How do engineers learn from failures?

A look at the 2007 collapse of the I-35W bridge in Minneapolis



Source: Mike Wells CC BY-SA 2.0 https://en.wikipedia.org/wiki/I-35W\_Mississippi\_River\_bridge#/media/File:I35\_Bridge\_Collapse\_4crop.jpg

Bridges are important. They allow people and traffic to cross rivers, canyons, other roads, etc. efficiently and easily. Engineers design bridges to be safe, but sometimes things go wrong and a failure can occur. We will look closely at the collapse of the I-35W bridge and see how the failure occurred and recreate the failure in small scale bridge models.

**The bridge:**

The I-35W bridge in Minneapolis was built in 1967. It carried traffic over the Mississippi River. It was a steel arch deck truss bridge. A deck truss means that traffic drives over the truss. The total length of the bridge was 1,907 ft, with the longest span over the Mississippi at 456 ft.

Image source: NTSB report: http://www.dot.state.mn.us/i35wbridge/pdf/ntsb-report.pdf

I-35 W bridge truss before collapse

**The Collapse:**

At 6:05pm the bridge experienced a sudden collapse that resulted in 13 fatalities. According to the NTSB report, the primary cause of the collapse was undersized gusset plates. These plates were ½ in. thick plates that connected the framing members in the truss. The collapse started when gusset plates at upper node 10 buckled and then fractured. These plates were already bowed (buckling) well before the collapse of the bridge indicating that they were under too much load. However, engineers design gusset plates to be very strong and not a normal location of failure, so the bowing was thought to be due to bending of the plates during construction. Contributing factors were overloading of the bridge from a 2 in. concrete topping that increased the loads in the bridge by 20% and 578,000 lbs of construction equipment on the bridge at the time of collapse. This additional weight could not be supported by the weak gusset plates and led to the bridge collapse.



I-35 W bridge after collapse





Fracture pattern in gusset plate after collapse

Bowed gusset plate before collapse

Image source: NTSB report: http://www.dot.state.mn.us/i35wbridge/pdf/ntsb-report.pdf



Additional construction equipment added weight to the bridge

See the complete NTSB report: http://www.dot.state.mn.us/i35wbridge/pdf/ntsb-report.pdf

What are gusset plates?

Gusset plates were a critical component in the collapse of the bridge – but what are they and how could they make a bridge collapse? Essentially gusset plates are thick pieces of steel designed to help join the truss members together. See the image below – the gusset plates connect the diagonals to the upper chord. Gusset plates are used extensively in steel truss connections as they provide a strong and buildable way to connect the truss members. The plates see all types of loads; compression, tension, and shear. Gusset plates are designed to be very strong – usually about twice as strong as they need to be. Because they join together many truss members, a failure in the plate could lead to disastrous consequences in the bridge. Engineers have procedures in place to design, and check the design, for every piece of the bridge. The checking process helps to make sure there are no mistakes in the design. However, in the case of the I-35W bridge, the design was flawed and that mistake was not found. As a result, the gusset plates were not strong enough. When the plates failed, the truss members were no longer connected and the entire bridge failed.



Image source: NTSB report: http://www.dot.state.mn.us/i35wbridge/pdf/ntsb-report.pdf

Gusset plate connecting truss members in I-35W bridge

Test it out!

Build a model bridge using craft sticks and carboard plates to see how the gusset plate failure can lead to failure of the bridge! Then come up with a new design that prevents the failure.

Project Goals

* Build a truss using craft sticks and pieces of paper or cardboard for gusset plates
* Load the bridge until failure
* Observe how the failure in the weak gusset plate leads to the failure of the bridge

Option 1: Build a single truss

What you need

* Craft sticks (about 11)
* Pieces of cardboard cut into 1.5in by 1.5 in squares
* Piece of paper cut into 1.5 in. by 1.5 in. square
* Glue (If you use Elmer’s glue you have to factor in time for the glue to completely dry before loading the bridge. If you use hot glue, loading can occur immediately once it is complete.)
* Books or other object to support truss off table



Directions

* Cut 6 pieces of cardboard to approximately 1.5 in. by 1.5 in. squares and one piece of paper into a 1.5 in. by 1.5 in. square
* Arrange your members in a Warren truss arrangement as shown (optional – you can use other truss arrangements but you may need more sticks or squares)
* Place glue dots where you want the truss members to join with the plates. IMPORTANT – make sure there is space between the truss members – the load needs to be able to go through the gusset plates.

 

space

* Glue the truss members to the plates and give it time to dry (at least a few hours)
* Now you can test the bridge! Support the ends of the truss on some books or other support. Because it is a single truss it won’t be stable on its own, so someone needs to hold the ends of the truss to support it (keep it from flopping over). Then another person can push down in the middle of the truss.
* See the gusset plate failure? The paper plate buckles and fails under the load.

support

Gusset plate failure



Loading

Option 2: Build a truss bridge



What you need

* Craft sticks (about 28)
* Pieces of cardboard cut into 1.5 in. by 2.5 in. rectangles
* Piece of paper cut into 1.5 in. by 2.5 in. rectangle
* Glue (If you use Elmer’s glue you have to factor in time for the glue to completely dry before loading the bridge. If you use hot glue, loading can occur immediately once it is complete.)
* Books or other object to support truss off table
* Cans or something heavy to load the bridge



Directions

* Cut 12 pieces of cardboard to approximately 1.5 in. by 2.5 in. rectangles and 2 pieces of paper into a 1.5 in. by 2.5 in. rectangles
* Start out by making the trusses. Arrange your members in a Warren truss arrangement as shown (optional – you can use other truss arrangements but you may need more sticks or squares)
* Place glue dots where you want the truss members to join with the plates. IMPORTANT – make sure there is space between the truss members – the load needs to be able to go through the gusset plates. Make sure there is extra space at the top and bottom of the plates (we will fold these over to connect the trusses to form the bridge).

 

space

Extra space

* Glue the truss members to the plates and give it time to dry (at least a few hours). You should have two dry trusses.
* Now we will assemble the trusses into a bridge. Fold over the cardboard and paper plates to form little tabs we will use to connect the two trusses.



Fold

Horizontal member

* With the tabs folded over you can glue the horizontal sticks in place that connect the two trusses. This may require some patience if your cardboard resists the folding. Having some extra clips or clothes pins on hand may help hold things together while the glue dries. (If you use hot glue the drying will be quicker). Let all the glue dry completely before testing.
* Now you can test the bridge! Support the ends of the truss on some books or other support. Place a small book (like a paperback) or other stiff object inside the truss to support the weights you will place on the bridge. Then load up with weights (like food cans) until failure.
* See the gusset plate failure? The paper plate buckles and fails under the load. 

Gusset plate failure

Let’s talk about it

Think about these questions on how bridges fail

About Gusset Plates

* Why are gusset plates used in bridge construction?
* Think about the loading in the gusset plate. What types of loads are on gusset plates?
* Engineers usually design gusset plates to be much stronger than the members they are connecting – why?
* Most engineering designs are checked before being built – what is the importance of checking the design?

About the I-35W collapse

* The I-35W bridge was built in 1967 but did not collapse until 2007. Why did it take so long for the bridge to collapse? What changes happened that may have led to the collapse?
* The gusset plates were bowed prior to the collapse. Why did the engineers not think this was a sign of danger?
* What was the main problem in the I-35W bridge that led to its collapse?

About your test bridge

* The collapse of the I-35W bridge could have been prevented if the plates were thicker. Do you think having a thicker plate in your test bridge would have helped? (If multiple groups are building bridges, you can try replacing the paper gusset plate with thicker materials to see which is strongest).
* How has building and testing this bridge helped you understand how the I-35W bridge collapsed?
* How did your bridge collapse? What could you have done differently to prevent the failure?

Do you want to be an engineer?

Do you like to solve problems, figure out how things work, or make them better? Then engineering might be for you! There is a wide variety of engineers out there and they need lots of different skills. What engineering skills do you have?

* Likes to solve problems
* Good at math and science
* Good at creative thinking (coming up with new ideas)
* Great at communication (writing and talking)
* Ability to organize and make connections
* Can get along well with others
* Determined to get things done and do a good job
* Leadership

Teacher Notes:

Prepare ahead of time

* Make sure you have enough supplies (first page) for all students. Students can work in groups.
* If you are using regular glue make sure you take drying time into account.
* Print out copies of instructions.

Introduce the challenge (20 min video + 10 min discussion)

* Show the video on how bridges fail.
* Talk with students about how bridges fail. What are the different types of failure? What would happed if a bridge they used everyday failed? Are all bridge failure the same – are some worse than others – are some bridges more important than others (major river crossing compared to a small creek)? How do engineers make sure that a bridge will not fail?
* Go over activity instructions and goals.

Prepare for activity (5 min)

* Give students about 5 min to look over instructions and gather supplies.
  + What do they think will happen when the truss is loaded
  + Optional – try other materials for the gusset plates – do stiffer or weaker materials change the results?

Build, Test, Evaluate (35 min)

* Have students build bridges.
* Test the bridges. Apply weight to the bridge until it fails. Failure is when the gusset plate buckles.
* If there is time let the students redesign and come up with a better bridge. Change the gusset plate material or change the truss design.

Discussion (20 min)

* Have the students consider the following questions

About Gusset Plates

* Why are gusset plates used in bridge construction? *Gusset plates are used when constructing trusses because it provides and strong and buildable way to connect the members of a truss.*
* Think about the loading in the gusset plate. What types of loads are on gusset plates? *Gusset plates see all types of load; compression, tension, and shear.*
* Engineers usually design gusset plates to be much stronger than the members they are connecting – why? *Because gusset plates form the critical connection between truss members engineers want to make sure this connection is strong. A failure in this connection could lead to failure of the bridge.*
* Most engineering designs are checked before being built – what is the importance of checking the design? *Everybody makes mistakes. Engineering designs are checked and rechecked to make sure any mistakes are found and corrected. However, in the case of the I-35W collapse the checks did not work and a poor design was built.*

About the I-35W collapse

* The I-35W bridge was built in 1967 but did not collapse until 2007. Why did it take so long for the bridge to collapse? What changes happened that may have led to the collapse? *The evidence of bowing in the plates indicated that they were experiencing excessive load. However, the additional loading due to the concrete topping and construction loads at the time of collapse was the last straw and the plates failed*.
* The gusset plates were bowed prior to the collapse. Why did the engineers not think this was a sign of danger? *In design, engineers make the gusset plates very strong. They are not a usual location for potential failure when inspecting a bridge. So inspectors assumed that the bowing happened in construction and not as a result of excessive loads on the plates.*
* What was the main problem in the I-35W bridge that led to its collapse? *The design mistake in the thickness of the plates ultimately led to the collapse.*

About your test bridge

* The collapse of the I-35W bridge could have been prevented if the plates were thicker. Do you think having a thicker plate in your test bridge would have helped? (If multiple groups are building bridges, you can try replacing the paper gusset plate with thicker materials to see which is strongest). *Yes, a thicker plate would help. If the plate is thicker then it can better resist the loading (tension and compression) without failure.*
* How has building and testing this bridge helped you understand how the I-35W bridge collapsed? *Open response…*

Optional – Inquiry based learning questions.

* Your class is asked to evaluate the failure of your I-35-W bridge. Consider the different failure methods of a bridge and determine which one most contributed to the failure. Build a model truss and test it to determine if the gusset plate failure is critical.
* Design your investigation.
  + Learn about the I-35W bridge.
  + What were possible contributing factors to the failure?
* Conduct experiment and record data.
  + Design and build example truss.
  + Test bridges. Does the gusset plate failure lead to bridge failure? (remember excessive deflections are also considered a failure)
* Analyze and interpret results.
  + Why is the gusset plate failure critical?
  + Why was the design error missed in the original inspections?
  + Are errors likely to occur in other bridges? How do engineers take this into consideration?
* State conclusions
  + What caused the failure of the I-35W bridge? Use your experiment to support your conclusions.