11

Bridging the Future

Kirk Elwell

Photo taken by Benjamin T. Erwin

Key Concepts
from Previous Chapters

- 2 Engineering Design Process
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The Central Artery/Tunnel Project is one of the largest and most technologically challenging highway projects in American history. The goal is to improve the traffic flow in Boston, Massachusetts, by changing the Central Artery, a large section of an above-ground highway, into an underground tunnel.

I'm Kirk Elwell, a lead field engineer working on the Central Artery/Tunnel Project, often dubbed the "Big Dig." When the original Central Artery opened in 1959, it carried about 75,000 vehicles a day without any problems. But as the number of people using this stretch of highway nearly tripled, it became one of the most congested highways in the country. Accident rates were nearly four times the average for urban interstates.

The situation was only going to get worse. Researchers estimated that by 2010 the deteriorating Central Artery would hold traffic at a stop-and-go pace for sixteen hours a day unless a solution was found. What's more, the Central Artery ran right through the busiest shopping and dining district in the city. The unsightly highway was bad for business.

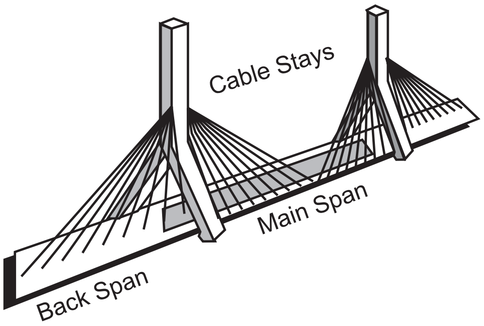
Since construction began in 1991, we have created a tunnel under the Boston Harbor. This tunnel connected Boston to the airport, built new connections to the highway from formerly inaccessible parts of town, and sunk much of the Central Artery below ground. One end of the Central Artery tunnel meets with the Leonard P. Zakim Bunker Hill Bridge, which opened to traffic in 2003. This bridge crosses the Charles River, connecting the city of Boston with surrounding suburbs. But beyond moving traffic, the bridge designers planned for it to become a city landmark—not unlike San Francisco's Golden Gate Bridge or St. Louis's Arch.


Courtesy of Wikipedia

The Leonard P. Zakim Bunker Hill Bridge

Even though our tax dollars are paying for the Big Dig, I don't work for the government. I work for Bechtel/Parsons Brinckerhoff, a company that was hired by state and federal government agencies to provide the engineering design and construction management for everyone from bricklayers and welders to carpenters and other technicians. This collaboration allows for better communications between management, engineers, and the construction crews on the job site.

As a field engineer, my usual "office" is the job site. I enjoy being outside and active, so this job is "right up my alley," so to speak. A structural engineer may spend a good deal of time in front of a computer calculating the structural forces of a bridge or tunnel. Field engineers spend most of their day ensuring that the job is being done right. Sure, I might spend a few hours at my desk looking at engineering and architectural plans, but unlike a structural engineer, I put my engineering skills into supervising and troubleshooting on the job site.



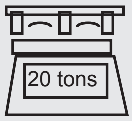
The process of designing the Zakim Bridge has been an interesting mix of architecture and engineering. After the site for the bridge was decided, the Federal Highway Administration asked several architects to draw possible designs for the bridge. Architects tend to specialize in the form of structures. Sure, they need to have a good sense of whether or not their design can actually be built. But, in general, architects focus more on how the structure will look and how people will interact with it. After an architect designs the plans, a structural engineer will make sure that the structure can withstand the forces of weather, traffic, people, or any other force that might act on it.

Christian Menn, a Swiss architect and engineer, submitted the winning design. The structural engineers worked out the specifications for all of the bridge's components. It was their job to make the bridge look the way Mr. Menn designed it, while withstanding all of the required loads. Engineers often refer to the weight and forces that a structure must support as "loads." Loads are broken into two categories: dead loads and live loads. A ***dead load*** is any load associated with the structure itself—the road, steel beams, and concrete. A ***live load*** is any other force applied to the structure due to cars, people, wind, snow, earthquakes, and so on. Today, engineers use computers to model how structures will behave under certain loads. Still, it took one engineer many months to design the structure of the two towers so that they would be as narrow as the architect wanted. The towers had to be able to withstand the predicted loads and maintain their slim appearance.

The architect and the engineers also had to decide what materials to use for construction. Most bridges are made of steel and concrete. Steel is a great material for a bridge because it is very lightweight but very strong. In fact, a steel bridge can usually support a live load equal to its dead load. This means that if you had a steel bridge with a dead load of 25,000 tons, it could support a live load of another 25,000 tons. This would give you a total load of 50,000 tons. ***Total load*** is the sum of the dead load and the live load.

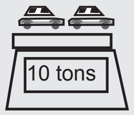
Dead Load + Live Load = Total Load

A ***dead load***
is load on a structure caused by the weight of the supported structure.



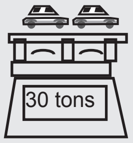
The bridge weighs 20 tons.

A ***live load***
is any other force on the structure caused by people, traffic, weather, and so on.



The cars on the bridge weigh 10 tons.

Total load
is the sum of dead load + live load.



Total load on the bridge = 20 tons +10 tons = 30 tons.

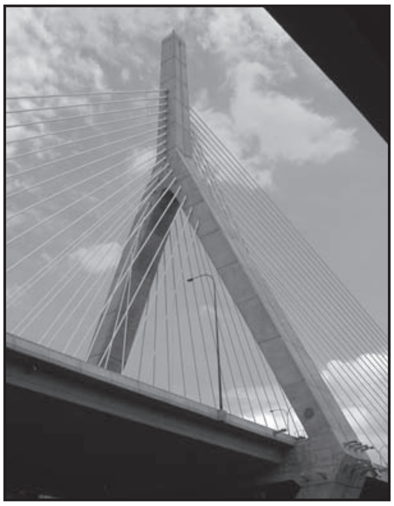


Photo taken by Benjamin T. Erwin

The Zakim is a hybrid of steel and concrete.

Steel vs. Concrete

	Steel	Concrete
Live Load	25,000 tons	25,000 tons
Dead Load	25,000 tons	75,000 tons
Total Load	50,000 tons	100,000 tons

A concrete bridge, on the other hand, can only carry a live load that is 25 percent, or one-quarter, of its total load. In order to carry a live load of 25,000 tons, the concrete bridge must have a dead load of 75,000 tons. That gives us a total load of 100,000 tons! The concrete bridge will be bigger and heavier. That's because concrete must be a lot thicker than steel to support the same live load.

It seems obvious that we'd build bridges out of steel, right? Actually, it's anything but obvious. Concrete, it turns out, is much less expensive than steel, and it's much easier than steel to maintain. Steel corrodes over time, but concrete will not. At the same time, concrete is fire-resistant, whereas steel will melt in a fire. Since the collapse of the World Trade Center Towers on September 11, 2001, we've had to be more careful about how public structures perform during fires. Engineers must consider a wide range of factors in addition to a material's strength.

We designed the Zakim Bridge to be a hybrid of both concrete and steel. That way we can get the best characteristics of both materials. We can also distribute the weight of the bridge more effectively with the hybrid design.

The Great Balancing Act

Menn chose a cable-stayed design for the bridge. The design has two main towers. Both the north and south towers are on land, so we don't have to worry about boat traffic on the river. Cables from the two towers support the main span and the roadways leading to the bridge. The bridge is high enough off of the river that sunlight can easily reach the water.

So how do you design a bridge to carry 100,000 tons of concrete, steel, and traffic? The two towers hold the majority of the weight. The towers straddle the eight-lane roadway, and then rise nearly 300 feet into the air above the bridge. Each tower requires a strong underground foundation that anchors it in place. For the Zakim bridge, the crew sank shafts 140 feet below ground level—deep enough so that each shaft extends through solid bedrock.

These shafts allow the towers to withstand immense compression forces. ***Compression*** occurs when the ends of an object are being pushed toward each other. The cables that attach the towers to the roadway pull the tower down, while the ground pushes the towers up. As a consequence, the towers are under tremendous compression.

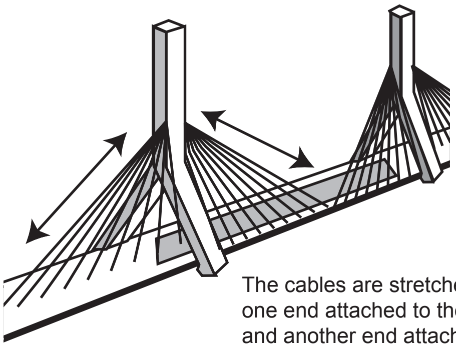
The cables themselves experience another force called tension. ***Tension*** occurs when the ends of an object are pulled away from each other. Just like a rope in a game of tug of war, the cables are pulled in one direction by the roadway and in the opposite direction by the towers.

It makes sense that we would hold up the part of the bridge over the water—called the main span—with cables. There's no other way to hold it up. But why do the cables support the roadway approaches that are over land, which we call the "back span"? Well, if we only attached the cables to the part of the bridge over the water, each tower would be pulled in toward the center of the bridge under the weight of the roadway. The towers would bend inward. This bending would occur due to one side of the tower being compressed and the other side being pulled in tension. So the back span acts as a counterweight, with the cable effectively pulling the towers out so that they do not bend in toward the main span. To improve the effectiveness, the back spans are made of heavier steel-reinforced concrete, while the main span is constructed with a more lightweight steel frame.

Balancing the Bridge

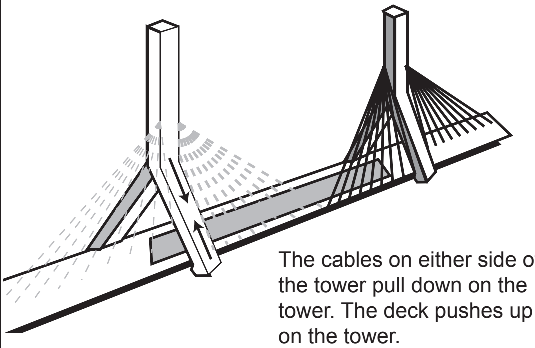
Forces on the Bridge

The cables experience **tension.**



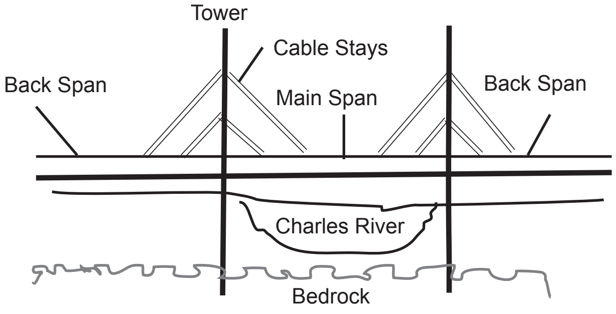
The cables are stretched from one end attached to the deck, and another end attached at the tower.

The towers experience **compression.**

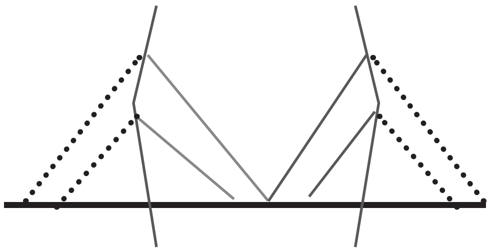


The cables on either side of the tower pull down on the tower. The deck pushes up on the tower.

Parts of the Bridge

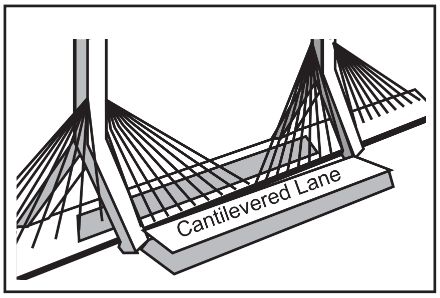


Underground **shafts** reaching 140 feet into solid bedrock provide the **foundation** for the towers.



On the bridge, the **towers** would bend inward toward each other if they were not attached to the **back span**.

A ***cantilever***
refers to a part of a structure that projects into space supported at only one end.



Forces and Structures

Compression
occurs when the ends of an object are pushed toward an object's center.

Tension
occurs when the ends of an object are pulled away or stretched from its center.

Bending
is when one side of an object experiences tension and the other side experiences compression.

Torsion
is a twisting force that results when one side of an object moves in a different direction than the other side.

As you can see, the bridge is a big balancing act! And the act would be much simpler if the bridge were perfectly symmetrical. But it's not. In addition to the main eight lanes, there are two additional lanes of traffic on the east side of the bridge. The extra lanes had to be built on the east because the bridge bumps up against a large sports stadium and a subway station on the west side. These lanes are cantilevered off of the main span. A ***cantilever*** refers to a part of a structure that projects into space supported only at one end. The cantilevered lanes are attached to the bridge on one side. The other side hangs freely over the river.

The weight of the extra two lanes throws the balance of the bridge off a bit, leading to torsion. ***Torsion*** is a twisting force that results when one side of an object moves relative to the other side. When you wring out a washcloth, the cloth is experiencing torsion as your hands twist parts of the cloth in different directions. Similarly, the weight of the two extra lanes causes the bridge to bend slightly. The bend is greatest at the center of the main span, while the back span remains fixed. As a result, the roadway experiences torsion (twisting force). Left uncorrected, the torsion could cause the roadway to fracture. To make the roadway safe for traffic, we moved the cable attachments on the tower a little bit off center to support the extra weight on the east side of the roadway, which prevents the main span from bending. We also made the cables on that side larger to bear the extra load of the additional lanes.

Designing for Construction

Loads that occur during construction often are different than the loads after a structure is completed. Not only did the structural engineers of the Zakim Bridge test a scale model of the bridge, they also tested models of the finished bridge step by step, as it would be at various stages of construction. This was to make sure that the bridge could withstand different loads. Heavy equipment also produces a higher load than a structure will experience with everyday use. In addition, the effects of the wind might be different on a partially built bridge.

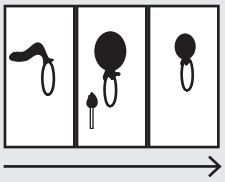
Temperature can also affect how construction materials behave during building. We got a lesson about that when we built the main span of the bridge. We first constructed the back spans of the bridge and then began building both sides of the main span from the towers out over the river. We attached the cables from the towers to each newly constructed section one-by-one as we progressed.

On an unusually warm May morning, we had reached the center of the main span, and the two sides of the main span were ready to be connected with a final piece of supporting steel. Our structural engineer calculated that the last piece of steel should be about 6’ 7.5” long. We had the steel cut with precision instruments by a company in Colorado to ensure that it would be the correct length.

But on this hot, hot day, we found that the piece of steel was too long! That’s because materials tend to expand as they get hotter and shrink as they get cooler. This phenomenon is referred to as ***thermal expansion.*** The steel cutters in Colorado knew that the steel piece would expand or shrink with temperature changes. They had calculated and cut the steel so its length would be just right at a temperature of about 50 degrees Fahrenheit, Boston’s average springtime temperature.

That morning it was about 55 degrees, but by noon the temperature hit 90 degrees! The steel expanded so much that it jammed itself into the incorrect position between the two halves of the bridge! We needed to come up with a solution. One engineer suggested running cold water down the length of the beams to cool them down. We ran hoses and sprinklers all over the bridge. After fourteen hours, the steel finally shrank one inch. That was all we needed to move the beam to the correct position and bolt it into place as quickly as we could.

Thermal expansion
is when materials expand as they get hotter and shrink as they get cooler.



When a flame is held to the test tube, the balloon heats up and expands. As time passes, the balloon cools down and shrinks.

Designing Relationships

Working as a field engineer isn’t just about making things run smoothly on the job site. It’s also about making sure that relationships with every organization involved with the construction of the bridge run smoothly. Sometimes managing these relationships can take a lot of time—and money! Most civil engineering projects involve many different organizations. The City of Boston, the Federal Highway Administration, Amtrak, a host of utilities companies, the Coast Guard, Boston’s subway system, and workers’ organizations are just a few of the groups involved in the Big Dig.

All of these groups influence how we do our work. For one section of the old highway that we are demolishing, we can only work between 1:30 and 4:30 A.M. We can only work when the subway is not operating, because debris could fall onto a moving subway train and injure passengers. The crew is only allowed to work these three hours each day, a total of fifteen hours a week. But because of labor laws, we have to pay them for forty hours a week. And during those hours, we can't make a lot of noise that could disturb the residents in nearby buildings, so we use more expensive equipment. It's very quiet, but it takes longer to complete the work. We've spent a lot of time and money taking this section of the highway down, but it's worth it. The city is happier with how we're getting the job done, so we feel it's a trade-off worth making.

The Big Dig is incredibly complex, but I like trying to figure out all of the different pieces. And I'm proud to be a part of such a historic effort. I've been working on the Big Dig for thirteen years—a long time for just one project—but when I think about the long-term impact of my work, thirteen years is really not so long. The Big Dig will make the roads safer and Boston more beautiful. That's good for tourism and business, and for everyone's quality of life. I feel very satisfied at the end of each day. And I get to work outside!

What's the Story?

1. According to Kirk, what are the main problems that the Central Artery Project is trying to solve?
2. Three engineers are designing a civic center for a small city: an architect, a structural engineer, and a field engineer. Describe how each team member would contribute to the construction project. Name at least three other individuals who might also work on the project.
3. What were the design requirements of the Zakim Bridge?

Designing with Math and Science

4. Describe at least three structural components that contribute to the dead load of your school building. Describe at least three components that contribute to the live load.
5. What is the minimum dead load (in tons) of a steel bridge that must carry 100 tons of traffic? What will be the total load of that bridge?
6. A scaffold has a dead load that is 60 percent of its total load. If the scaffold weighs 1,200 pounds, how much live load is it supporting?
7. Define compression and tension. Would the rope in a tug-of-war contest experience compression or tension?
8. Describe how bending occurs in a diving board with someone standing on the end. You may want to draw a sketch to help you.

Connecting the Dots

9. In "The Art of Engineering," Robert Hartmann discussed how an object's "look and feel" is as important as its function. Would Kirk Elwell agree? Copy two or more sentences from this chapter that support your answer.

What Do You Think?

10. Kirk talks about the importance of keeping relationships with other organizations running smoothly, even if it means spending more money on the project. What might the consequences be if engineers and managers working on the Central Artery Project ignored the interests of civic organizations? How does this relate to your own life? What relationships are important for you to keep running smoothly every day?