Wind tunnel testing of structures – bridges, chimney, tall towers and buildings, antennas – is routinely done to prevent wind induced structural failures of the type described below by Kármán. Many such failues are due to resonances caused by shedding of Kármán vortices.

Jaywant H Arakeri

Collapse of the Tacoma Narrows Bridge

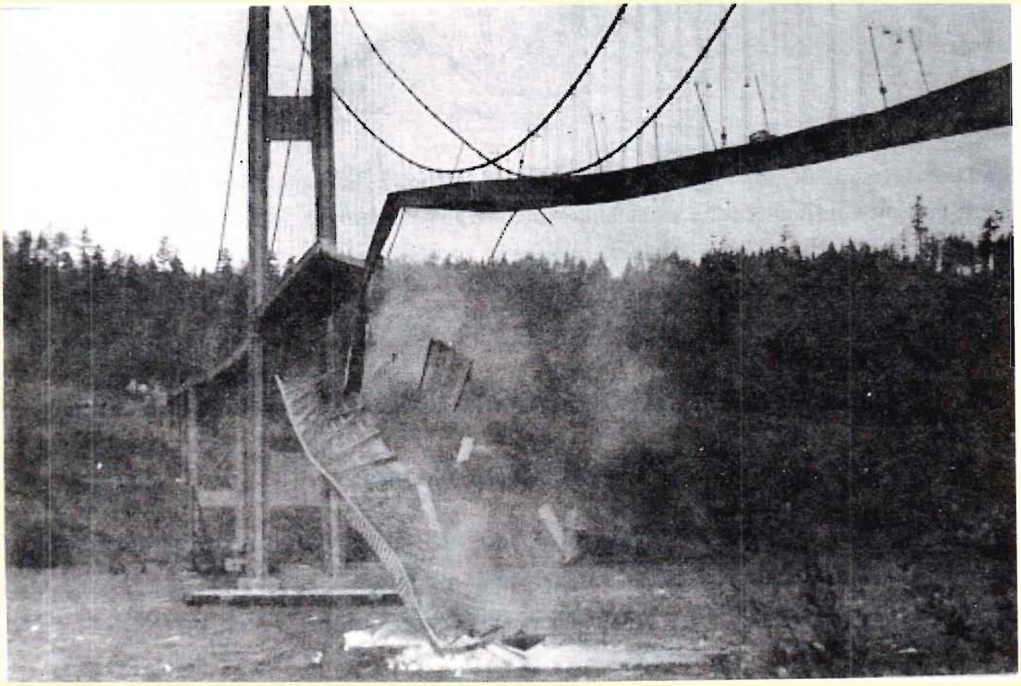
Theodore von Kármán

THE MOST remarkable "adventure" I had with aerodynamics occurred in 1940. It began when a newspaper headline gripped my attention "TACOMA NARROWS BRIDGE COLLAPSES." I read the story with fascination.

The state of Washington's new $6,400,000 suspension bridge, described as the fanciest single span in the world, had broken up in a light gale and plunged 190 feet into Puget Sound. The engineer who built it – L. S. Moisseiff – was rich, successful, and famous in bridge-building circles. The mile-long bridge, the third longest of its kind, was regarded as his finest achievement and the last word in construction. It was a highly flexible, very pretty, thin ribbon of steel spanning the narrowest section of the Sound and connecting the Olympic Peninsula with the rest of the state. Nobody dreamed that less than a year after it was built the bridge would be a mass of rubble.

Yet from the day of its opening on July 1, 1940, and even during its construction, something was noticeably wrong with the bridge. The span undulated in relatively mild breezes, rising up and down as much as four feet in winds of three to four miles per hour. So spectacular was the motion at times that the bridge was soon nicknamed Galloping Gertie, and visitors came from distant areas for the thrill of riding the galloping roller coaster. At one point engineers tried to take some of the sway out of the structure by stabilizing it with heavy cables anchored in concrete blocks at each side. Other measures were also tried. But nothing seemed to change the bridge's galloping motion.

Excerpt from "The Wind and Beyond, Theodore von Kármán, Pioneer in Aviation and Pathfinder in Space", by Theodore von Kármán with Lee Edson, Little, Brown and Co., 1967.



Caption. Photograph showing the collapse of the Tacoma Narrows Bridge. This photo was taken a few minutes after the first piece of concrete fell, and shows a 600 foot section of the suspension span crashing in to the waters below. A stranded car can be seen on the top right corner. (Picture taken from http://www.enm.bris.ac.uk/research/nonlinear/tacoma/tacoma.html)

For four hectic months Galloping Gertie did a roaring business while observers kept a careful watch of her behavior. As no changes in motion occurred, the authorities became increasingly confident that the bndge was structurally safe. Indeed, according to one story, they were planning to replace their high-premium insurance policies with new ones in reduced amount. The morning of the collapse – November 7, 1940 – began with no hint of what was to come. Even though a storm had arisen during the night the bridge was bouncing in the usual manner. By 10 A.M. the wind had risen to forty-two miles per hour, the severest the bridge had yet encountered. But except for an increased amplitude in the oscillation of the midspan, observers still reported little change in the overall bridge movement. Suddenly, at a few minutes past ten, the motion took on a new character. The rhythmic up-and-down action abruptly gave way to a violent twisting spiral motion, and, as one observer put it, the bridge "appeared to be about to roll completely over." Alarmed, the authorities stopped traffic over the bridge.

In the next few minutes the writhing corkscrew motion continued with increasing violence. At one moment one edge of the roadway appeared to an observer to be as much as twenty-eight feet higher than the other edge. The next it was twenty-eight feet lower. The cables in the main span, instead of rising and falling together as in the usual bouncing movement, pulled and wrenched in opposite directions, tilting the deck from side to side as much as forty-five degrees from the horizontal. Lamp poles on the bridge were tilted almost horizontal. For a half hour the steel girders, suspenders, and concrete roadway were subjected to these terrible stresses. Finally at 11 A.M. the structure could take no more. Lamp posts started to give way and fall. The center span buckled, and a six hundred-foot section of girders and roadway tore loose and went crashing into the Sound with a deafening roar. Ten minutes later the rest of the center span followed. The side spans, losing support, twitched and sagged, forcing the towers to lean toward shore; So violent was the shock generated in the side span as the main span fell that Professor F. B. Farquharson of the University of Washington, who had been on the side span taking motion pictures throughout the ordeal, was thrown to the concrete floor. He managed to pick himself up and get out of harm's way.

Only one stalled automobile was on the bridge when it collapsed. The owner, a newspaper reporter, had been hurled from the vehicle when the span started its twisting motions. He managed to hang on to the curb for several minutes until the bridge temporarily quieted, and then crawled on hands and knees to safety. An effort was made to retrieve the car and its remaining occupant, a pet dog, but it was too late. The dog went down with the car and the span – the only life lost in the disaster.

Like millions of people I followed the grim details with tremendous interest. But what really startled me was a news item, on the following day that reported the Governor of Washington as saying the bridge was built correctly and that a new one would be built according to the same basic design. I felt that something was wrong. That evening I took home from Cal Tech a small rubber model of the bridge which one of my mechanics had made for me. I set it on the living-room table and turned on an electric fan. The model wavered in the breeze. I varied the setting of the fan. At a certain wind speed, the model started to oscillate, showing instability which grew greater when the oscillation coincided with the rhythm of the air movement from the fan.

As I had suspected: the villain was the Kármán vortices.

That same night I sent a wire to Governor Clarence D. Martin of Washington. I said in effect that if he were to permit the new bridge to be built in the same way as the old bridge, it would fall in the same way. Expecting spirited discussion, I also wrote a short paper for the Engineering News Record, explaining the cause of the failure and comparing it to the structural instability of a badly designed airplane wing under certain flying conditions. This instability occurs when an accidental twisting of the wing produces forces which increase the twist. I sent a copy of the paper to the University of Washington's Dr. Farquharson, who, I knew, had been conducting studies of the bridge motion.

The Governor did not answer my wire, but a month or so later John M. Carmody, Administrator of the Federal Works Agency, phoned to inform me that the Federal government wanted me on a committee which was being formed to investigate the collapse of the bridge. The committee's chairman was to be O. H. Ammann, a Swiss-born engineer, who was the chief engineer of the Port Authority of New York. He was also the designer of the Triborough Bridge and other bridges in the New York area. Two other civil engineers were on hand. They represented bridge trusses and beams. I said jokingly that I was there only to represent the wind.

My guess was that the bridge experts would have to recognize that the culprit in the Tacoma disaster was the Kármán Vortex Street. The bridge had a solid sidewall, and it was evident to me that the plates making up this wall were pushed by the wind until they shed vortices of air in a periodic manner, causing the oscillations that sent the great bridge to its doom.

In case others had trouble in following this explanation, however, I decided to come to Seattle armed with data to show how the Kármán Vortices caused the bridge to fall. I asked my assistant, Louis Dunn (who incidentally later became director of Cal Tech's Jet Propulsion Laboratory), to test a model of the bridge under varying wind conditions in the Cal Tech wind tunnel. We found that the model was quiet – no oscillations – until we reached a specific wind velocity. Then the model vibrated violently as its oscillation synchronized with the frequency of the vortex shedding. Professor Duncan Rannie made the necessary calculations, and later he wrote up a theory of the vibration of suspension bridges that was an important piece of scientific work. The results of Dunn's and Rannie's experiments fitted exactly with what we knew had happened in Tacoma. I felt well equipped to face the experts in Seattle.

But I hadn't reckoned on the depth and long standing of the prejudices of the bridge engineers. Their thinking was still largely influenced by consideration of "static forces," like weight and pressure which create no motion, instead of "dynamic forces" which produce motion or changes of motion. Bridges had been observed to oscillate in wind before, but nobody had thought such motion was important. Bridge failures were usually blamed on other things. On top of all this, the bridge engineers, excellent though they were, couldn't see how a science applied to a small unstable thing like an airplane wing could also be applied to a huge, solid, nonflying structure like a bridge.

This attitude resulted in some definite undercurrents of rivalry between the experts and me. I recall one meeting where, after a discussion of aerodynamics, Mr. Ammann asked me point-blank to tell him the magnitude of the forces acting on the bridge as I saw them. I took out my documents and gave him the figures. He reached into his own pocket and pulled out a set of numbers, which he identified as having come from Professor Farquharson of the University of Washington.

"See," he said triumphantly, reading them off. "We have calculated our design for a load three times that much."

I was annoyed. This was exactly the kind of thinking that I had been trying to overcome. Mr. Ammann was talking about static load. He was refusing to recognize that small loads can also be very dangerous when they cause repeated oscillation.

On another occasion, when I proposed that the engineers conduct wind-tunnel tests preparatory to building the new bridge, Mr. Ammann interrupted acidly: "You don't mean to say that we shall build a bridge and put it into a wind tunnel?"

I am sure that he knew better, but long tradition was dictating his remarks.

Despite these initial disputes with the engineers I must admit that the sessions at Seattle ended with most of the committee convinced of the worth of the new science of aerodynamics in bridge building. The meetings closed with agreements to experiment with models in the wind tunnel prior to building a new suspension bridge across the Tacoma Narrows. The University of Washington got a contract for "aerodynamic investigations" and so did Cal Tech. So far as I know these were the first contracts of their kind.

There was another difference in thinking between the other engineers and myself. But in this case they proved capable of winning me quickly to their side. A government representative had asked me my fee for the consultation. I started to say fifty dollars a day – my standard fee for government work at that time – but my colleagues quickly hushed me up. They said they would do the talking. They bargained for a sizeable percentage of the value of the bridge, which after all was insured for six million dollars. And they got it. I realized then that architects and engineers who build bridges and other giant structures approach their compensation in the right way, while we aeronautical engineers are only "elevated laborers" insofar as fees are concerned. I learned a good deal in a non engineering way from this experience.

The Seattle meeting concluded with two proposals. One was to replace the solid plate with one containing a lot of big holes and the other was to cut slots in the deck. This would prevent a difference of pressure above and below deck, so there would be no oscillation of the floor of the bridge. The deck slots would not interfere with traffic. These ideas were incorporated in the new bridge across the Tacoma Narrows which was built a couple of years later.

After the meeting, the Federal government also worked up a plan for examining all the major suspension bridges – Golden Gate, Triborough, and Oakland Bay – from this dynamic point of view. All these bridges checked out safely. At the Golden Gate, for instance, the wind meets an open network of stiffening trusses. To develop dangerous oscillations, the wind would have to appear at a certain time and at a velocity of one hundred ten miles an hour over a long period of time. No such velocity has ever been recorded in that area, so I think the Golden Gate is relatively safe.

What about the aftermath of the greatest bridge collapse in modern times? This too proved interesting from a human point of view. When the state of Washington sought to collect the six-million-dollar insurance on the bridge, they found that the insurance agent had pocketed the premium and had not obtained a policy. He never figured that something as big and durable as a bridge would collapse. He ended up in jail, one of the unluckiest men in the world.