THE FRACTURE MECHANICS OF STEEL GUSSET PLATES

By Saura M. Jost

Department of Civil Engineering

INTRODUCTION

There are many factors that affect the strength of a gusset plate. This project focuses on how the strength varies with the spacing of rivet holes. Sometimes cracks can develop near the rivet holes in the presence of plastic deformation, which reduces the plate's strength. The study was inspired by the University of Minnesota's research on the failed gusset plate in the I-35W bridge collapse. Their research investigated the failure of the gusset plate as a yield-dominant failure (occurred by plastic collapse), and this research expands on that analysis but focuses on the possibility of a fracture-dominated failure.

GOAL

To develop design curves that relate rivet hole spacing and material properties to load-carrying capacity.

METHODS

The finite element program, ABAQUS, was used to simulate tensile loading on a gusset plate. The computational model used to simulate crack growth relied on the Dugdale Strip Model which is based on non-linear fracture mechanics. This model was used to account for the plastic deformation and also because it predicts the transition between plasticity (yield-dominated failure) and linear elastic fracture mechanics. It assumes the plasticity that develops ahead of a crack tip can be approximated by a distribution of stresses that resist crack opening. Iterations of tensile loading were performed until the critical stress was reached. At this point, the crack is unstable and the plate will tear apart.

This iterative process was used to verify the analytical solution for the Dugdale Strip Model. To model an infinite plate with a rivet hole and rivet holes at a given spacing, a linear softening material model was used. This was done because ABAQUS is more robust at modeling this type of material.

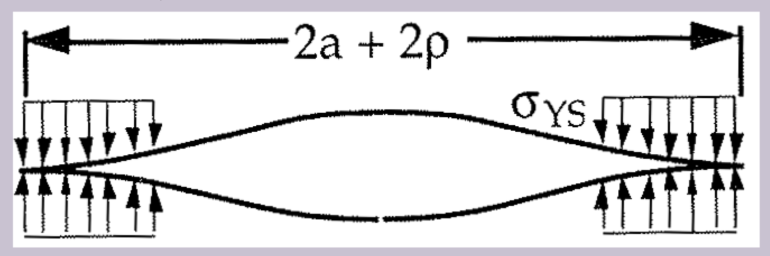

Figure 1: Dugdale strip model [1]

For plates with rivet holes, crack initiation was modeled using cohesive elements to simulate the damage evolution. This reduces the amount of iteration required for the user to arrive at the critical stress.

To characterize the transition between a ductile and brittle failure, the material parameter ρ_1 was used. The radius of the rivet hole (R) or the crack length (a) can be divided by ρ_1 to express the ductility or brittleness as non-dimensional. A smaller ratio indicates a more ductile section that is yielding and less affected by the presence of a crack. As the ratio increases, the presence of the crack causes the strength to decreases as an inverse square law.

$$\rho_1 \sim \frac{G_c E}{{\sigma_{ys}}^2}$$

G_c : Energy release rate which is a measure of resistance to crack extension
E: Modulus of elasticity
σ_{ys}: Yield strength

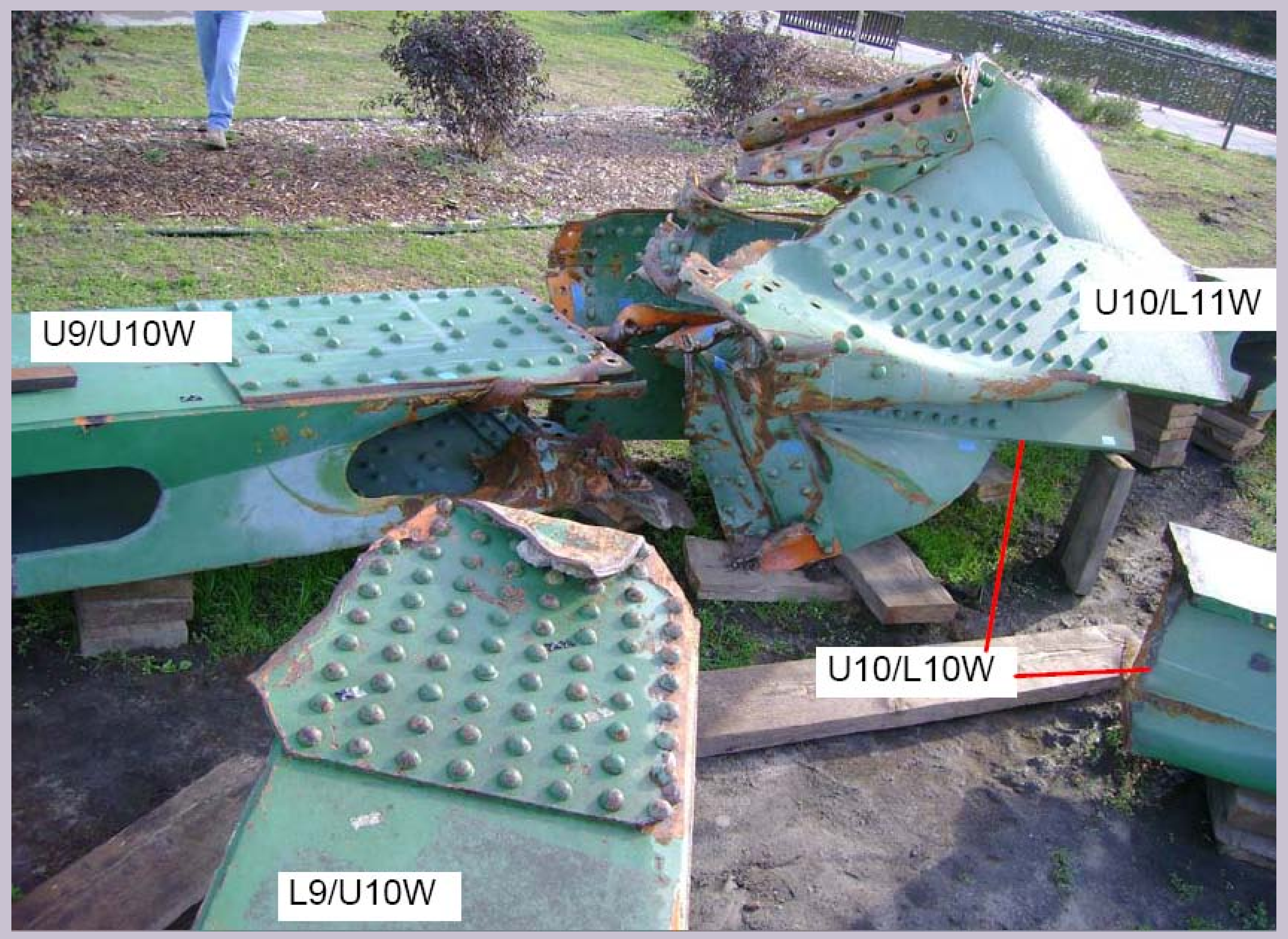

Figure 2: Failed gusset plate from I-35W Bridge collapse [2]

RESULTS

Dugdale Strip Model Test Case

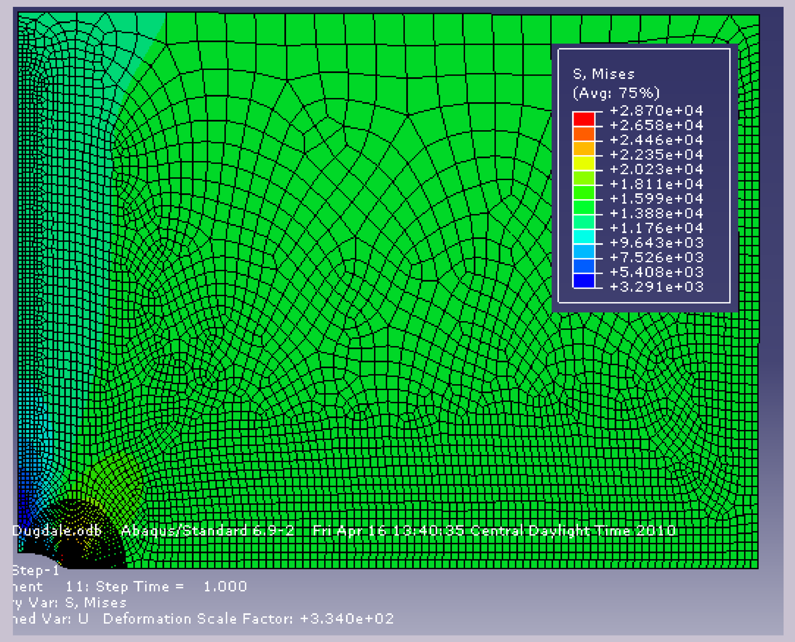

Figure 3: Gusset Plate Model in ABAQUS

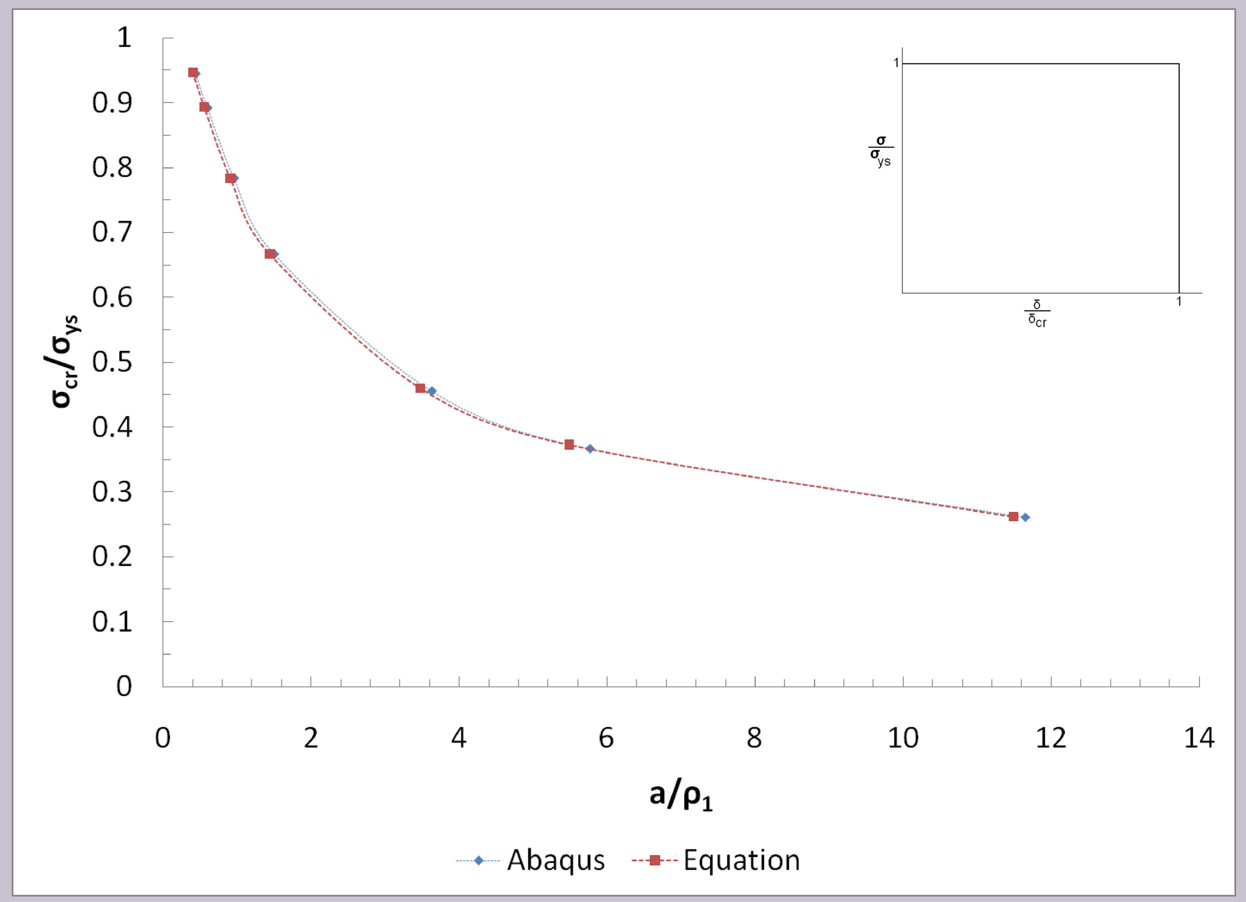

Figure 4: Dugdale Test Case Data

Dugdale Strip Model Equations

Dugdale Strip Model Equilibrium

$$\frac{\sigma_{cr}}{\sigma_{ys}} = \frac{2}{\pi}\cos^{-1}\left(\frac{1}{1+\frac{\rho}{a}}\right)$$

σ_{cr}: Critical stress at which crack extension will occur
σ_{ys}: Yield strength
ρ: Size of plastic zone

Critical Crack Opening Displacement

$$\delta_{cr} = \frac{8\sigma_{ys}\rho_1}{\pi E}$$

σ_{ys}: Yield strength
E: Modulus of elasticity
ρ_1: Plastic zone size for small scale yielding (material property)

Gusset plate with rivet holes

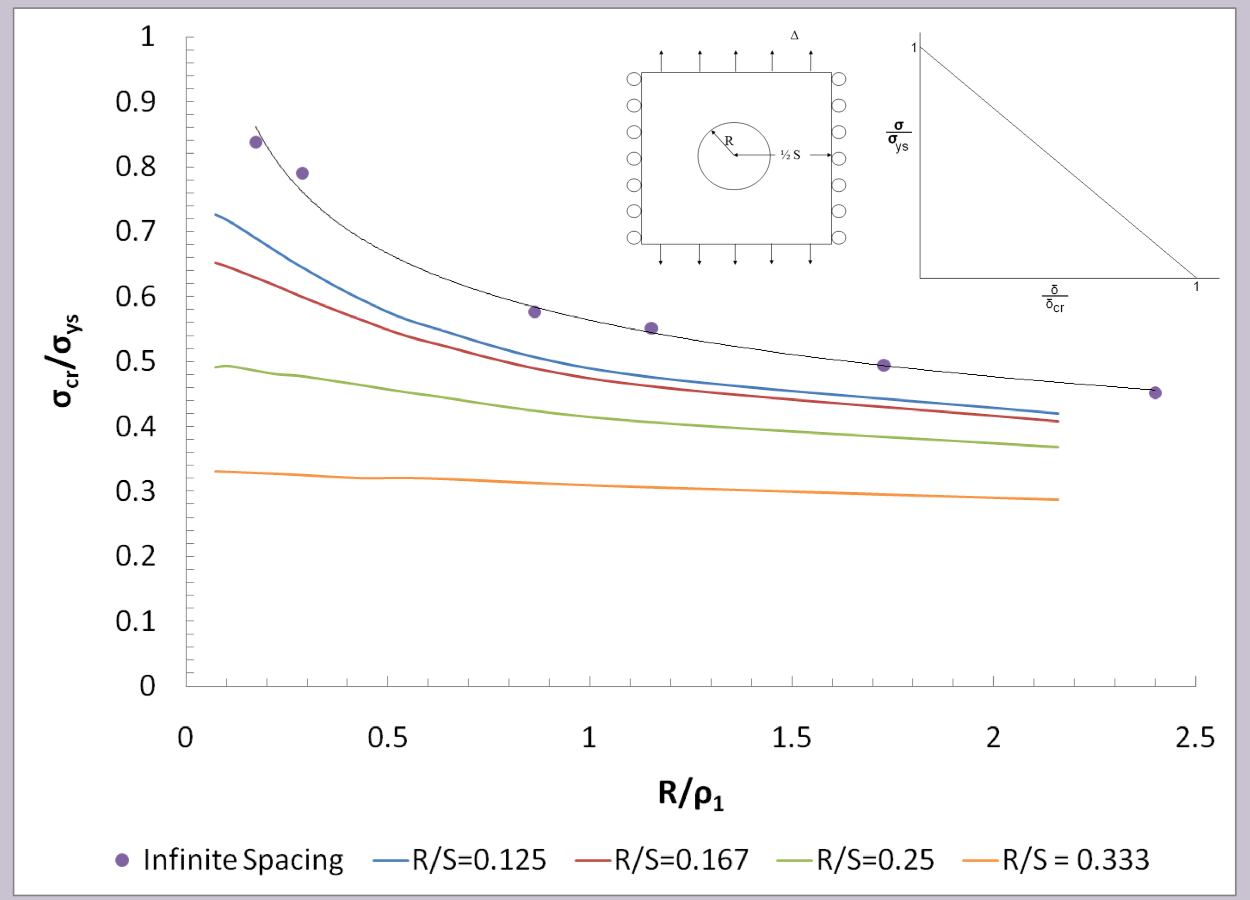

Figure 5: Gusset plate with rivet hole spacing data

CONCLUSIONS

The results from the Dugdale Test Case Experiment show that ABAQUS is able to simulate the Dugdale Strip Model for an infinite plate.

Using a Linear Softening Model, the results for an infinite plate indicate that the normalized critical stress decreases as the brittleness of the material increases, approaching the value 1/3 corresponding to the strength of an elastic plate containing a hole.

When rivet hole spacing is modeled in a gusset plate, the results are qualitatively different. While the normalized strength decreases with spacing, it is a much weaker function of brittleness.

REFERENCES

1) Anderson, T.L.. Fracture Mechanics: Fundamentals and Applications. 2nd edition. Boca Raton, FL: CRC Press, Inc., 1995.
2) Ballarini, Roberto, and Taichiro Okazaki. The Infamous Gusset Plates, to appear in The City, The River, The Bridge, University of Minnesota, 2009.
3) Janssen, Michael, Russell Wanhill, and Jan Zuidema. Fracture Mechanics. 2nd edition. New York, NY: Spon Press, 2004.
4) Roylance, David. Finite Element Analysis. Massachusetts Institute of Technology, 2001.

ACKNOWLEDGEMENTS

Professor Roberto Ballarini, Department of Civil Engineering
CE Graduate Students: Minmao Liao and Roberto Piccinin