Punching Shear Analysis Caused by Wind Loads on Small Traffic Signs

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Abstract — *Small traffic signs are the most typical type of traffic signs encountered throughout the streets and roads. Since Puerto Rico is located in a hurricane prone region, is reasonable to ask if these traffic signs could withstand the design wind loads established by the current codes and if the existing different types of plate-to-post connections are safe. To accomplish the investigation, laboratory experiments were conducted to verify the resistance to punching shear on sign plates. Results were compared to design calculations obtained from codes. It was observed that the different types of connections evaluated have the required strength to withstand design wind loads.*

Key Terms — *Punching, Shear, Traffic Sign, Wind Loads.*

INTRODUCTION

Daily, thousands of commuters that travel through the streets and roads of Puerto Rico are encountered with different types of signs; most of them are traffic signs ranging from a small red stop sign to a large green guide sign at the highway. These traffic signs have multiple functions like: notify transit regulations to road users, warn about road conditions and offer orientation so that commuters obtain directions to their destinies. The primary function of traffic signs is to provide to the commuters an organized and safe way to travel.

The responsibility for the design, placement, operation, maintenance, and uniformity of traffic control devices rests with the public agency or the official having jurisdiction, or, in the case of private roads open to public travel, with the private owner or private official having jurisdiction [1]. Traffic signs should be designed, placed properly and supported with bolted connections and foundations that withstand weathering and different climate conditions. Traffic signs have a plate connected with bolts to a single post, making them vulnerable and flexible structures. These supports shall withstand wind forces as specified on the AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaries, and Traffic Signals. The Puerto Rico Highway and Transportation Authority (PRHTA) and the Department of Transportation and Public Works design standards were reviewed in this study.

Research Objectives

This article focuses on the small traffic signs plate connections and assess the effectiveness of those connections under design wind loads. Laboratory experiments were conducted to verify the resistance to punching shear of the plate. Different bolted connections were used to identify which one is complying with the current design codes and provides the more cost-effective solution. The objectives of this project are:

- Verify that the existing small traffic signs connections that have different types of bolts, washers and nuts would be safe and wind-load resistance as established by design codes.
- Perform a punching shear analysis on the plate considering the plate material, mechanical properties, the difference between the bolt geometric characteristics and the wind design load that bolts should carry.

BACKGROUND

Small traffic signs are distinguished from guide signs because they have a smaller surface area. This research focuses on small traffic signs with a surface area smaller than 10.8 square feet and a plate thickness of 1/16". For small traffic signs over 10.8 square feet, the plate thickness is 1/8" [2]. Small traffic signs are most frequently encountered at the right-side of the roadway. The most common small traffic sign type configuration consists of a single post roadside plate sign. Some of these signs are used for different functions:

- Regulation – stop, yield, speed, do not enter, only, etc.
- Warning – lane reduction, divided highway, road narrow, etc.
- Route markers – highway number, cardinal points, arrows, etc.

The design and installation of small traffic signs in Puerto Rico are governed by the PRHTA and the Department of Transportation and Public Works design standards. These standards make reference to the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) publications. Most of these small traffic signs configurations consist of a plate attached with two connections (bolt, washer and nut) to a steel flange channel post. Figures 1 and 2 show the described configuration.

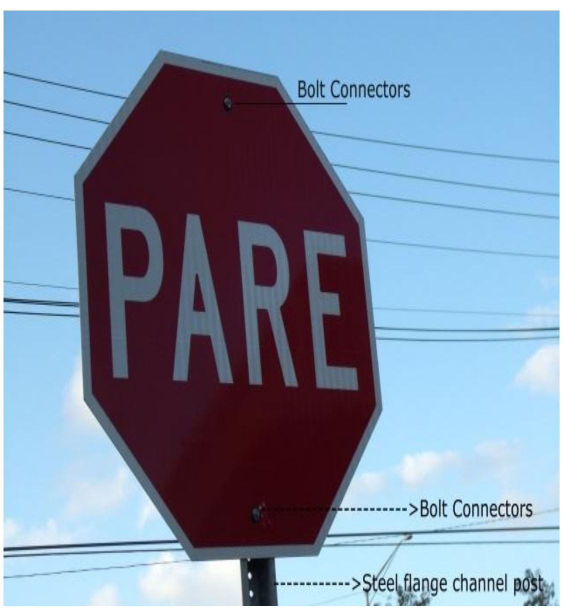


Figure 1
Small Traffic Sign

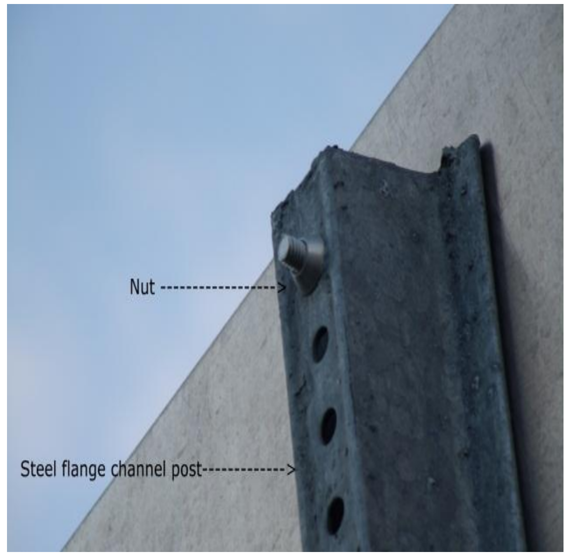
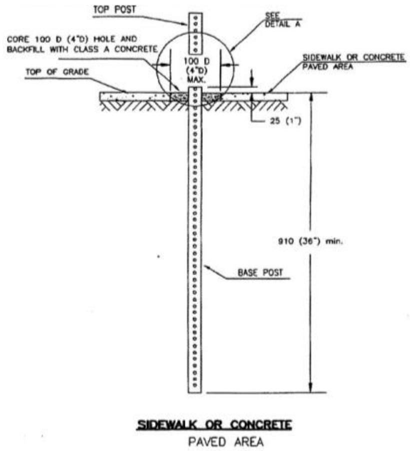


Figure 2
Nut and Steel Flange Post

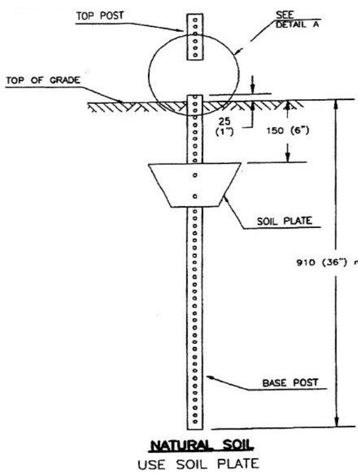
Signs installed at the side of the road in rural districts are supposed to be at least 5 ft measured from the bottom of the sign to the near edge of the pavement. Where parking or pedestrian movements occur, the clearance to the bottom of the sign shall be at least 7 ft [1]. The steel flange channel post must meet the requirements of ASTM A499, grade 60. The steel post is basically supported by three types of foundations for the different encountered ground conditions, such a sidewalk, natural soil and rock condition (as shown in Figure 3).

Traffic Sign Materials

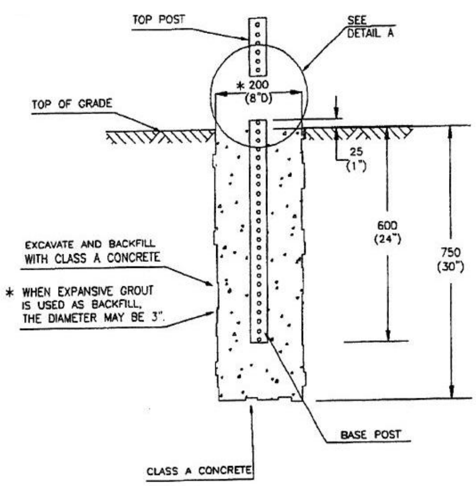
The plate material used for small traffic signs consists of aluminum sheet that meets the ASTM alloys, B-209, 6061-T6, 5052-H36, 5052-H38, 5086-H34, 5153-H36, covered by high intensity reflective sheeting, consisting of spherical lens diamonds adhered to a synthetic resin and encapsulated by a flexible, transparent weatherproof plastic coat. The bolts used to attach the plate to the post are made of aluminum conforming the A307 requirements. Generally they have a length between 1.45 and 1.55 inches and a diameter of 5/16". A neoprene or fiber washer is used between the sheeting sign face and the bolt head. Figure 4 show the different types of bolts, washers and nuts recommended by the PRHTA.



(a)

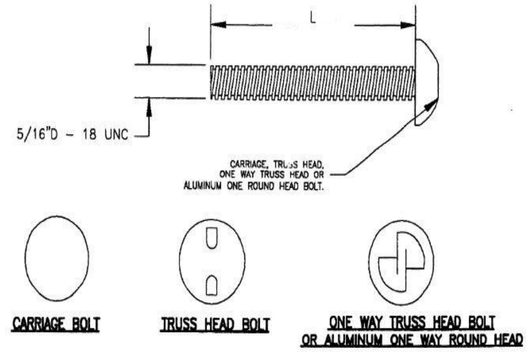


(b)

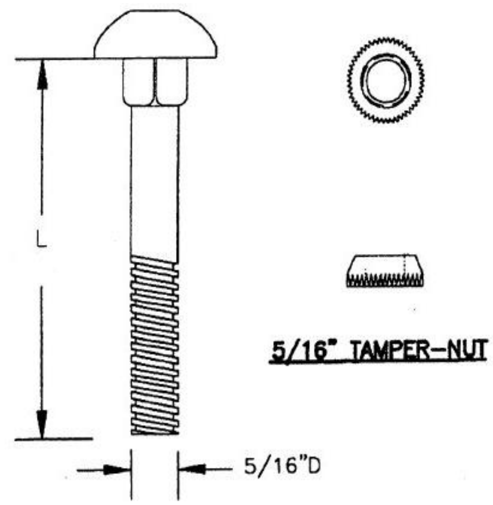


(c)

Figure 3
Roadside Sign Post Foundations:
(a) Sidewalk or Concrete; (b) Natural Soil;
(c) Rock Condition. [2]



(a)



(b)

Figure 4
Required Bolts and Nuts: (a) Different Security Bolt Types;
(b) Typical Bolt and Nut Configuration. [2]

The PRHTA Standard Drawings indicate that the bolt used for small traffic sign connection shall be the security bolt [2]. A security bolt connection provides protection against vandalism. The Department of Transportation and Public Works uses the hexagonal bolt with plastic washer. Otherwise, considering the whole structure (sign and post), most of the small traffic signs failures due to wind loads occur at the foundations [3].

The sign plate and steel post as a combination forms a very flexible structure that must be designed using the wind design criteria stated on the AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaries, and Traffic Signals. Equation (1) based in the fundamental fluid-flow theory is used in order to calculate the wind pressure at the surface of plate [4]:

$$p_z = 0.00256 K_z G V^2 I_r C_d \quad \text{(psf)} \qquad (1)$$

where;

K_z = Height and exposure factor,1

G = Gust Effect Factor, 1.4

V = Basic Wind Speed, 125 mph.

I_r = Importance Factor, 1.00

C_d = Drag Coefficient, 1.12

The values specified above are based in the AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaries, and Traffic Signals, Chapter 3. The basic wind speed for Puerto Rico is 125 mph as stated on the wind speed map based on 3 second gusts [4]. Equation (1) is used to calculate the design wind pressure for a small traffic sign surface and a value of approximately 48.9 psf is obtained.

The design procedure established on the ASCE-7-05, section 6.5.14, Design Wind Loads on Solid Freestanding Walls and Solid Signs uses a basic wind speed of 145 mph [5]. ASCE-7-05, section 6.5.10 specifies the following formula (2) to calculate the velocity pressure:

$$q_z = 0.00256 K_z K_{zt} K_d V^2 I \ (psf) \qquad (2)$$

where:

K_z = velocity pressure exposure coefficient evaluated at height z, 1

K_{zt} = topographic factor, 0.85

K_d = Wind directionality factor, 1

V = Basic wind speed, 145 mph.

I = Importance factor, 0.77

A value of approximately 35.2 psf is obtained from (2).

ASCE-07-05 section 6.5.14 establishes the following formula (3) to find the wind force in a solid sign:

$$F = q_h G C_f A_s \quad \text{(lb)} \qquad (3)$$

where;

q_h = wind pressure obtained in (2), 35.2 psf.

G = Gust Effect Factor, 1.4

C_f = Force Coefficient, 1.8

A_s = the gross area of free standing wall or solid sign, ft^2.

Performing an algebraic manipulation on (3) by the dividing the wind force F by the gross area A_s, then the following formula (4) is obtained:

$$P = q_h G C_f \quad \text{(psf)} \qquad (4)$$

Using (4), a wind pressure value of about 72.3 psf is obtained.

Comparing the wind pressure obtained with the AASHTO Specifications and with the one determined with ASCE-7-05 there is a difference of over 23.4 psf. The main reason for this difference is the basic wind speed used for each formula. By switching the basic wind speeds among the presented design procedures and calculating the wind pressure, closer values are obtained with a percentage of difference of 9.3%, as shown in Table 1.

Table 1
Velocity Pressure Comparison between the ASCE-07-05 and the AASTHO Specifications 2005.

***	ASCE-7-05	AASHTO 2009	%diff.
Velocity (mph)	Wind Pressure (p.s.f.)	Wind Pressure (p.s.f.)	
125	53.7	48.9	9.3
145	72.3	65.8	9.3

Although the scope of this research investigates the punching shear on sign plate caused by wind load normal to the plate surface, is worth to mention that conducted wind load studies show that the most critical load condition is not always in the normal direction to the plate surface. The sign shape and the angle of the applied wind load at the sign plate influence how the reactions at sing support might behave. The combination from the normal force and the twisting moment provides a critical load condition on the plate [6]. Also, there are other effects not covered by this investigation like fatigue, vortex shedding, wind-induced vibration or other advanced aerodynamic effects.

Puerto Rico is located in a hurricane prone region. It is distinctly possible for many traffic signs to fail under wind loads in the case of a hurricane. Yet, in a visit made to the Department of Transportation and Public Works it was found that the agency does not keep a statistical record of the quantity of damaged small traffic signs during a hurricane event.

A site visit to randomly selected municipalities from the metropolitan area was carried out to gather information about the condition of the existing small traffic signs. Pictures of 136 signs were randomly taken, distributed into 68 from the San Juan and Bayamón Municipal jurisdictions and 68 from the State jurisdiction. It was observed that different types of bolt connections, washers and nuts are commonly used; they were classified into three major types of bolt connection and three major types of washers. The encountered bolt cases are:

- Hexagonal – bolt that has a hexagonal head.
- Security – carriage bolt head.
- None – when the sign does not have a bolt in one of its connections.

The encountered washer cases are:

- Plastic – neoprene plastic washer.
- Metal – metal washer.
- None - when the sign does not have a washer.

Table 2 summarized the gathered data and Table 3 shows the statistics summary, both from the visit.

From the obtained data it could be observed that small traffic signs from the Sate jurisdiction have more secure connections than the signs from the Municipal jurisdiction. Also there were about 3 % of connections that did not have bolts from both jurisdictions. The 39.3% and 66.7% of State and Municipal connections did not have washers, respectively. The average connection per sign is 2 bolts; this demonstrates that the vast majority of small traffic signs are of the single post roadside plate sign configuration.

Table 2
Data Summary

DATA SUMMARY								
SIGN JURISDICTION	QTY.	BOLT TYPE			WASHER			CONNECTIONS
		HEXAGONAL	SECURITY	NONE	PLASTIC	METAL	NONE	
STATE	68	34	111	5	88	1	59	150
MUNICIPAL	68	66	73	5	37	11	96	144

Table 3
Statistics Summary

STATISTICS SUMMARY								
SIGN JURISDICTION	QTY.	BOLT TYPE			WASHER			AVERAGE CONNECTIONS PER SIGN
		HEXAGONAL	SECURITY	NONE	PLASTIC	METAL	NONE	
STATE	68	22.7%	74.0%	3.3%	58.7%	0.7%	39.3%	2.2
MUNICIPAL	68	45.8%	50.7%	3.5%	25.7%	7.6%	66.7%	2.1

METHODOLOGY

The punching shear calculation was determined for two types of bolts: hexagonal and security bolt (also known as carriage bolt). Signs with 1/16” thickness and made of aluminum plate 5052-H36 with shear strength of 23,000 psi were used.

Equation (5) is used to calculate the punching shear stress:

$$\tau = P/A_p \quad (5)$$

where;

τ = punching shear stress, 23,000 psi.

P = Punching force, lb.

A_p= Plate area from the perimeter that surround the bolt interface, ft^2.

An algebraic manipulation is performed to solve for the punching force as shown in (6):

$$P = \tau\, A_p \quad (6)$$

Table 4 shows the required Punching Force obtained from Punching Shear Analysis.

Table 4
Punching Shear Force

Bolt Type	Punching Force (lb.)
Security	3,022.54
Hexagonal	2,353.20

A design wind load of 48.9 psf obtained from (1) was used to perform a structural static analysis on the sign plate to determine the wind force reaction per sign connection. Punching shear stress on the plate was calculated using (5) for two types of bolts: hexagonal and security type. Each item from the Table 5 corresponds to the gathered data from the existing signs. The information was arranged by sign geometry and dimensions.

Is evident that a bolt with bigger head carries less punching shear to the plate, therefore the security bolt develops less shear stress into plate. The data from Table 4 states that security bolts transfer 28.4% more resistance to the plate than the hexagonal bolts. To verify these calculations, laboratory tests were conducted using full scale traffic signs and bolts donated by the Department of Transportation and Public Works.

The laboratory tests consisted of 12 punching resistance tests. These tests were divided into four different cases that represent the different configurations of small traffic sign connections founded in the site visit. These cases were:

- Hexagonal bolt without washer.
- Hexagonal bolt with plastic washer.
- Hexagonal bolt with metal washer.
- Security bolt without washer.

Each case was evaluated with 3 specimens, applying direct force over the bolt's head using the Magnus HI-TECH Test Frame, therefore producing a punching shear failure to the plate.

The bolts used were A325 as specified by the PRHTA and the Department of Transportation. Figure 5 shows the bolts and washers used for the laboratory test. In this figure, presented from left to right are the security bolt, the hexagonal bolt with metal washer, the hexagonal bolt with plastic washer and the hexagonal bolt without washer.

Table 5
Static Analysis and Shear Stress on Plate

STATIC ANALYSIS ON SIGN PLATE

ITEM	SIGN GEOMETRY	WIDTH (IN.)	HEIGHT (IN.)	AREA (S.F.)	WIND PRESSURE (P.S.F.)	NO. OF BOLTS CONN.	WIND FORCE* (LB.)	FORCE PER BOLT CONN.
1	SQUARE	12	12	1.00	48.9	2	48.9	24.5
2	RECTANGLE	12	18	1.50	48.9	2	73.4	36.7
3	RECTANGLE	12	24	2.00	48.9	2	97.8	48.9
4	RECTANGLE	12	30	2.50	48.9	2	122.3	61.1
5	RECTANGLE	12	36	3.00	48.9	2	146.7	73.4
6	RECTANGLE	15	21	2.19	48.9	2	107.0	53.5
7	RECTANGLE	18	18	2.25	48.9	2	110.0	55.0
8	RECTANGLE	18	36	4.50	48.9	4	220.1	55.0
9	RECTANGLE	24	24	4.00	48.9	2	195.6	97.8
10	RECTANGLE	24	30	5.00	48.9	2	244.5	122.3
11	RECTANGLE	24	48	8.00	48.9	2	391.2	195.6
12	OCTAGONAL	30	30	5.19	48.9	2	253.7	126.8
13	SQUARE	30	30	6.25	48.9	2	305.6	152.8
14	POLYGONAL	30	30	4.69	48.9	2	229.2	114.6
15	SQUARE	36	36	9.00	48.9	2	440.1	220.1
16	SQUARE	36	36	9.00	48.9	4	440.1	110.0
17	RECTANGLE	30	48	10.00	48.9	4	489.0	122.3

PUNCHING SHEAR STREESS ON PLATE

ITEM	HEXAG			SECURITY		
	CONTACT AREA (S.I.)	PERIMETER (IN.)	SHEAR STRESS PLATE (P.S.I.)	CONTACT AREA (S.I.)	PERIMETER (IN.)	SHEAR STRESS PLATE (P.S.I.)
1	0.1166	1.6370	238.97	0.2646	2.1026	186.06
2	0.1166	1.6370	358.46	0.2646	2.1026	279.08
3	0.1166	1.6370	477.95	0.2646	2.1026	372.11
4	0.1166	1.6370	597.43	0.2646	2.1026	465.14
5	0.1166	1.6370	716.92	0.2646	2.1026	558.17
6	0.1166	1.6370	522.76	0.2646	2.1026	407.00
7	0.1166	1.6370	537.69	0.2646	2.1026	418.62
8	0.1166	1.6370	537.69	0.2646	2.1026	418.62
9	0.1166	1.6370	955.89	0.2646	2.1026	744.22
10	0.1166	1.6370	1,194.87	0.2646	2.1026	930.28
11	0.1166	1.6370	1,911.79	0.2646	2.1026	1,488.44
12	0.1166	1.6370	1,239.68	0.2646	2.1026	965.16
13	0.1166	1.6370	1,493.59	0.2646	2.1026	1,162.85
14	0.1166	1.6370	1,120.19	0.2646	2.1026	872.13
15	0.1166	1.6370	2,150.76	0.2646	2.1026	1,674.50
16	0.1166	1.6370	1,075.38	0.2646	2.1026	837.25
17	0.1166	1.6370	1,194.87	0.2646	2.1026	930.28

NOTES:
PLATE THICKNESS= 0.0625 (IN.)
SHEAR STRENGTH= 23,000 (P.S.I.) ALUMINUM 5052-H36

Figure 5
Bolt and Washers Used in the Laboratory Test

Laboratory Procedure

The laboratory procedure was as follows:

- Place the small traffic sign plate over a steel bearing plate with a designed hole to let the bolt only get in contact with the sign plate with its head and without touching the bearing plate.

- Place the bolt and washer corresponding to each case as described before.
- Set the laboratory machine to start applying load directly to the bolt head.
- Load the bolt until the sign begins to deflect and record the data.
- Continue loading the bolt until the sing plate fails and record the data.

Figure 6 shows the laboratory setting.

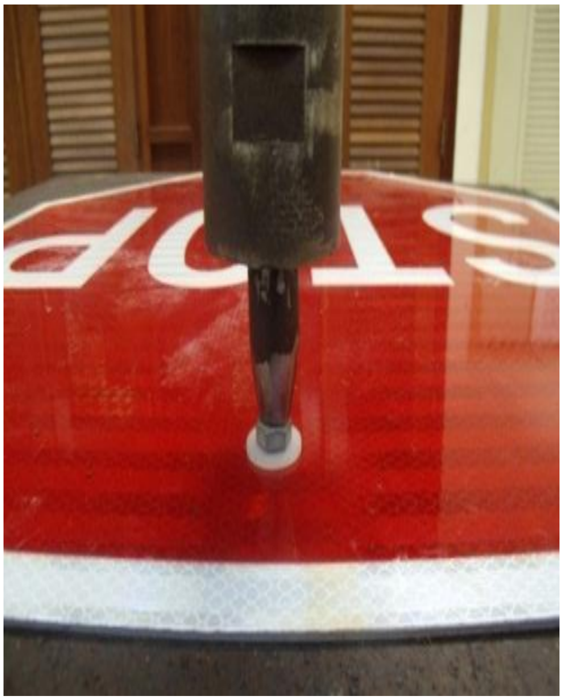


Figure 6
Laboratory Setting

After performing the experiments, the values obtained were used to estimate the wind speed necessary to cause the punching shear failure of the sign plate. Using the experimental values by inserting them into Equation (1) and solving for the basic wind speed, it was determined that a wind speed of over 400 mph would be necessary to cause a punching shear failure onto the sign plate.

RESULTS AND DISCUSSIONS

Results obtained in this study provide information of how safe is the connection (bolt and plate interaction) of small traffic signs. Table 6 shows the results obtained from the laboratory test.

Table 6
Laboratory Test Results

TEST 1: HEXAGONAL BOLT ONLY

SPECIMEN: 1		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
8	1,798.47	WASHER DEFLECTED
9	2,023.28	PLATE RUPTURE
SPECIMEN: 2		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
9	2,023.28	WASHER DEFLECTED
9.8	2,203.13	PLATE RUPTURE
SPECIMEN: 3		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
6	1,348.85	WASHER DEFLECTED
9	2,023.28	PLATE RUPTURE

TEST 2: HEXAGONAL BOLT WITH PLASTIC WASHER

SPECIMEN: 4		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
8	1,798.47	PLATE DEFLECTED
10	2,248.09	PLATE RUPTURE
SPECIMEN: 5		
FORCE (kN.)	FORCE (KIP.)	OBSERVATION
8	1,798.47	PLATE DEFLECTED
10	2,248.09	PLATE RUPTURE
SPECIMEN: 6		
FORCE (kN.)	FORCE (KIP.)	OBSERVATION
7.8	1,753.51	PLATE DEFLECTED
10	2,248.09	PLATE RUPTURE

TEST 3: HEXAGONAL BOLT WITH METAL WASHER

SPECIMEN: 7		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
14.2	3,192.29	WASHER RUPTURE
16	3,596.94	PLATE RUPTURE
SPECIMEN: 8		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
15	3,372.14	WASHER RUPTURE
16	3,596.94	PLATE RUPTURE
SPECIMEN: 9		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
14	3,147.33	WASHER RUPTURE
16	3,596.94	PLATE RUPTURE

TEST 4: SECURITY BOLT ONLY

SPECIMEN: 10		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
16.2	3,641.91	PLATE DEFLECTED
18	4,046.56	PLATE RUPTURE
SPECIMEN: 11		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
17	3,821.75	PLATE DEFLECTED
18	4,046.56	PLATE RUPTURE
SPECIMEN: 12		
FORCE (kN.)	FORCE (lb.)	OBSERVATION
16	3,596.94	PLATE DEFLECTED
17.9	4,024.08	PLATE RUPTURE

Comparing the calculated punching shear loads from the theoretical data with the results obtained from the laboratory test, it can be observed how close both values are. Table 7 shows the percentage of error between the stated values.

Table 7
Comparison of Theoretical Values With Experimental Results

Bolt Type	Calculated Punching Force (lb.)	Laboratory Punching Force (lb.)	% Error
Security	3,022.54	4,046.56	33.9
Hexagonal	2,353.20	2,023.28	14.0

Regarding the theoretical and laboratory values of punching shear force versus the calculated from the static analysis on the sign plate previously presented on Table 5, it can be observed that the force needed to make a small traffic sign reach a punching shear failure is from 10 to 18 times larger than the calculated from the wind design analysis. The calculated maximum wind load value per connection was 220.10 lb. The maximum punching shear load that a sign plate can bear with security bolt of 4,046.56 lb. Regardless the bolted connection used, the sign is safe to withstand wind loads. A brief cost comparison is presented in Table 8.

Table 8
Cost comparison

Case	Cost $	Punching shear resistance* %
Hexagonal only	0.18	100
Hexagonal Plastic Washer	0.39	111
Hexagonal Metal Washer	0.34	160
Security Only	0.16	180
Security with carriage adapter	0.31	NOT TESTED

* Punching Shear resistance values are relative to Hexagonal bolt case.

CONCLUSION AND RECOMMENDATIONS

Even though there are many types of connections encountered in small traffic signs, it was observed that the connections have the required strength to withstand design wind loads. These signs have a resistance to punching shear load from 10 to 18 times larger than the calculated from the wind design analysis, demonstrating how safe these connections are. Also, because the small traffic sign plate surface is less than 4 ft^2, the reaction force in the connection is very low when compared to a wind force in a connection of a guide sign.

This conclusion is based only on the performed static punching shear analysis. There are other types of analysis that might be considered to evaluate the whole structure performance, like dynamic and fatigue resistance. Further analysis is recommended for an evaluation of the dynamic behavior of small traffic sign plates under wind loads. After the performed analysis, the installation of small traffic signs with the different bolt and washers types are recommended because the punching shear resistance is safer than the required by the current code standards. Also, the costs among the different types of bolt and washer cases are not substantially different.

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