 | G | ---- | L | 24.00 | Q | 22.18 | V | ---- |
| C | 165.75 | H | 39.54 | M | 57.75 | R | 15.38 | W | ---- |
| D | 34.00 | I | 6.75 | N | 52.12 | S | 8.00 | X | ---- |
| E | 98.75 | J | 21.25 | O | 28.25 | T | 66.12 | | ---- |

Wheel Center Ht Front 11.00 Wheel Center Ht Rear 11.00

| **GVWR Ratings:** | | **Mass:** lb | Curb | Test Inertial | Gross Static |
|---|---|---|---|---|---|
| Front | 1918 | $M_{front}$ | 1468 | 1464 | 1553 |
| Back | 1874 | $M_{rear}$ | 859 | 978 | 1064 |
| Total | 3638 | $M_{Total}$ | 2327 | 2442 | 2617 |

**Mass Distribution:**
lb LF: 744 RF: 724 LR: 417 RR: 442

## Table D8. Exterior Crush Measurements for Test No. 466393-3.

| | | | | | |
|---|---|---|---|---|---|
| Date: | 2013-08-23 | Test No.: | 466393-2 | VIN No.: | KNADE123286429839 |
| Year: | 2008 | Make: | Kia | Model: | Rio |

VEHICLE CRUSH MEASUREMENT SHEET[1]

| Complete When Applicable | |
|---|---|
| End Damage | Side Damage |
| Undeformed end width ________<br>Corner shift: A1 ________<br>A2 ________<br>End shift at frame (CDC)<br>(check one)<br>< 4 inches ________<br>≥ 4 inches ________ | Bowing: B1 _____ X1 _____<br>B2 _____ X2 _____<br>Bowing constant<br>$\frac{X1+X2}{2}$ = ______ |

Note: Measure $C_1$ to $C_6$ from Driver to Passenger Side in Front or Rear impacts – Rear to Front in Side Impacts.

| Specific Impact Number | Plane* of C-Measurements | Direct Damage | | Field L** | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | ±D |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Width** (CDC) | Max*** Crush | | | | | | | | |
| 1 | Front plane at bumper ht | Slight scuff marks up the hood | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | Measurements recorded | | | | | | | | | | |
| | **in inches** | | | | | | | | | | |
| | | | | | | | | | | | |

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

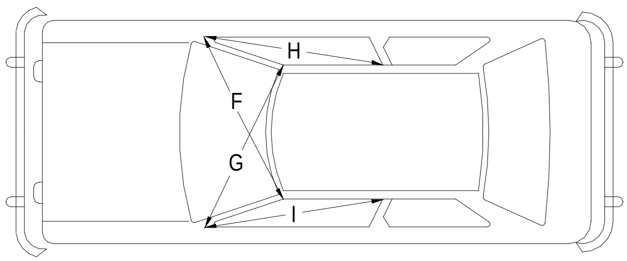
***Measure and document on the vehicle diagram the location of the maximum crush.

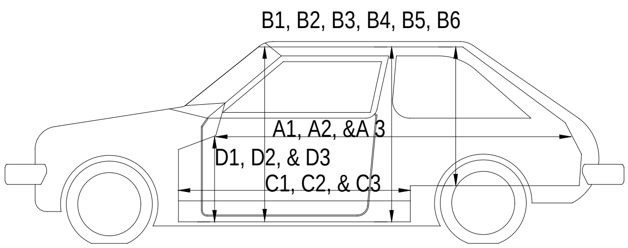
Note: Use as many lines/columns as necessary to describe each damage profile.

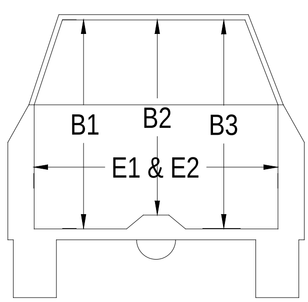
**Table D9. Occupant Compartment Measurements for Test No. 466393-3.**

Date: 2013-08-23 Test No.: 466393-2 VIN No.: KNADE123286429839

Year: 2008 Make: Kia Model: Rio



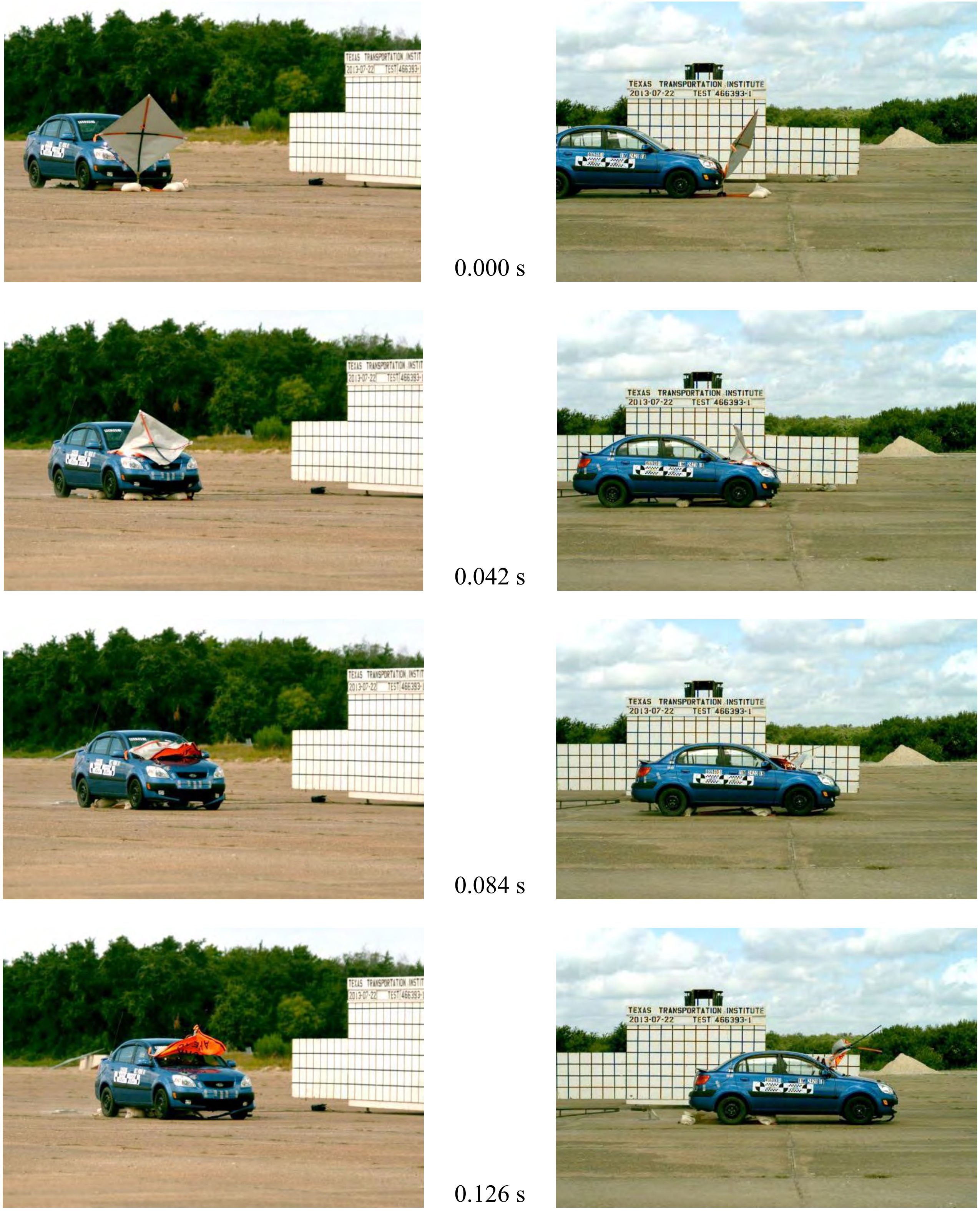




**OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT**

| | Before (inches) | After (inches) |
|---|---|---|
| A1 | 69.50 | 69.50 |
| A2 | 69.00 | 69.00 |
| A3 | 69.50 | 69.50 |
| B1 | 40.50 | 40.50 |
| B2 | 36.50 | 36.50 |
| B3 | 41.00 | 41.00 |
| B4 | 37.25 | 37.25 |
| B5 | 37.00 | 37.00 |
| B6 | 37.00 | 37.00 |
| C1 | 21.75 | 21.75 |
| C2 | 25.50 | 25.50 |
| C3 | 21.50 | 21.50 |
| D1 | 9.50 | 9.50 |
| D2 | 10.00 | 10.00 |
| D3 | 10.00 | 10.00 |
| E1 | 48.25 | 48.25 |
| E2 | 51.50 | 51.50 |
| F | 50.00 | 50.00 |
| G | 50.00 | 50.00 |
| H | 36.50 | 36.50 |
| I | 36.50 | 36.50 |
| J* | 51.00 | 51.00 |

*Lateral area across the cab from driver's side kick panel to passenger's side kick panel.

# APPENDIX E.  SEQUENTIAL PHOTOGRAPHS




0.000 s

0.042 s

0.084 s

0.126 s

**Figure E1.  Sequential Photographs for Test No. 466393-1 (Oblique and Perpendicular Views).**

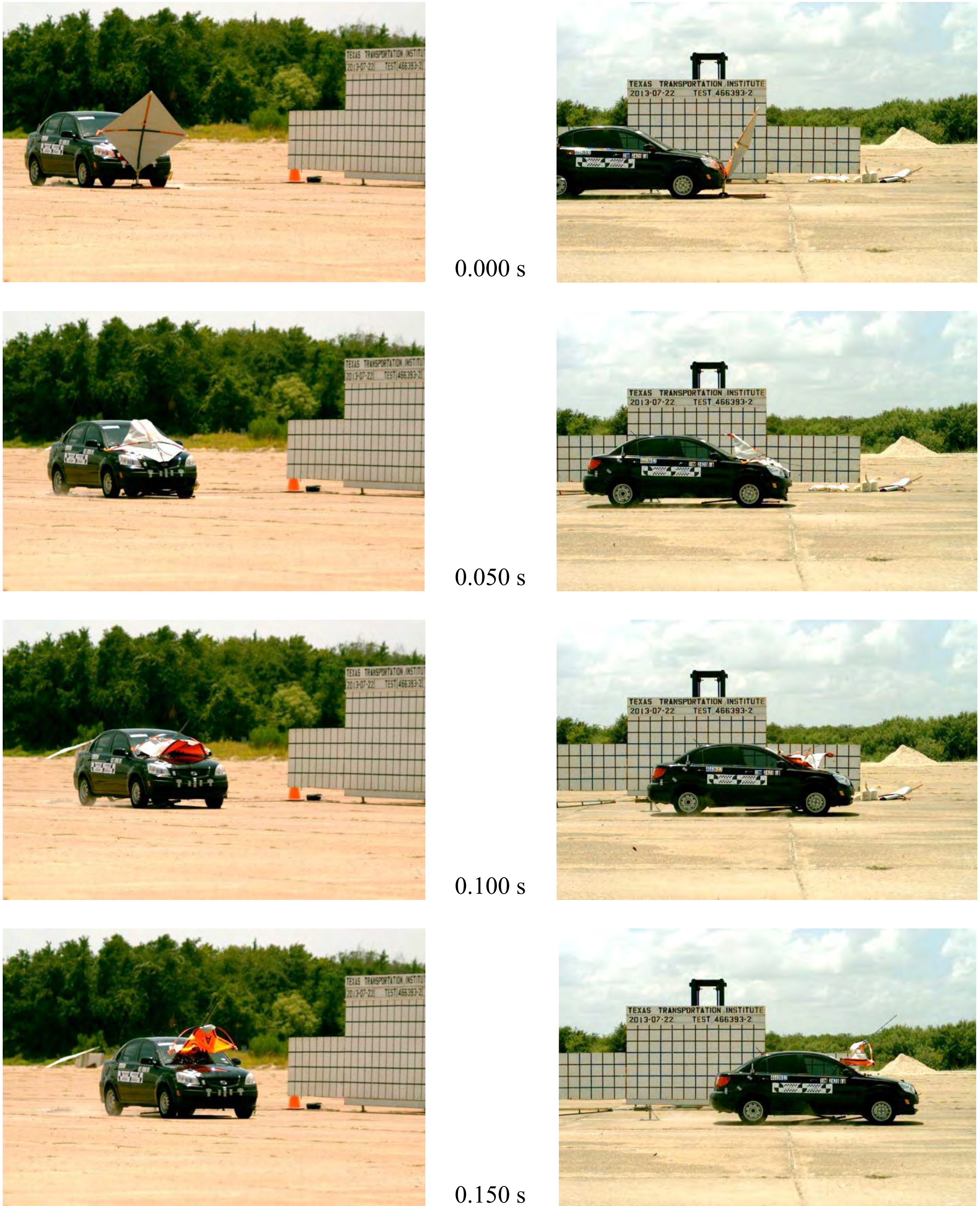
0.168 s


0.210 s


0.252 s


0.294 s


**Figure E1. Sequential Photographs for Test No. 466393-1 (Oblique and Perpendicular Views) (continued).**




0.000 s

0.050 s

0.100 s

0.150 s

**Figure E2. Sequential Photographs for Test No. 466393-2 (Oblique and Perpendicular Views).**

0.200 s



0.250 s



0.300 s



0.350 s


**Figure E1. Sequential Photographs for Test No. 466393-1**
**(Oblique and Perpendicular Views) (continued).**

# APPENDIX II

# SUGGESTED CHANGES TO TXDOT 801-12-77

TEXAS DEPARTMENT OF TRANSPORTATION

GENERAL SERVICES DIVISION

SPECIFICATION NO.
TXDOT 801-12-77*
~~REVISED: MAY 2010~~ REVISED OCTOBER 2013
DHT NO.: 148842

**STAND, SIGN, PORTABLE, FOR ROLL-UP SIGNS, 1 FOOT MOUNTING HEIGHT**

PUBLICATION

This specification is a product of the Texas Department of Transportation (TxDOT). It is the practice of TxDOT to support other entities by making this specification available through the National Institute of Governmental Purchasing (NIGP). This specification may not be sold for profit or monetary gain. If this specification is altered in any way, the header, and any and all references to TxDOT must be removed. TxDOT does not assume nor accept any liability when this specification is used in the procurement process by any other entity.

PART I

GENERAL CLAUSES AND CONDITIONS

1. The equipment furnished under this specification shall be the latest improved model in current production, as offered to commercial trade, and shall be of quality workmanship and material. The respondent represents that all equipment offered under this specification shall be new. USED, SHOPWORN, DEMONSTRATOR, PROTOTYPE, REMANUFACTURED, RECONDITIONED OR DISCONTINUED MODELS ARE NOT ACCEPTABLE.

2. Respondent should submit with the solicitation or have on file with TxDOT, Austin, Texas, the latest printed literature and detailed specifications on equipment the respondent proposes to furnish. This literature is for informational purposes only.

3. All parts not specifically mentioned which are necessary for the unit to be complete and ready for operation or which are normally furnished as standard equipment shall be furnished by the vendor. All parts shall conform in strength, quality and workmanship to the accepted standard of the industry.

4. The unit provided shall meet or exceed all federal and state of Texas safety, health, lighting and noise regulations and standards in effect and applicable to equipment furnished at the time of manufacture.

5. It is the intent of TxDOT to purchase goods, equipment and services having the least adverse environmental impact, within the constraints of statutory purchasing requirements, TxDOT need, availability, and sound economical considerations. Suggested changes and environmental enhancements for possible inclusion in future revisions of this specification are encouraged.

* This Specification Supersedes Specification No. TxDOT 801-12-77, Revised ~~July 2003~~ May 2010.

6. TxDOT encourages all manufacturers to comply voluntarily with the Society of Automotive Engineers (SAE) Recommended Practice for marking of plastic parts per current SAE J1344 standard. All plastic components furnished to this specification should have an imprinted SAE symbol identifying the resin composition of the component so that the item can be recycled after its useful life. Manufacturers are encouraged to use recycled plastics and materials in the manufacture of their products in order to conserve natural resources, energy and landfill space. Respondents should note that future specification revisions may require mandatory compliance with the SAE plastic coding system.

7. TxDOT is committed to procuring quality goods and equipment. TxDOT encourages manufacturers to adopt the International Organization for Standardization (ISO) 9001-9003 standards, technically equivalent to the current American National Standards Institute/American Society for Quality Control (ANSI/ASQC Q91-93), and obtain certification. Adopting and implementing these standards is considered beneficial to the manufacturer, TxDOT, and the environment. It is TxDOT's position that the total quality management concepts contained within these standards can result in reduced production costs, higher quality products, and more efficient use of energy and natural resources.

## PART II

## SPECIFICATIONS

1. SCOPE: This specification describes a portable sign stand 1 foot mounting height bottom to grade for roll up signs used for traffic control. The sign stand provided shall meet the requirements of ~~the National Cooperative Highway Research Program (NCHRP) Report 350~~ the AASHTO Manual for Assessing Safety Hardware (MASH)[see Comment 1], the Federal/Texas Manual on Uniform Traffic Controls (MUTCD), and be listed on the TxDOT Prequalified Products List (QPL).

2. PREQUALIFICATION REQUIREMENTS AND RESTRICTIONS

   2.1. Only products listed by manufacturer and product code listed on the TxDOT QPL maintained by the General Services Division (GSD) will be considered for purchase in connection with this specification.

   2.2. The GSD QPL is available at http://www.txdot.gov/gsd/purchasing/supps.htm. A respondent wishing to have their product(s) considered for future advertisements should contact TxDOT, GSD Purchasing, at 125 East 11th Street, Austin, Texas 78701-2483.

3. FUNCTIONAL REQUIREMENTS

   3.1. The portable sign stand shall be constructed of aluminum or material that is rustproof, treated or coated to prevent rust.

   3.2. The portable sign stand shall support a 48 inch x 48 inch diamond-shaped, roll-up sign, furnished by TxDOT.

   3.3. DESIGN: Shall be a fold-up design with four legs. Each leg shall have spring-loaded catches and a rubber-like tip on each end. Legs shall have a minimum of two adjustable positions for leveling on rough terrain. The legs shall lock securely in each of the adjustable and fold-up positions. The legs shall have a one step release for each leg or pair of legs. Stand shall be easily deployed by one person, simple to handle, and rapidly stowed for transport and storage.

3.4. SIGN ATTACHMENT: Shall include a spring-loaded universal, snap-in, pocket-type roll-up sign receiver bracket, ~~or~~ universal bracket with turn knob and pressure plate which secures vertical batten, or universal bracket with a through- bolt which secures vertical batten [see Comment 2]. Sign attachment shall hold any manufacturers 48 inch x 48 inch diamond-shaped, roll-up sign. All parts shall be rust resistant in accordance with ASTM B117 (latest revision). Sign bracket shall not require any tools to attach bracket to the roll-up sign. The universal, snap-in, pocket-type roll-up sign receiver bracket or universal bracket with turn knob and pressure plate which secures vertical batten shall contact either the polyurethane/ lexan plastic corner pocket of the roll-up sign, or the roll-up sign fiberglass battens, for a single point sign-to-stand attachment. Stand shall be compatible with all TxDOT roll-up signs currently in use, including roll-up signs described in Specification No. TxDOT 801-60-66, latest revision.

3.5. WIND RESISTANCE: Shall withstand wind gusts of up to 50 mph without tipping over when a 48 inch x 48 inch sign is mounted on the stand. This shall be accomplished without the use of sandbags or other means of anchoring sign to the ground.

4. DIMENSIONS AND WEIGHT CHARACTERISTICS

4.1. In the storage position, the stand shall not exceed 25 inches in height, 8 inches in width, and a depth of 8 inches.

4.2. In the upright position, with a 48 inch x 48 inch diamond-shaped roll-up sign attached, the bottom of the sign shall be a minimum of 1 foot above the surface (grade) upon which the sign stand is placed.

4.3. In the flat surface position, the stand shall have a minimum footprint of 39 inches x 64 inches.

4.4. The stand shall not exceed 23 pounds in weight.

5. WARRANTY: The sign stand shall be warranted against defective materials, workmanship, and failures for a minimum of 24 months, and shall be permanently stamped or etched with the manufacturer’s make, model, and batch number (if available). Ink stamping is unacceptable. If the manufacturer’s standard warranty is for a period in excess of 24 months, the standard warranty shall apply.

6. ACCEPTANCE INSPECTION: The sign stand will be subject to acceptance inspection upon receipt. Acceptance inspection will not take more than five working days, weather permitting. The vendor will be notified within this time frame of any sign stands not delivered in full compliance with the purchase order specifications. If any sign stands are canceled for non-acceptance, the needed sign stands may be purchased elsewhere and the vendor may be charged any additional increase in cost and handling.

**Comment 1**

The AASHTO Manual for Assessing Safety Hardware (MASH) is published in 2009. It is an update to and supersedes NCHRP Report 350 for the purpose of evaluating new safety hardware devices.

**Comment 2**

Two different types of connection details were evaluated in the crashworthiness tests for the proposed roll-up sign design as shown in Figure 1. One type was a spring-loaded universal, snap-in, pocket-type sign receiver bracket provided by TrafFix Inc. and currently listed on the TxDOT QPL maintained by the General Services Division (GSD). The other type of connection was fabricated in the laboratory by modifying the spring-loaded universal, snap-in, pocket-type sign receiver bracket. The modification required drilling a 3/8 in.-hole on each side of the bracket and inserting a 3/8 in.-through bolt. A schematic design representation of the through bolt connection is shown in Figure 2, and Figure 3 shows the prototype through-bolt connection used for a crashworthiness test sample.

From the observation on the crashworthiness test results, it was found that the prototype through-bolt connection could be an effective way to protect the windshield from penetration by the vertical batten. With the through-bolt connection, the vertical batten was not pulled out from the bracket at the impact and did not hit the windshield as shown in Figure 4. On the other hand, when the spring-loaded universal, snap-in, pocket-type roll-up sign receiver bracket were used, the vertical batten slipped out from the bracket at the impact and the top end of the vertical batten hit the windshield, tearing the plastic liner (i.e., making a punch hole in the windshield), which caused a failure to meet the MASH requirements, as shown in Figure 5.

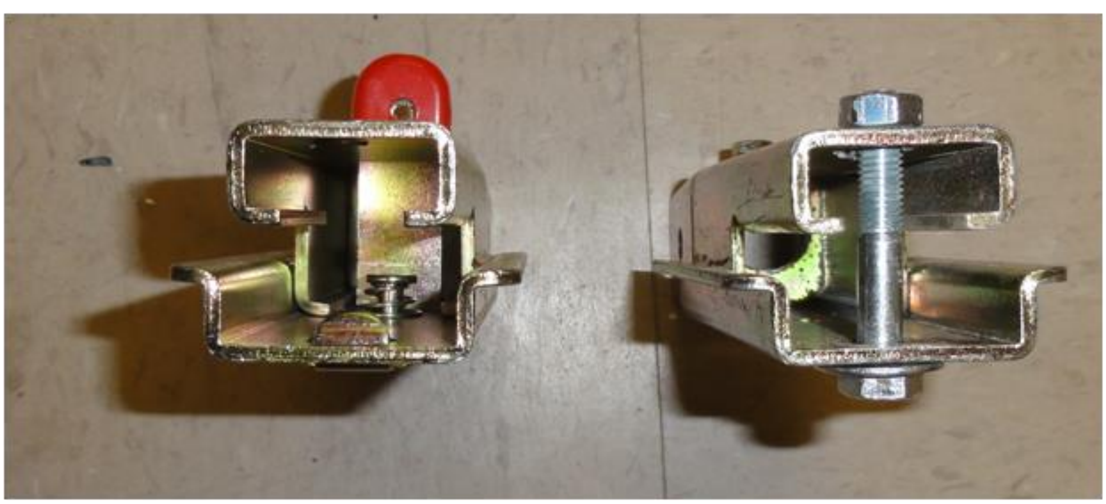


Figure 1. Spring-loaded universal, snap-in, pocket-type roll-up sign receiver bracket (Left) and the prototype through-bolt bracket

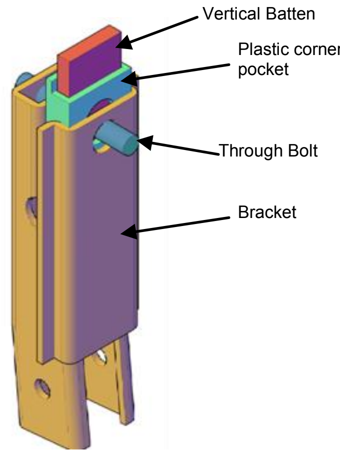



Figure 2. Schematic design representation of the prototype through-bolt connection used for fabricating the proposed roll-up sign design

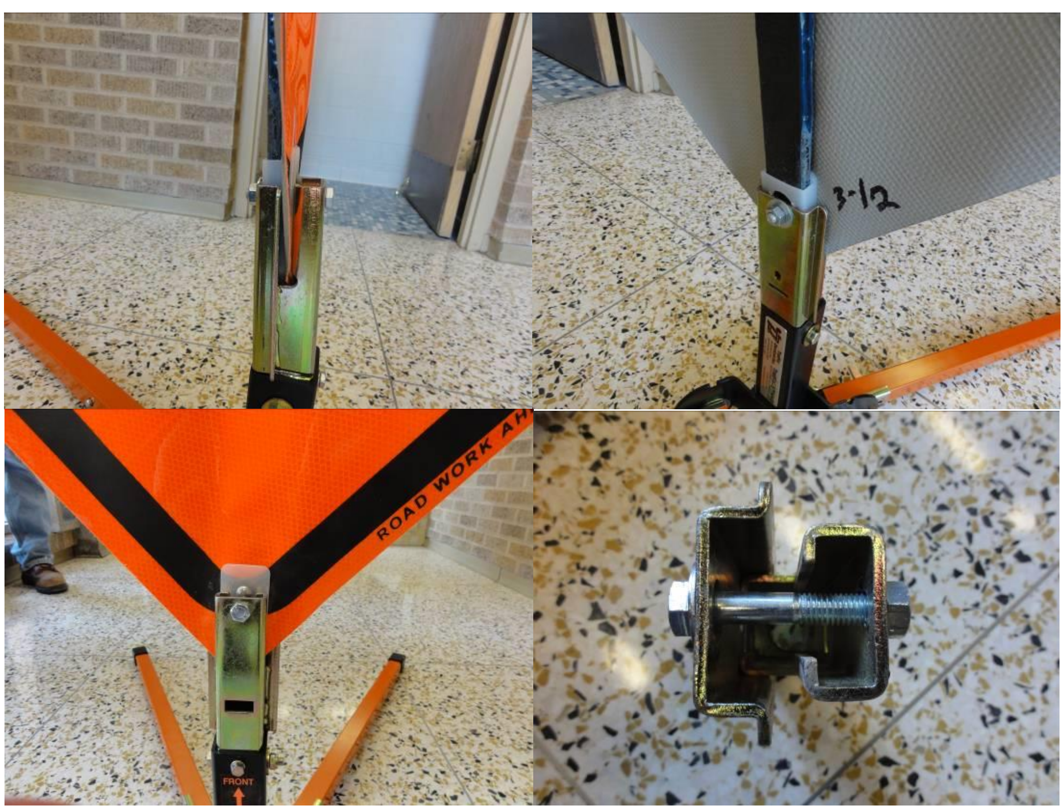



Figure 3. Photos of the fabricated prototype through-bolt connection used for a crashworthiness test specimen

Figure 4. Photos of the crashworthiness test on the proposed roll-up sign design with the prototype through-bolt connection.


Figure 5. Photos of the crashworthiness test on the proposed roll-up sign design with spring-loaded universal, snap-in, pocket-type roll-up sign receiver bracket.

# APPENDIX III

# SUGGESTED CHANGES TO TXDOT 801-60-66

TEXAS DEPARTMENT OF TRANSPORTATION
GENERAL SERVICES DIVISION

SPECIFICATION NO.
TxDOT 801-60-66* T
~~REVISED: JUNE 2010~~OCTOBER 2013

SIGN FACE, ROLL-UP, REFLECTIVE, CONSTRUCTION AND WORK ZONE

PUBLICATION

This specification is a product of the Texas Department of Transportation (TxDOT). It is the practice of TxDOT to support other entities by making this specification available through the National Institute of Governmental Purchasing (NIGP). This specification may not be sold for profit or monetary gain. If this specification is altered in any way, the header, and any and all references to TxDOT must be removed. TxDOT does not assume nor accept any liability when this specification is used in the procurement process by any other entity.

PART I

GENERAL CLAUSES AND CONDITIONS

1. The equipment furnished under this specification shall be the latest improved model in current production, as offered to commercial trade, and shall be of quality workmanship and material. The respondent represents that all equipment offered under this specification shall be new. USED, SHOPWORN, DEMONSTRATOR, PROTOTYPE, REMANUFACTURED, RECONDITIONED OR DISCONTINUED MODELS ARE NOT ACCEPTABLE.

2. Respondent should submit with the solicitation or have on file with TxDOT, Austin, Texas, the latest printed literature and detailed specifications on equipment the respondent proposes to furnish. This literature is for informational purposes only.

3. All parts not specifically mentioned which are necessary for the unit to be complete and ready for operation or which are normally furnished as standard equipment shall be furnished by the vendor. All parts shall conform in strength, quality and workmanship to the accepted standard of the industry.

4. The unit provided shall meet or exceed all federal and state of Texas safety, health, lighting and noise regulations and standards in effect and applicable to equipment furnished at the time of manufacture.

5. It is the intent of TxDOT to purchase goods, equipment and services having the least adverse environmental impact, within the constraints of statutory purchasing requirements, TxDOT need, availability, and sound economical considerations. Suggested changes and environmental enhancements for possible inclusion in future revisions of this specification are encouraged.

* This Specification Supersedes Specification No. TxDOT 801-60-66, Revised ~~July 2003~~ June 2010.

6. TxDOT encourages all manufacturers to comply voluntarily with the Society of Automotive Engineers (SAE) Recommended Practice for marking of plastic parts per current SAE J1344 standard. All plastic components furnished to this specification should have an imprinted SAE symbol identifying the resin composition of the component so that the item can be recycled after its useful life. Manufacturers are encouraged to use recycled plastics and materials in the manufacture of their products in order to conserve natural resources, energy and landfill space. Respondents should note that future specification revisions may require mandatory compliance with the SAE plastic coding system.

7. TxDOT is committed to procuring quality goods and equipment. TxDOT encourages manufacturers to adopt the International Organization for Standardization (ISO) 9001-9003 standards, technically equivalent to the current American National Standards Institute/American Society for Quality Control (ANSI/ASQC Q91-93), and obtain certification. Adopting and implementing these standards is considered beneficial to the manufacturer, TxDOT, and the environment. It is TxDOT's position that the total quality management concepts contained within these standards can result in reduced production costs, higher quality products, and more efficient use of energy and natural resources.

## PART II

## SPECIFICATIONS

1. SCOPE: This specification describes roll-up traffic signs used with the portable sign stands referenced in TxDOT 801-12-77 (1 foot) and TxDOT 801-12-78 (7 foot) in construction and maintenance zones. The sign material and battens provided shall meet the requirements of the AASHTO Manual for Assessing Safety Hardware (MASH)[see Comment 1].

2. SIGN MATERIAL: Signs shall be made of highly reflective fluorescent orange material with standard black screen legends of manufacturer compatible permanent printed ink. The sign face and legends on the sign shall conform to Federal/Texas Manual on Uniform Traffic Control Devices (MUTCD) and the Standard Highway Sign Designs for Texas.

3. PREQUALIFICATION REQUIREMENTS AND RESTRICTIONS

   3.1. Only products listed by manufacturer and product code listed on the TxDOT Prequalified Products List (QPL) maintained by the General Services Division (GSD) will be considered for purchase in connection with this specification.

   3.2. The GSD QPL is available at http://www.txdot.gov/gsd/purchasing/supps.htm. Vendors wishing to have their product(s) considered for future advertisements should contact TxDOT, GSD Purchasing, at 125 East 11th Street, Austin, Texas 78701-2483.

4. SIGN FACE CHARACTERISTICS: The reflective sheeting and other materials used to produce the face of flexible roll-up reflective signs shall meet the following requirements:

   4.1. FLEXIBILITY: There shall be no signs of cracking or crazing when flexed repeatedly over a 1/16 inch mandrel to 180-degrees at 77°F.

   4.2. CHEMICAL RESISTANCE: The surface of the sheeting or the face of a completed sign shall be chemical resistant to the extent that there will be no surface change when wiped with a soft, clean cloth dampened with VM & P naphtha, mineral spirits, turpentine, mild soaps, or mild detergents.

   4.3. GLOSS: The sheeting's face and screened areas shall have an 85-degree gloss meter rating of not less than 35 when tested in accordance with ASTM D523.

4.4. DIFFUSE DAY COLOR

4.4.1. The Committee for International Color (CIE) chromaticity coordinates of reflective sheeting shall fall within the areas having the corner points and reflectance requirements for the various colors as shown in the following table before and after weatherometer (sunshine type) exposure, as described in the durability section of this specification.

| **Chromaticity Coordinates** | | | |
|---|---|---|---|
| **Color** | **Chromaticity** | | **Reflectance** |
| | **x** | **y** | **Y** |
| White | 0.310 | 0.300 | |
| | 0.290 | 0.320 | |
| | 0.360 | 0.360 | 40 Minimum |
| | 0.340 | 0.380 | |
| Orange | 0.530 | 0.360 | |
| | 0.530 | 0.400 | |
| | 0.590 | 0.410 | 12 – 30 |
| | 0.640 | 0.360 | |

4.4.2. Color shall be determined in accordance with Test Method “Tex-839-B, Determining Color in Reflective Materials”.

4.5. REFLECTED NIGHT COLOR: The reflected night color shall appear to be essentially the same as the day color when observed at 50-feet.

4.6. DURABILITY: Sheeting or sign faces shall show no cracking, crazing, blistering, chalking, or dimensional change after 250-hours exposure in a weatherometer utilizing an 18-102 cam, in accordance with ASTM G 23, Method I, Type EH.

4.7. MILDEW RESISTANCE: The sheeting shall evidence no fungus growth when tested by Federal Test Method 6271.1, “Mildew Resistance”, under the following conditions:

4.7.1. Test specimens shall be leached with water before inoculation.

4.7.2. The test organism shall be pullularia pullulans.

4.7.3. The length of the incubation period shall be 21-days.

4.8. SPECIFIC INTENSITY

4.8.1. Reflective sheeting shall have the minimum brightness values, before exposure, as shown in the following tables:

4.8.2. Brightness values shall be determined at the divergence and entrance angles shown and shall be expressed in units of candlepower per foot-candle per square foot.

| **Specific Intensity Minimum Brightness Values** | | | | |
|---|---|---|---|---|
| **Brightness Values** | | | | |
| **Color** | **Divergence** | **Angle of Incidence Specific Intensity cp/ftc/ft$^2$** | | |
| | **Angle** | **2°** | **10°** | **20°** |
| White | 0.2° | 75 | 50 | 25 |
| | .33° | 60 | 35 | 12 |
| Orange | 0.2° | 18 | 14 | 6 |
| | .33° | 12 | 8 | 4 |

4.8.3. Specific intensity will be determined in accordance with Test Method “Tex-842-B, Measuring Retroreflectivity”.

4.8.4. The reflective sheeting shall retain a minimum of 50% of the specific intensity values after the weatherometer exposure as described in durability section Paragraph 4.6 of this specification.

4.8.5. No process ink used to produce message(s) on the sign face shall be removed when tested according to Federal Test Method 6301, “Adhesion (Wet) Tape Test”, after a minimum of 96-hours after processing, or after exposure in the weatherometer.

5. SIGN BATTENS

5.1. Battens for the signs shall consist of two battens, one vertical and one horizontal. Each shall be made of polished ~~fiberglass~~ fiber reinforced polymer composite (FRP) materials [see Comment 2] with no exposed fibers and shall meet the following dimensions [all dimensions ± 0.05 inch]:

5.1.1. Length: 64.5 inches to 66.5 inches

5.1.2. Width: 1.25 inches

5.1.3. Thickness: .312 inch to .330 inch vertical and .187 inch horizontal

5.2. Cut ends of the battens shall have .125 inch x .125 inch 45-degree chamfer. Battens shall be either bolted together at the center with a bolt, three washers, and a self-locking nut or riveted together with stainless steel or aluminum rivets. Horizontal batten rotates to the left and right corners.

5.3. The vertical battens provided shall have fibers in at least two directions, i.e., in the longitudinal direction (0 degree) and in transverse direction (90 degree) [see Comment 3].

5.4. The flexural resistance of vertical battens in the longitudinal direction as determined in accordance with ASTM D790-10, shall not be less than 2,000 lb-in [see Comment 4].

5.5. The torsion resistance of vertical battens in the transverse direction, as determined in accordance with the test procedure provided in Appendix of this specification, shall not be less than 2,000 lb-in [see Comment 5].

5.6. The vertical battens should have a hole with a diameter of .5 in. at the bottom of the sign face if through-bolt connection is used [see Comment 2 of TxDOT 801-12-77].

6. SIGN FACE: The back of each sign face shall have four (one in each corner) translucent molded corner pockets of Lexan or Polyurethane riveted in two places to the sign with stainless steel, aluminum, or steel zinc plated rivets. If slide and lock pockets will be used then the sign face shall have one translucent molded corner pocket of Lexan or Polyurethane riveted in two places to the sign with stainless steel, aluminum, or steel zinc plated rivets at the bottom of the sign face for universal pocket type mounting and two (one on each side) slide and lock pockets. There shall be no sharp edges to damage the sign face. Front side of the sign face shall have a flat piece of the same dimensions as the batten corner pocket and made of the same material. Corner pocket outside dimensions shall be as follows [all dimensions ± 0.05 inch]:

6.1. BATTEN CORNER POCKET (INCLUDING ADJACENT PLATE IF PROVIDED)

6.1.1. Length: 2.5 inches to 4 inches

6.1.2. Width: 1.5 inches to 2.5 inches

6.1.3. Depth: .56 inch to .63 inch

6.1.4. Wall Thickness: .1 inch

6.2. FRONT CORNER POCKET PLATE

6.2.1. Length: 2.5 inches to 3.6 inches

6.2.2. Width: 1.5 inches

6.2.3. Thickness: .1 inch

6.3. The corner pocket shall have a minimum of one each .75 inch diameter hole, to accommodate a sign stand-latching device.

6.4. Signs shall have anti-kiting strap mounted 2 inches to 8 inches above the center point of the sign. If sign face is riveted to sign battens, then anti-kiting strap not required.

6.5. The corner pocket at the bottom of sign face shall be design to accommodate a thought-bolt if through-bolt connection is used [see Comment 2 of TxDOT

7. WARNING FLAGS: Signs shall have minimum two each 18 inch square orange flags mechanically fastened to polished fiberglass flagstaffs. Flagstaffs shall be minimum 26 inches long by minimum 5/8 inch wide by minimum 11/64 inch thick [± 0.05 inch]. The flagstaffs shall be attached to the vertical batten immediately below the pocket or rivet on the top of the vertical batten. The flags and staffs shall roll up for storage in the sign without disassembling.

8. OVERLAYS: All signs with the message “Ahead” or “Right“ or any other signs which could have a similar message shall be set with snaps to accommodate overlay display and storage.

8.1. Snaps shall be black anodized brass meeting Military Specification Standard No. 27980. The stud portion of the snap shall be used on the sign and the socket portion shall be used on the overlays. Four studs shall be centered around the overlayable word for display (sign face) and four studs for storage (back of sign) per the overlayable word for a minimum of eight studs per sign. Overlays shall have eight sockets per double-sided overlay, one per corner per side. Snaps shall be .75 inch from corner of the edges of the overlay.

8.2. DIMENSIONS OF OVERLAYS

| SIGN LEGEND | OVERLAY WORD | DIMENSION OF OVERLAY |
|---|---|---|
| Any Legend with “AHEAD” | 500 / 1,000 / 1,500 / 1/2 MILE / 1 MILE | 8 inch by 30 inch |
| “RIGHT” LANE CLOSED AHEAD | LEFT / CENTER | 8 inch by 22 inch |
| “RIGHT” LANE CLOSED | LEFT / CENTER | 9 inch by 28 inch |

9. STORAGE AND PACKAGING OF SIGNS: Signs shall be equipped with a Velcro strap attached to the back of the sign face for storing or packing sign in rolled up position. Signs shall also be packaged in an appropriate size box (one per box), clearly labeled with sign legend and purchase order number.

10. WARRANTY: The signs and material shall be warranted against defective materials, workmanship, and failures for 24-months from the date of acceptance. If the manufacturer's standard warranty period is in excess of 24-months, the standard warranty period shall apply.

11. ACCEPTANCE INSPECTION: The signs will be subject to acceptance inspection upon receipt. Acceptance inspection will not take more than five working days, weather permitting. The vendor will be notified within this time frame of any signs not delivered in full compliance with the purchase order specifications. If any signs are canceled for non-acceptance, the needed signs may be purchased elsewhere and the vendor may be charged any additional increase in cost and handling.

**Comment 1**

The crashworthiness performance of portable roll-up sign assemblies is dependent not only on the design and the material characteristics of the sign stands used in the assemblies, but also on the overall impact behavior of the assemblies. Therefore, it is required that a portable roll-up sign assembly be crash tested to determine whether or not the assembly passes the MASH requirements.

**Comment 2**

The fiberglass is the only material currently adopted in the market products listed on the TxDOT Prequalified Products List (QPL) maintained by the General Services Division (GSD battens. However, other types of fibers, such as carbon and aramid, can be used to improve the performance of battens. Therefore, it is necessary to replace "fiberglass" with "fiber reinforced polymer (FRP) composite materials". It should be noted that the use of FRP composite materials including fiberglass for fabricating battens has many advantages over the use of metallic materials such as steel and aluminum. One of the advantages of FRP composite materials is the ability to produce it with the layers of fibers oriented at various angles, therefore, it is easy to improve the performance of battens while meeting the stand dimensions specified in the current specifications. In addition, the change in weight is negligible even if different types of fibers are used. As a result, it is more likely to pass the crashworthiness tests, regardless of the composite designs (i.e., selection of the fiber types for each part in a batten and the orientations of different fiber layers).

**Comment 3**

The fiberglass battens currently adopted by TxDOT have glass fibers in one direction (i.e., 0 degree with respect to the longitudinal direction). According to the test results obtained in this project, the failure of vertical battens under wind loading is due to the progressive cracking of resin between the fibers in the longitudinal direction. Therefore, fibers must be used in the transverse direction of the battens (90 degree with respect to the longitudinal direction) to avoid the cracking.

**Comment 4**

The test results of this project showed that the vertical battens of the test signs, made of fiberglass, did not fail in bending and the fiberglass battens showed minimum flexural resistance of 2,000 lb-in. Therefore, it is suggested that the minimum flexural resistance of vertical batten be 2,000 lb-in.. Detailed information about the material characterization tests of fiberglass battens is available in Tech Memo 2.

**Comment 5**

The suggested torsional resistance is based on the observed performance of the vertical batten with the transverse direction properties being improved by carbon fibers. The torsional resistance of fiberglass battens without carbon fibers in the transverse direction was approximately 400 to 500 lb-in at the first cracking and 500 to 650 lb-in. at ultimate. On the other hand, the vertical battens with carbon fiber in the transverse direction showed a similar torsional resistance at the first cracking, but the torsional resistance at ultimate was approximately 2,200 lb-in. to 2,900 lb-in. Furthermore, the maximum torsional load observed in the tests was around 2,000 lb-in from the field measurement and the vehicle-induce wind tests. For more information, please refer to the final report of TxDOT Project 0-6639.

# APPENDIX IV

# TEST METHOD TO DETERMINE TORSIONAL RESISTANCE OF FRAME MEMERS

**Test Method to Determine the Torsional Resistance of Frame Members to Support Flexible Sign Surfaces of Portable Roll-Up Signs**

## 1. Scope and Limits

1.1. This test method covers the determination of the torsional resistance of fiber-reinforced plastic (FRP) materials that can be accepted by the current TxDOT Specification No. 801-60-66 - *Sign Face, Roll-Up, Reflective, Construction and Work Zone*.
1.2. The test apparatus specified in this document was a prototype developed under TxDOT Research Project No. 0-6639; and thus a modification can be made as necessary.
1.3. This test method does not address all of the safety concerns, if any, associated with its use. It is the responsibility of the user to determine proper safety measures prior to use.

## 2. Apparatus

2.1. A loading machine capable of being operated with deformation control is required.
2.2. A load cell that can measure tension force up to 3 kips is required.
2.3. A schematic representation of the test set-up required to determine torsional resistance is shown in Figure 1.
2.4. The test set-up should be able to hold a test specimen at the both ends with one end being fixed and the other end being free of rotation.
2.5. A Prototype test set-up, realizing the schematic concept presented in Figure 1, is presented in Figures 2 and 3.

## 3. Sampling and Test Specimen

3.1. Test at least five specimens per test condition unless valid results can be gained through the use of fewer specimens.
3.2. The test specimen size should conform to the size of vertical frames that can be accepted by TxDOT 801-60-66: the width should be 1.25 in. and the thickness should be 0.312 in. to 0.330 in.
3.3. The length of the test specimen should be equal to or slightly longer than 8 in.

## 4. Loading

4.1. The loading should be applied using deformation control to avoid a sudden drop of the applied load due to initial cracking.
4.2. Loading Rate: Following ASTM D790-10 *Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*, determine the rate of crosshead motion as

$$R = ZL^2 / 6d \qquad \text{Eq. (1)}$$

where, $R$ = rate of crosshead motion, in./min, $L$ = support span, $Z$ = rate of straining of the outer fiber, in./in./min, shall be equal to 0.01, and $d$ = thickness of specimen.

## 5. Calculation and Report

5.1. The following information should be reported.

5.1.1. Width, thickness, and length of test specimen with the accuracy of 0.001 in.

5.1.2. Torsional resistance

5.2. Torsional resistance is defined as the maximum torque measured at the time of failure of test specimen, and torque at any stage of the loading can be determined as

$$T = P \cdot X \quad \text{Eq. (2)}$$

where, $T$ = torsional resistance, $P$ = tension force in the steel cable (see Figure 1), $X$ = distance from the center of test specimen to the center of steel cable (see Figure 1)

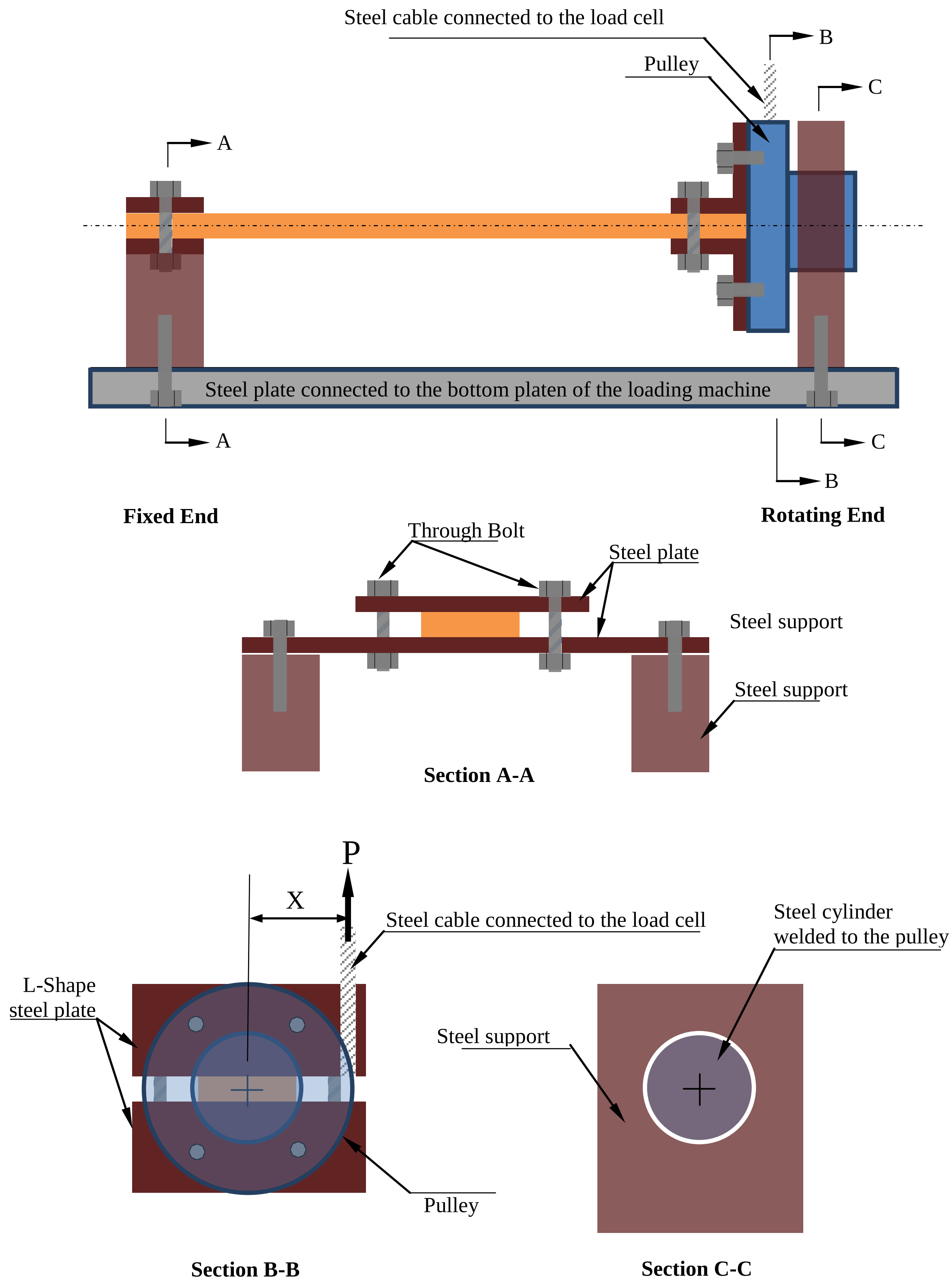



Figure 1. Schematic of Test Set-Up

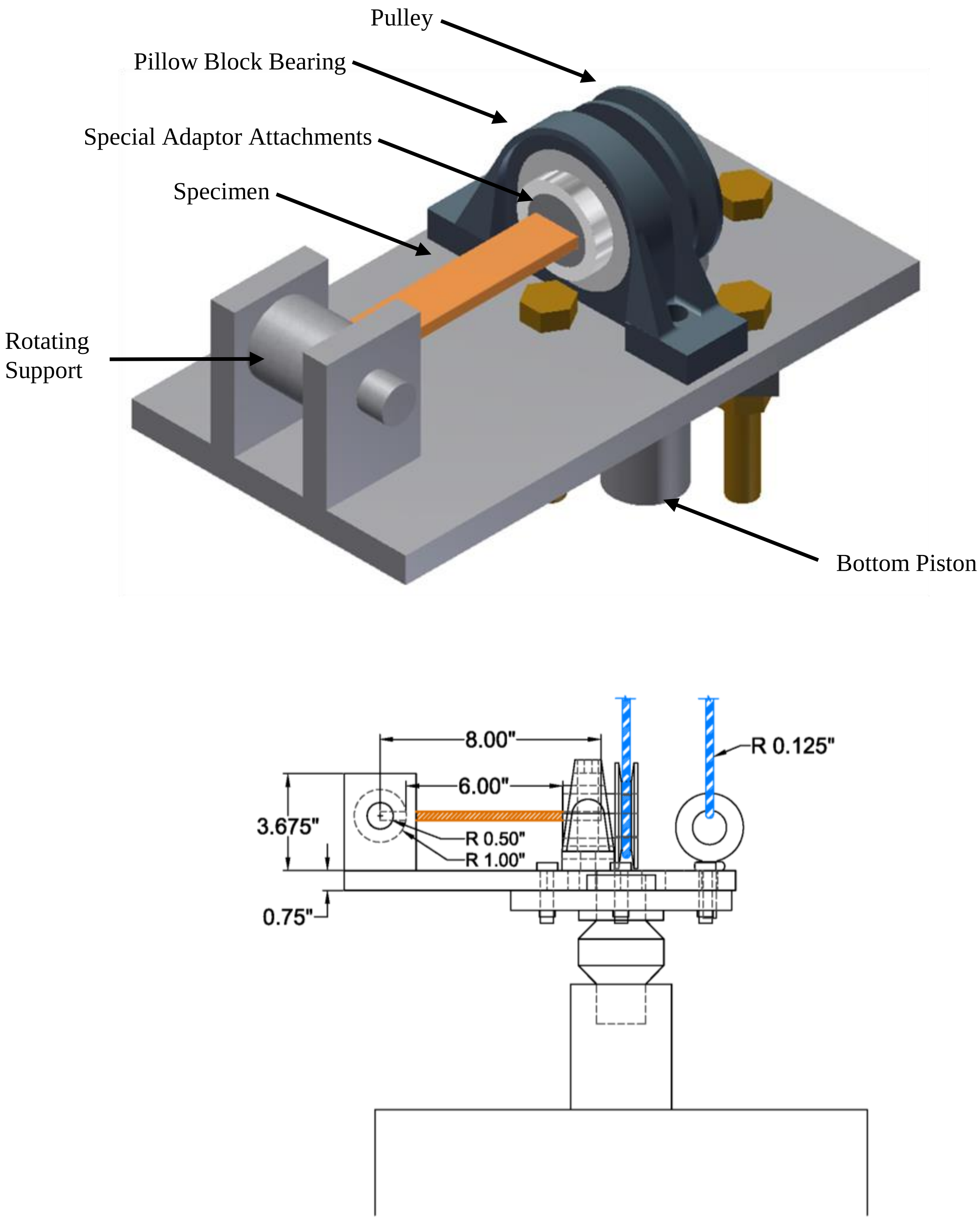



Figure 2. Test Set-Up Developed at Texas Tech University

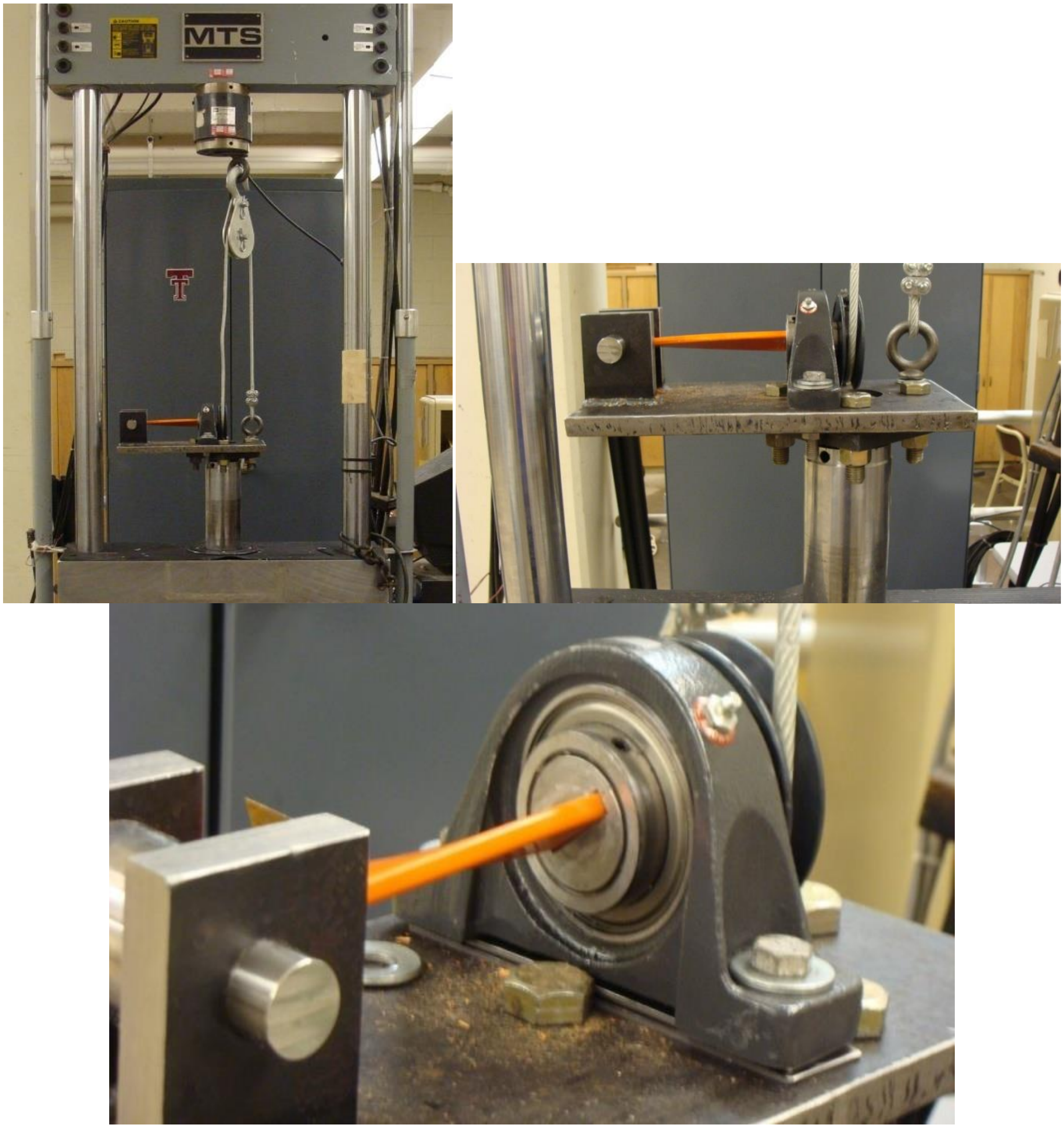



Figure 3. Test Set-Up Developed at Texas Tech University

TEXAS TECH UNIVERSITY
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