CLASSICAL STRESS ANALYSIS OF A FUSE PLATE THAT FAILED DURING HURRICANE MARÍA IN PUERTO RICO[1]

Juan C. Morales[2], Jey N. Sánchez[3], Seira N. De Jesús[4], Jorge A. Caraballo[5]

ABSTRACT: A large number of breakaway-type highway signs toppled over during hurricane María in Puerto Rico. The cause was the unintended rupture of the fuse plates, a key component of the breakaway system. The design of fuse plates is unusual because two opposing constraints must be precisely balanced: 1. they must be weak enough to rupture during collision of an errant vehicle, thus minimizing injuries to passengers and damage to the vehicle, but 2. strong enough to resist wind loads. These uncommon constraints attracted the interest of the authors. The following question guided the research: Could classical stress analysis, in conjunction with established failure theories, predict the failure of an actual fuse plate that fractured during hurricane María? This investigation fills a gap in the literature by examining a more refined classical model of the stresses than previously considered. A wind gust speed of 155 mph at the top of the sign was assumed. The yield and ultimate strengths were obtained experimentally with one tensile specimen machined from a failed fuse plate. The classical stress analysis, in conjunction with the von Mises yield failure criterion, accurately predicted yielding of the fuse plate; however, higher wind speeds would have been required to reach fracture. It was concluded that the simplified model available in the literature is adequate to predict yielding. Its error was less than 1% when compared to the more refined model developed in this study.

Keywords: failure theory, fuse plate, hurricane, breakaway sign, stress analysis

ANÁLISIS CLÁSICO DE ESFUERZOS DE UNA PLACA FUSIBLE QUE FALLÓ DURANTE EL HURACÁN MARÍA EN PUERTO RICO

RESUMEN: Una gran cantidad de letreros de base deslizable se volcaron durante el huracán María en Puerto Rico. La causa fue la ruptura involuntaria de las placas fusibles, un componente vital del sistema. El diseño de placas fusibles es inusual porque deben equilibrarse precisamente dos restricciones opuestas: 1. ser suficientemente débiles como para romperse durante la colisión de un vehículo errante, minimizando así lesiones a pasajeros y daños al vehículo, pero 2. suficientemente fuertes para resistir cargas de viento. Estas limitaciones poco comunes interesaron a los autores. La siguiente pregunta guió la investigación: ¿Podría el análisis clásico de esfuerzos, junto con teorías de falla establecidas, predecir la fractura de una placa fusible que falló durante el huracán María? Esta investigación llena un vacío en la literatura al usar un modelo de esfuerzos más refinado que el modelo considerado anteriormente. Se consideró una velocidad de ráfaga del viento de 155 mph en el tope del letrero. El límite elástico y la resistencia final del material se obtuvieron experimentalmente con un espécimen creado a partir de una placa fusible fracturada durante el huracán María. El análisis de esfuerzos clásico, junto con la teoría de falla de von Mises, predijo precisamente la falla hasta el nivel de cedencia (límite elástico); sin embargo, se habrían requerido velocidades del viento más altas para fracturarla. Se concluyó que el modelo simplificado disponible en la literatura es adecuado. Su error fue menor al 1% en comparación con el modelo más refinado desarrollado en este estudio.

Palabras clave: análisis de esfuerzos, huracán, placa fusible, rótulo de base deslizable, teorías de falla

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[2] Professor and Head of Mechanical Engineering, Ana G. Méndez University – Gurabo Campus, PO Box 3030, Gurabo, Puerto Rico 00778. Email: jcmorales@uagm.edu

[3] Senior student of Mechanical Engineering, Ana G. Méndez University – Gurabo Campus. Email: jsanchez407@outlook.com

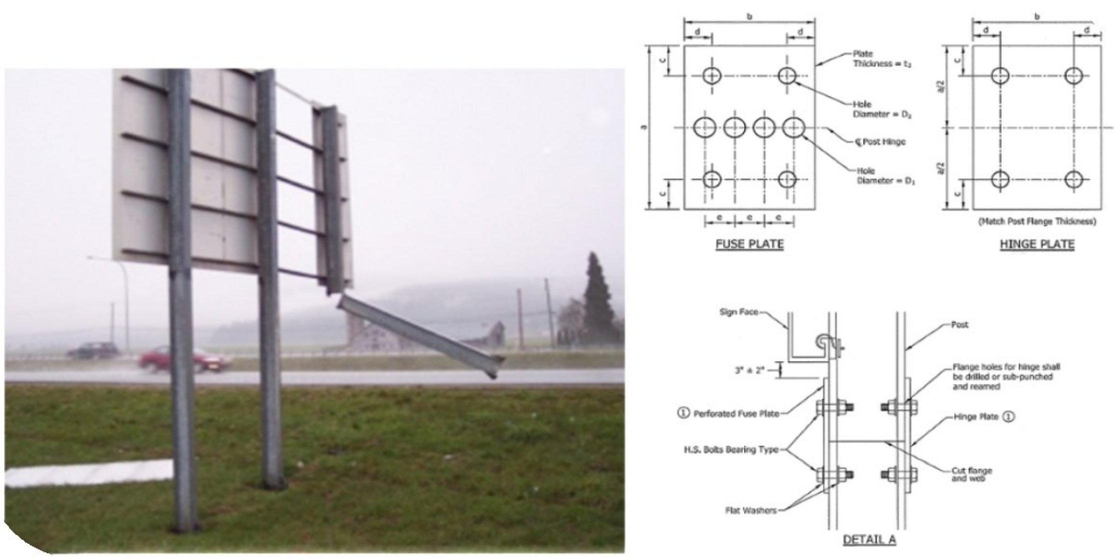
[4] Senior student of Mechanical Engineering, Ana G. Méndez University – Gurabo Campus. Email: seiradejesus@outlook.com

[5] Senior student of Mechanical Engineering, Ana G. Méndez University – Gurabo Campus. Email: JCaraballo11-1@outlook.es

INTRODUCTION

This investigation was motivated by the large number of roadway signs that failed in September 2017 during the passage of hurricane María through Puerto Rico. The Puerto Rico Department of Transportation (DTOP-PR) indicated that more than 6,000 signs were affected (Diaz, 2019). This investigation only considered breakaway-type highway signs that toppled over, as shown in Figure 1. The fuse plate – the critical component that unintendedly ruptured – is the focus of interest in this research project.

Figure 1: Unintended rupture of fuse plates led to the toppling of breakaway-type highway signs during hurricane María. This sign was located on PR-30 in Gurabo, Puerto Rico. Photos by UAGM students.



(a) **(b)**

Figure 2: (a) Intended rupture of fuse plate due to collision of an errant vehicle (taken from Transpo Industries Inc). (b) Drawing of fuse and hinge plates and a detail of their connection to the upper and lower posts of the sign (taken from Boruff, 2015)

Fuse plates are intended to fail only when the lower post of the sign is impacted by an errant vehicle, "thereby minimizing injuries to the occupants and damage to the vehicle" (AASHTO, 2017, p. 12-1). In an accident, the base of the post slips out of its "breakaway" footing, the fuse plate ruptures, and the post swings upward. A hinge plate located on the opposite side of the fuse plate bends plastically and keeps the post out of the way of the vehicle (Figure 2a). Drawings of typical fuse and hinge plates are shown in Figure 2b.

The plate's behavior as a fuse is induced by weakening it at the middle with a row of horizontally aligned holes. Figure 2b shows a case that used four holes to create the fuse. The number of holes and their diameter controls the force at which the fuse plate ruptures. Rupture occurs at the thinnest section, i.e., the horizontal plane defined by the centerlines of the holes. Hinge plates, on the other hand, are not perforated (except for the four bolt holes used to connect it to the upper and lower posts) because its objective is to create a plastic hinge.

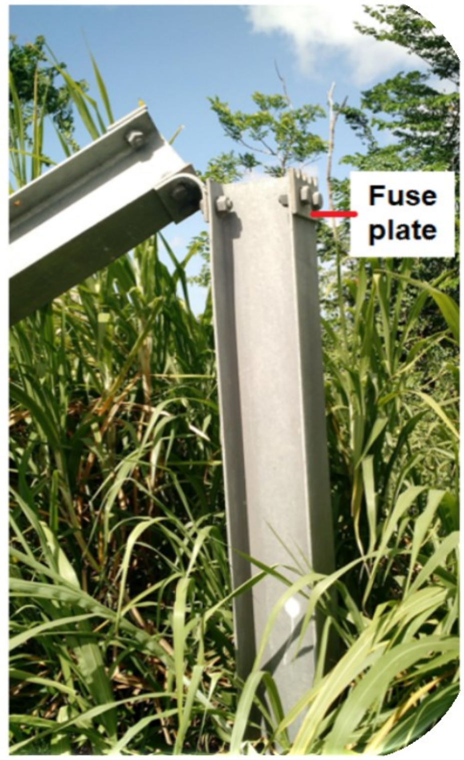
The ingenious design of fuse plates is unusual because two opposing constraints must be precisely balanced: 1. they must be weak enough to rupture during collision of an errant vehicle, thus minimizing injuries to passengers and damage to the vehicle, but 2. strong enough to resist wind loads. These uncommon constraints attracted the interest of the authors.

A literature survey showed that simplified models have been used to consider wind effects on the fuse plate (i.e., Pfeifer, 1993, and Paulsen et al., 1995). These studies only considered stresses due to the overturning moment of the wind load. The literature review also showed that the responsibility for fuse plate sizing and certification is designated to its manufacturers (AASHTO, 2017, p. 12-2). The models used by manufacturers for sizing and calculations remain private and confidential. This investigation fills a gap in the literature by examining a more refined model of the stresses than previously considered. It also offers a glimpse into one possible process used by manufacturers.

The following question guided the research: Could classical stress analysis, in conjunction with established failure theories, predict failure of a fuse plate that ruptured due to the wind load of hurricane María? This research question satisfied the needs of the project. It was also appropriate for the academic level of the three undergraduate students that were part of the research group. They were senior mechanical engineering students who had been exposed to the required knowledge in the following courses: Statics, Mechanics of Materials, Machine Design, and Materials Testing Laboratory. The investigation was conducted in one semester and fulfilled the requirements of the elective course MEEN 498 Undergraduate Research Experience I.

METHODOLOGY

The methodology was based on analyzing one specific case of a breakaway-type highway sign that toppled over during hurricane María (Figure 3a). A wind gust speed of 155 mph was assumed at the top of the sign. This was the measured sustained wind speed of María as it entered Puerto Rico. The yield strength and ultimate strength of the fuse plate were obtained experimentally with one tensile specimen machined from one of the fuse plates that ruptured. The actual fuse plate that was used is shown in Figure 3b. Finally, compare the stress analysis to an appropriate failure theory, discuss the results, and reach a conclusion



(a) **(b)**

Figure 3: (a) Sign used in the case study, as it looked before hurricane María. It was located on PR-52 between PR-199 and PR-177 in the direction from Caguas to San Juan. Photo obtained from Google Earth, Street View. (b) The remains of the sign after María. Only the left posts survived (upper and lower). The fuse plate indicated in the photo was removed before the remains were scrapped. The torque required to unfasten the bolts was approximately 2200 lb; ft, using a 6 ft moment arm. Photo taken by first author.

ASSUMPTIONS

1. Loads are applied statically. Fatigue design (cyclic loading) is only required for overhead cantilevered and non-cantilevered signs, traffic signal structures, and high-mast lighting towers (AASHTO, 2009, p. 11-3).

2. The area of both the large and small sign ("SALIDA 1" in Figure 3a) contribute to the wind load.

   a. The load on the large sign is centered and divided equally between the two posts.
   b. The load on the small sign is offset from the centerline. It is considered as a centered load (divided equally between the two posts) plus a torsional moment due to the offset. The torsional moment is resisted by the fuse and hinge plates as torsional shear stresses.

3. All of the sign components, except for the fuse and hinge plates, are considered rigid bodies. In addition, the sign components below the fuse plate centerline remain stationary.

4. The fuse and hinge plates remain in contact with the flanges of the posts. Also, the flanges provide a rigid support to the fuse plate except at the hinge line (rupture plane).

5. For analysis purposes, the stress state at the failure plane of the fuse plate is a biaxial state of stress (plane stress).

6. The overturning moment – due to the tendency of the sign to rotate as a rigid body – is applied as a couple defined by the fuse plate (purely tensile load) and the hinge plate (purely compressive load).

7. The fuse and hinge plates act in parallel to resist the tendency of the sign to translate as a rigid body, i.e., there is shear strain compatibility, so shear deformations are assumed equal for both plates.

8. The weight of the sign above the fuse plates may be calculated from the components of similar signs that did not fail during María. Most of the sign structure that was analyzed did not survive.

9. The size of the sign may be scaled off from the Google Earth photo (Figure 3a). The flange width of the post that survived (Figure 3b) was measured and served as the basis to determine the scale.

10. The wind direction is perpendicular to the sign and has a uniform profile (no changes with elevation).

11. The wind gust speed is 155 mph at the top of the sign. It corresponds to the measured sustained speed of María as it entered Puerto Rico. This was chosen as a nominal wind gust speed to conduct the analysis because the actual wind gust speed at the site during María remains unknown.

12. The air density is taken at a pressure of 14.7 psi and a temperature of 59˚F.

13. The four holes in the fuse plate are equally spaced.

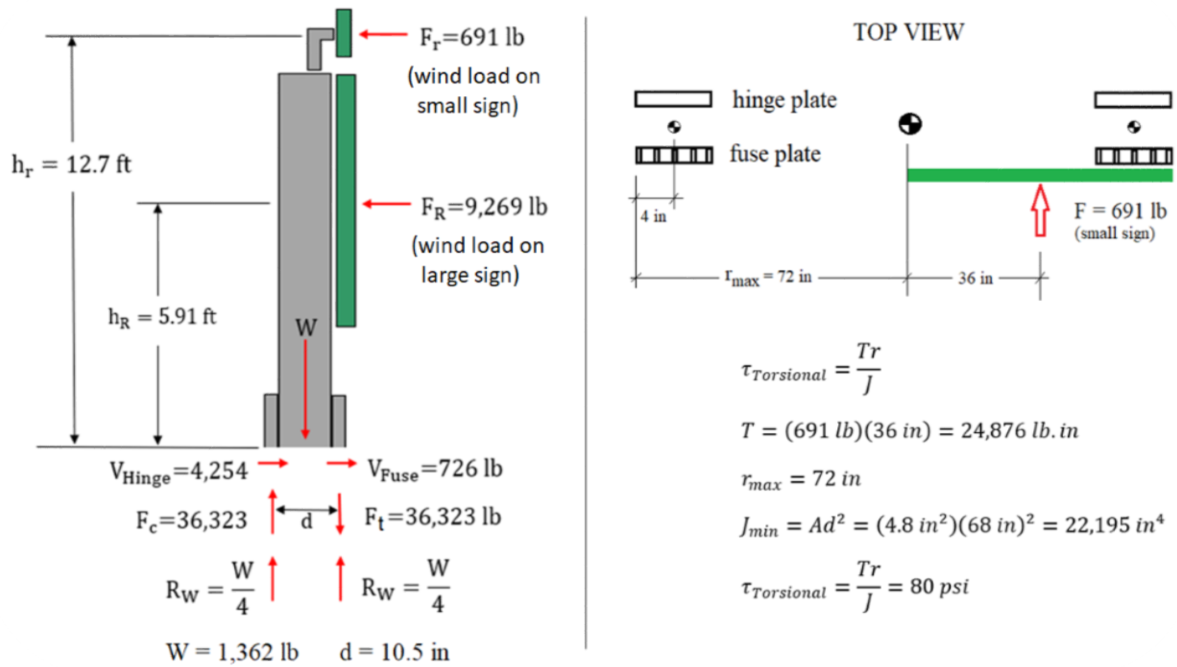
14. The material of the fuse plate is considered homogeneous and isotropic.

15. The yield strength of the material is defined by the 0.2% offset strain.

CLASSICAL STRESS ANALYSIS

Figure 4a is a free body diagram that summarizes the forces acting on the structure. It was defined by cutting the structure at the hinge line (plane of failure). The forces at the cut correspond to one half of the reactions, based on Assumption (2), and were calculated using the equations of static equilibrium.

Figure 4b shows the relevant components of a top view of the structure that was used to calculate the maximum torsional shear stress due to the offset small sign, per Assumption 2b. The calculation of the polar moment of inertia of area, J, was simplified and only included the most significant term, Ad^2. It is a minimum value, so it is a conservative estimate



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(a) **(b)**

Figure 4: (a) Free body diagram of the structure cut at the hinge line (failure plane). The forces at the cut correspond to one-half of the reactions (they split equally between the two posts). (b) Top view of structure used to calculate the torsional shear stress resulting from the centerline offset of the small sign.

The following information was used to calculate the forces:

- Scaled-off large-sign dimensions: 11.25 ft (height) x 12 ft (width). Corner radius = 1.0 ft.
- Scaled-off small-sign dimensions: 1.75 ft (height) x 5.75 ft (width). Corner radius = 0.25 ft.
- Number of holes in the fuse plate = 4
- Measured width of fuse plate = 8.2 in
- Measured thickness of fuse plate = 0.5 in
- Measured diameter of holes in the fuse plate = 1.7 in (average of measurements of the four holes)
- Calculated area of fuse plate on hinge line = $A_{Fuse} = 0.7\ in^2$
- Calculated area of hinge plate on hinge line = $A_{Hinge} = 4.1\ in^2$
- C_D = 1.12 (based on AASHTO, 2017, p. 3-19)
- Air density = ρ = 0.00237696 slug/ft^3

- Wind gust speed = v = 155 miles/hr = 227.33 ft/s
- The wind force was calculated using the classical drag force equation (1), shown below:

$$F_W = \frac{1}{2}\rho C_D A v^2 \tag{1}$$

In addition, the unequal shear forces V_{Fuse} and V_{Hinge}, shown in Figure 4a, were calculated based on shear strain compatibility as per Assumption 7. The details are provided below:

Shear strain compatibility, given in equation (2), requires that the shear strains in both plates be equal because they act in parallel in opposing the tendency of the sign to translate as a rigid body. This step was required to take into consideration the reduction in area of the fuse plate (due to the four holes) which reduces the shear stiffness of the fuse plate relative to the hinge plate.

$$\gamma_{Fuse} = \gamma_{Hinge} \tag{2}$$

Shear strain is defined as the shear stress (τ) divided by the shear modulus (G), as shown in the constitutive equation (3), while direct shear stress (τ) is defined as the shear force (V) divided by the area (A), as shown in equation (4).

$$\gamma = \frac{\tau}{G} \tag{3}$$

$$\tau = \frac{V}{A} \tag{4}$$

Substituting equations (3) and (4) into equation (2), results in the relationship for the shear forces as a function of the areas as shown in equation (5). As expected, the fuse plate takes a smaller portion of the shear force.

$$V_{Fuse} = \frac{A_{Fuse}}{A_{Hinge}} V_{Hinge} \tag{5}$$

The biaxial stress state at a point in the failure plane of the fuse plate is shown in Figure 5. Stress calculations are based on the forces shown in Figure 4. It is evident that the major contributor to the stress state is σ_y and is due to the overturning moment (51,890 psi). The first-order effects of the weight are only 488 psi and they are beneficial because they act in compression and are therefore subtracted. The direct shear stress contributes 1,038 psi. The torsional shear stress due to the offset small sign only contributes 80 psi due to the large value of the polar moment of inertia of area.

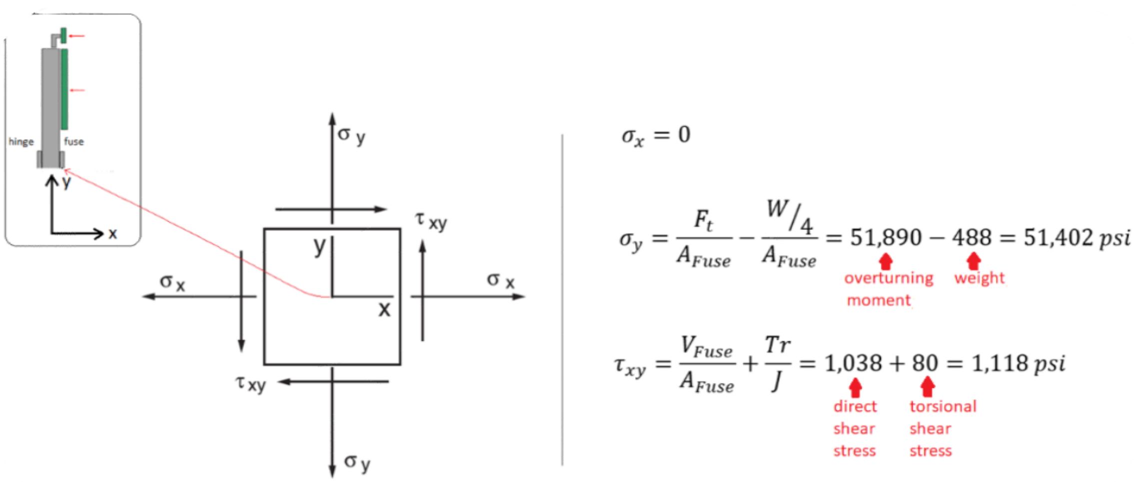

Figure 5: Biaxial stress state (plane stress) at a point in the failure plane of the fuse plate.

MECHANICAL PROPERTIES OF THE FUSE PLATE

The mechanical properties were determined by machining an 8-inch tensile specimen from the bottom section (below the bolt holes) of the actual fuse plate (Figure 6). The dimensions of the specimen were based on the ASTM A370 (2016) standard.

Figure 6: Actual fuse plate that failed and the specimen machined from the bottom of the plate.

The specimen was tested in the Instron 8502-55 Kip Capacity Servohydraulic Universal Testing Machine available in the Materials Testing Lab of the Department of Mechanical Engineering at UAGM. The test procedure was based on the ASTM E8 (2016) standard. The engineering stress-strain curve is shown in Figure 7. The broken specimen is included as an inset in the graph. The value of Sy at 0.2% strain offset was determined graphically using a higher resolution graph that was created with the Excel data file of the test. The modulus of elasticity (E = $30.4x10^6$ psi) was calculated as the slope of the elastic portion of the curve using values from the Excel data file.resolution graph that was created with the Excel data file of the test. The modulus of elasticity (E = $30.4x10^6$ psi) was calculated as the slope of the elastic portion of the curve using values from the Excel data file.

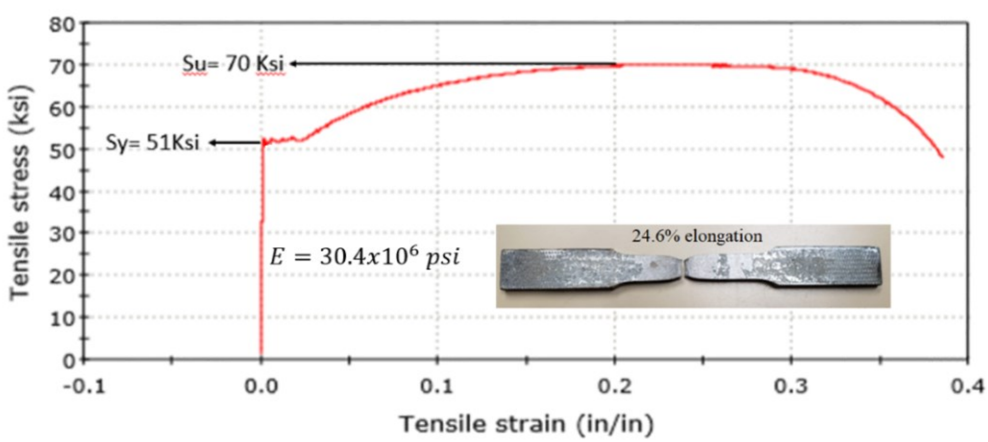

Figure 7: Engineering stress-strain curve of the specimen. The broken specimen is shown as an inset.

STATIC FAILURE THEORIES

The selection of a static loading failure theory depends on whether the material is ductile or brittle. For ductile materials, the failure criterion is based on yield strength (S_y). For brittle materials, the failure criterion is based on ultimate strength (S_u). The reason for the different criteria arises because the stress analysis used in these failure theories is a linear elastic analysis, i.e., based on the linear portion of the stress-strain curve whose slope is given by Young's elastic modulus (from F to G, or F to A in Figure 8). A brittle material fractures shortly after reaching the yield strength (point H in Figure 8); therefore, using S_u as a criterion for brittle materials is valid even though the stresses slightly enter into the inelastic region of the stress-strain curve (from G to H in Figure 8). If the material is truly brittle (short increment from G to H), the error incurred in using a linear elastic model up to S_u should be small.

A ductile material, on the other hand, reaches its ultimate strength after undergoing significant plastic deformation (B to D in Figure 8). The ultimate strength is not a reasonable failure criterion for ductile materials because the linear elastic stress analysis – governed by the steep slope that defines Young's modulus – does not correctly model the material behavior beyond the yield strength. The error incurred in using S_u as the failure criterion for ductile materials, as required for example, in the Maximum Normal Stress Failure Theory, would be unacceptable. Therefore, ductile materials must use yield strength as the failure criterion.

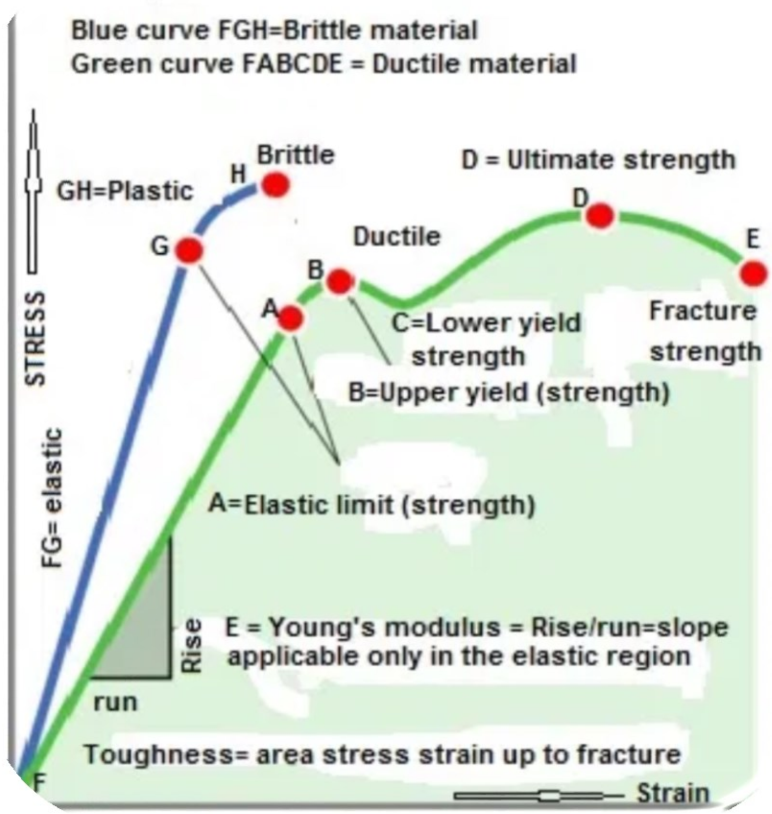

Figure 8. Schematic of stress-strain curves for brittle and ductile materials. Taken from http://www.mesubjects.net/st-venants-principle-stress-strain-curve/.

Figure 7 clearly shows that the fuse plate material is ductile so the Maximum Distortion Energy failure theory for ductile materials was selected (Juvinall and Marshek, 2012, p. 267). This theory, best known as the von Mises yield criterion, is formulated in equation (6). The left-hand side of equation (6) is commonly known as the von Mises stress and may be determined through classical stress analysis or computational methods. The right-hand side of equation (6) establishes the strength criterion of the material, in this case the yield strength. The safety factor (S.F.) is included as a strength reduction factor on the right-hand side of the equation (LRFD has not yet made its way into mechanical engineering).

$$(\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau_{xy}^2)^{1/2} = \frac{S_y}{S.F.} \tag{6}$$

All that remains is to substitute the stresses shown in Figure 5 into equation (6). The von Mises stress was calculated for two cases. The first case – the refined model developed in this study – considers all the stresses present in the failure plane that are shown in Figure 5. The second case – the simplified models used by Pfeifer (1993) and Paulsen et al. (1995) – only considered the stresses due to the overturning moment. In both cases the safety factor was set equal to 1.0. The results are summarized in Table 1.

Table 1: Predictions of equation (6) with a safety factor equal to 1.0.

Case	von Mises stress (left-hand side of equation 6) (Calculated)	Yield strength S_y (Experimental)	% difference
Refined Model (Includes all the stresses shown in Figure 5)	51,413 psi	51,000 psi	0.8%
Simplified Model (Only includes the stress due to the overturning moment) Used by Pfeifer (1993) and Paulsen et al. (1995).	51,890 psi	51,000 psi	1.75%

DISCUSSION

The first row of Table 1 shows the results of the refined model used in this study. There is excellent agreement between the calculated von Mises stress and the experimental value of yield strength. The percent difference was only 0.8%.

The second row of Table 1 shows the results of the simplified model used by Pfeifer (1993) and Paulsen et al. (1995). The error increased by less than 1%; therefore, sizing of the plate can be simplified even further, and still remain accurate.

These results are encouraging; however, the fuse plate surpassed the yield state and ruptured. The only way that fracture could be explained with the assumed wind gust velocity of 155 mph would be if the material had ideal elastic-perfectly-plastic behavior. For perfectly plastic behavior, once yielding was reached, the plate would deform plastically without increasing the load, until it fractured. However, Figure 7 shows strain hardening of the material which increases the strength by 19 ksi (S_u – S_y = 19 ksi). Thus, a higher velocity wind gust would be required to overcome the additional strength and reach rupture.

A post-yield non-linear incremental load analysis is required to provide a better understanding of the behavior of the fuse plate once it starts yielding and to predict the wind gust speed for rupture. This analysis was not contemplated in the scope of this project. Still, a few things may be conceptually inferred in the post-yield sequence that may assist in a better understanding the situation.

- The stresses that arise in the failure plane are primary stresses because they develop from the applied wind load and are not self-limiting. For primary stresses, once yielding is reached, the plastic deformation continues unabated unless force equilibrium is reached. In this case, the increase in strength due to strain hardening would ensure equilibrium and stop the deformation prior to rupture.

- The holes in the fuse plate generate stress concentrations. The locations of these stress raisers are exactly in the failure plane of the fuse plate (the thinnest section of the plate) and at the circumference of the holes. These locations would be expected to reach yielding before any other point. Additional loads would be redistributed into the adjacent material between the holes that have not yet reached yield because they are stiffer (still governed by Young's modulus) and attract the load. The plasticized locations would become "softer" in terms of stiffness, thus the redistribution into the stiffer material.

- At some instant in time in the sequence to rupture, the entire failure plane should become fully plastic ("soft") because there are no other "stiffer" locations between the holes to redistribute the primary stresses. The material has reached a state where any increase in the load will lead to gross yielding of the section. It seems plausible to suppose that the fuse plate could reach this "gross yielding" onset state with the 155-mph wind gust.

- A final push would be required to conclude the gross yielding state and reach rupture. For example, a higher velocity wind gust could increase the load and overcome the increased strength due to strain hardening. Also, one point on the fuse plate could fracture earlier than the others which would decrease the available area to carry the load, thus starting a sequence of local ruptures that ended in full fracture. Figure 6 clearly shows that the holes are not equally spaced, and that the fracture zones are different from one hole to the next.

The preceding discussion reveals part of the authors' interest in this interesting structural element. Typical mechanical engineering applications only require the designer to size an element so that it never reaches the yield strength under the applied static loads. Safety factors generally ensure that this objective is accomplished. The designer rarely faces a situation in which a safety factor is not warranted, i.e., a safety factor of 1.0. The fuse plate is such a case. A safety factor larger than 1.0 – to avoid failure due to wind loads – would introduce uncertainty on the activation of the fuse. An overdesigned plate may not rupture when the post is struck by an errant vehicle, thus defeating the intended purpose of the fuse plate.

Although the lower end of the design was not included in the scope of this project (plate rupture when the post is struck by a vehicle), it is clear that it will face the same issues discussed here.

LIMITATIONS

Two primary limitations were confronted in this study: 1.) Due to the limited amount of material (Figure 6), only one specimen was tested to determine the mechanical properties, i.e., an average from several specimens could not be determined. 2.) A wind gust speed of 155 mph at the top of the sign was assumed because the wind speed at the site remains unknown.

In addition, several of the assumptions used in the study limited the accuracy of the stress analysis. For example, the sign dimensions were scaled off from a photograph because the sign disappeared after María. Also, the study assumed that the holes in the fuse plate were equally spaced; however, Figure 6 clearly shows that they were not. The study also assumed that all points in the failure plane were equally stressed which may not have been the case.

CONCLUSIONS

Despite the limitations, the study concludes that classical stress analysis, in conjunction with the von Mises yield failure criterion, accurately predicted yielding of the fuse plate. Furthermore, that the stress analysis may be simplified – with less than a 1% error increase – by only considering the stresses caused by the overturning moment. This simplification was used by Pfeifer (1993) and Paulsen et al. (1995) and is hereby validated. A safety factor of 1.0 is recommended due to the dual constraints that the fuse plate must satisfy. This is justified if the designers/manufacturers use plate material with certified mechanical properties.

Although the model accurately predicted yielding, a post-yield non-linear incremental load analysis is required to predict the higher wind gust speed that would be required to rupture the fuse plate.

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