A Bridge Built to Sway When the Earth Shakes

Henry Fountain, New York Times, 2-9-12

SAN FRANCISCO — Venture deep inside the new skyway of the San Francisco-Oakland Bay Bridge, and it becomes clear that the bridge's engineers have planned for the long term.

At intervals inside the elevated roadway's box girders — which have the closed-in feel of a submarine, if a submarine were made of concrete — are anchor blocks, called deadmen, cast into the structure. They are meant to be used decades from now, perhaps in the next century, when in their old age the concrete girders will start to sag. By running cables from deadman to deadman and tightening them, workers will be able to restore the girders to their original alignment.

The deadmen are one sign that the new eastern span of the Bay Bridge, which includes the skyway and a unique suspension bridge, is meant to last at least 150 years after its expected opening in 2013. (The existing eastern bridge, which is still in use, will then be torn down.)

But to make it to the 22nd century, the new span may at some point have to survive a major earthquake, like the one that destroyed much of San Francisco in 1906 or the one that partly severed the Bay Bridge in 1989. With two faults nearby that are capable of producing such large quakes, survival is no simple matter.

Say what you want about the project — and as the construction timeline has lengthened past a decade and costs have soared over $6 billion, plenty has been said — keeping the bridge intact in an earthquake has always been the engineers' chief goal.

And to meet that goal, they are going with the flow: designing flexible structures in which any potential damage would be limited to specific elements.

"We wanted to make this bridge flexible so that when the earthquake comes in, the flexibility of the system is such that it basically rides the earthquake," said its lead designer, Marwan Nader, a vice president at the engineering firm T. Y. Lin International.

That contrasts with another potential approach: making the bridge structures large enough, and rigid enough, to resist movement. "Massive and stiff structures would look absolutely ugly and be very, very expensive," said Frieder Seible, dean of the Jacobs School of Engineering at the University of California, San Diego, who tested many elements of the bridge design.

That design includes a 525-foot-tall suspension bridge tower made up of four steel shafts that should sway in a major earthquake, up to about five feet at the top. But the brunt of the force would be absorbed by connecting plates between the shafts, called shear links.

The bridge's concrete piers are designed to sway as well, limiting damage to areas with extra steel reinforcing. And at joints along the entire span there are 60-foot sliding steel tubes, called hinge pipe beams, with sacrificial sections of weaker steel that should help spare the rest of the structure as it moves in a quake.

"At the seismic displacement that we anticipate, there will be damage," Mr. Nader said. "But the damage is repairable and the bridge can be serviceable with no problems."

Emergency vehicles and personnel, at the least, should be able to use the bridge within hours of a major earthquake, after crews inspect the structure and make temporary fixes, like placing steel plates over certain joints. Given that the Bay Area's two major airports would be expected to be out of service after such a disaster, this bridge and the Benicia-Martinez Bridge, another seismically secure span about 20 miles to the northeast, would be "lifeline" structures to bring assistance to the stricken region from an Air Force base inland, said Bart Ney, a spokesman for the California Department of Transportation.

It was an earthquake that made this replacement span, which runs for 2.2 miles between Oakland and Yerba Buena Island in the middle of San Francisco Bay, necessary. The Loma Prieta quake of 1989, the first to occur along the San Andreas fault zone since the 1906 disaster, caused part of the existing steel-truss span to collapse, killing a motorist. The bridge was closed for a month. That quake, with a magnitude of 6.9, caused strong shaking that lasted about 15 seconds and movement far greater than the 1930s-vintage bridge had been designed to handle.

"When the bridge was subjected to those earthquake motions in 1989, it literally was stretched and, basically, one of the spans fell off," Mr. Nader said. Most experts agree that a stronger quake, most likely along the San Andreas or the Hayward fault, in the East Bay, could cause a total collapse of the old span.

There is a strong likelihood of a large earthquake in the Bay Area — about a 2-in-3 chance of magnitude 6.7 or larger before 2036, according to the United States Geological Survey and other institutions. But Mr. Nader and his colleagues were not so much concerned with magnitude measured at the epicenter as they were with ground motions at the bridge site. They planned for the largest motions expected to occur within 1,500 years.

After the 1989 quake, engineers determined that the bridge's western span — a double suspension bridge between San Francisco and Yerba Buena Island — could be made seismically safe, with some modifications. But the eastern truss bridge and causeway would eventually have to come down. (The Golden Gate Bridge was undamaged in the quake, but has been retrofitted to prepare it for a larger one.)

Among the eastern span's problems were that the foundations of the piers were sitting not on rock, but in mud that could shake like jelly in a quake, magnifying the motion.

The planning for the bridge's replacement was delayed by squabbles over the path the new bridge would take across the bay and the "look" of the span, with East Bay residents especially vocal about their desires.

"Folks would say that they feel that all the glamorous signature spans tend to be on the San Francisco side of the bay and that the East Bay gets the simple and utilitarian type of bridge," said Mr. Nader, who earned his doctorate at the University of California, Berkeley, and experienced the 1989 quake firsthand. "So they wanted a signature span."

They got one. Unlike more conventional suspension bridges, in which parallel cables are slung over towers and anchored at both ends in rock or concrete, the 2,047-foot suspension bridge has only a single tower and a single cable that is anchored to the road deck itself, looping from the eastern end to the western end and back again. (With a conventional design it would have been extremely difficult to create an anchorage on the eastern end, in the middle of the bay.)

The new bridge is the longest self-anchored suspension bridge in the world, and it is asymmetrical, with one side of the span longer than the other. (Mr. Nader says it looks like half a conventional suspension bridge.) The choice of such a design raised the cost of the project significantly. In a conventional suspension bridge, the road deck is added last, hung from suspender cables attached to the main cables. In a self-anchored design, the deck has to be built first.

"You have a kind of chicken-and-egg situation," Mr. Nader said. "You need the deck to carry the compression so that the cable anchors into it, but the deck can't carry itself until the cable is there to carry it. So you have to build a temporary system."

That system, called falsework, is basically a bridge to hold up the road deck until the cable is in place — an operation that began in late December and was expected to take up to six months. The falsework needs to be seismically secure as well, adding to the cost.

In all the discussions over a signature span, Mr. Nader said, there was deep interest in having only a single tower. But that created design problems. "In a single tower, there is a lack of redundancy," he said. "Just like a pole. If you have a pole and the pole starts shaking, all the damage will occur at the bottom."

The solution, fleshed out in conversations with the bridge's architects, was to split the tower into four shafts and tie them together with the shear links, which Mr. Nader had become familiar with during his Berkeley years through a professor who had tested them in certain kinds of building frames.

The links are of a special grade of steel that deforms more easily than other grades, and they are placed at specific points along the length of the tower, which affects how the shafts will move in a quake. "Based on where you place the shear links, you can tune the dynamic response of your tower," said Dr. Seible, of the University of California, San Diego.

Under normal conditions, the shear links help to stiffen the four shafts against wind and other loads. "But when you come to larger earthquake loads, these links start yielding," Mr. Nader said. "It's taking the energy that's being pumped into the tower."

Mr. Nader said he already knew which shear links would be most damaged in a major earthquake — those that are about two-thirds of the way up the tower. But the tower would still be structurally sound, he said, and the links would not even have to be replaced immediately.

It's like what happens after a fender bender, he said. "Your car is perfectly drivable, and it's designed that way, with a bumper that can take the shock.

"So you basically stop, just to make sure," he went on. "You see everything's O.K., and you can come in anytime you want to repair your bumper."