Aerodynamics of Suspension Bridges

D. B. STEINMAN
Consulting Engineer
New York City

The decade ending in 1940 witnessed more rapid progress in bridge building, as measured by lengthening spans, boldness of proportions, and increasing magnitude of projects, than all the centuries preceding. It took 40 years (1889 to 1929) to increase the world's record span length from 1700 ft. (Forth Bridge) to 1850 ft. (Ambassador Bridge at Detroit); and then, in the next eight years (1929 to 1937), in two leaps (George Washington Bridge and Golden Gate Bridge), the record span length was more than doubled, from 1850 ft. to 4200 ft. The five longest spans in the world were all completed during this decade (Golden Gate, 4200 ft.; George Washington, 3500 ft.; Tacoma Narrows, 2800 ft.; Transbay, 2310 ft.; Bronx-Whitestone, 2300 ft.) The largest bridge project in history, the Transbay Bridge between San Francisco and Oakland, 8 miles long, costing $77,200,000, was completed in 1936. A record foundation depth of 240 ft. was reached for one of the piers. A bridge project of still greater aggregate magnitude, the "Tor der Welt" over the Elbe River and Elbe Canal at Hamburg, to involve 500,000 tons of steel and to include a 2296-ft. suspension span and a record-breaking plate girder of 854 ft. span, was started in 1938 but construction was suspended at the outbreak of the war in 1939.[1] The decade witnessed new records of span length achieved in steel arches, continuous trusses, vertical lift bridges, bascule bridges, and concrete arches, in addition to the five new record-breaking spans of the suspension type.

When progress is rapid—too rapidly accelerated—we may expect new problems to be discovered, sometimes with the impact of catastrophe.

On July 1, 1940, the Tacoma Narrows Bridge at Puget Sound was completed and opened to traffic. Built at a cost of $6,400,000, with a main span of 2800 feet, it was the third longest span in the world. On November 7, 1940, four months and six days after the official opening, the oscillations of the bridge in a gale increased to destructive amplitude until the main span broke up, ripping loose from the cables and crashing into the waters of Puget Sound.

The cause of the catastrophe was soon recognized by the profession. It was a combination of two factors which were more marked in the design of the Tacoma span than in any other modern bridge. One was extreme *flexibility* of the span; and the other was a peculiar characteristic of the cross-section, that may best briefly be described as *"aerodynamic instability."* The combination of the two, unless corrected, may spell disaster.

The Tacoma Narrows bridge was by far the most flexible of all modern suspension bridges. Whereas authorities had formerly recommended for suspension bridges a minimum width of 1/30 of the span, the width center to center of cables of the Tacoma Bridge was only 39 feet, or 1/72 of the span. It looked like a slender ribbon from bank to bank. This lateral flexibility of the bridge, however, was *not* a factor in the failure. Although the bridge was calculated to have a theoretical maximum lateral deflection of 21 feet at full wind pressure, its actual maximum lateral deflection at mid-span never exceeded four feet, even during the gale which destroyed it.

What proved critical, however, was the *vertical* slenderness of the span. A generation earlier, authorities had recommended for the stiffening trusses of suspension bridges a minimum depth of 1/40th of the span, and this recommendation of minimum depth-ratio had later been reduced to 1/90th to 1/150th for spans between 2,000 and 3,000 feet. The stiffening girders of the Tacoma Bridge were made only eight feet deep in a span of 2800 feet, or only 1/350th of the span! The resulting extreme vertical flexibility *was* a factor in the failure. High flexible towers and long suspended side spans added to the flexibility of the design, and a fatal coincidence of natural oscillation periods of towers and spans aggravated the susceptibility of the structure to the setting up of harmonic motions of dangerous magnitude.

The other factor was the newly discovered phenomenon called *aerodynamic instability*. The Tacoma Bridge had solid-web plate girders, and when a solid bridge floor is framed into the solid webs of such plate girders, the resulting cross-section is peculiarly sensitive to aerodynamic effects, even in a steady wind, particularly if the span is highly flexible. Once any small undulation of the bridge is started, the resultant effect of a wind nearly horizontal tends to cause a building up of the vertical undulations to a higher amplitude; and, if adequate restraining or corrective measures have not been provided, there is then a tendency for the undulations to change into a twisting motion, with further progressive increase of amplitude until these torsional oscillations reach dangerous or destructive proportions. The small initial undulations may be started by the longitudinal component of a quartering wind acting on the highly arched span like an aerofoil or airplane wing to produce lift by pressure or suction, or it may be started by the "von Karman vortex effect" producing a periodic flutter, like the "singing" of telephone wires in a wind. The ensuing building up of the undulations is explained by the "den Hartog effect", like the violent periodic "dancing" of high-tension transmission lines when they are coated with ice to form a vertically elongated surface. The subsequent change from vertical undulations to the catastrophic torsional oscillations of increasing magnitude may also be predicted by an extension of the theory of the "den Hartog effect". The entire action can be demonstrated by mathematical analysis and by simple wind-actuated models.

From the slender proportions and the characteristics of the cross-section, trouble was anticipated by bridge engineers as soon as the design of the Tacoma span was announced. Even before the bridge was completed, when the forms were placed for concreting the roadway, the motions of the span were so violent that the bridgemen working on the steelwork became seasick.

From the day of its opening, the peculiar motions of the span attracted attention and it soon was locally nicknamed "Galloping Gertie". The story is told, strange as it may seem, that traffic on the bridge trebled as a result of its novel behavior, and people came hundreds of miles in their cars to enjoy the curious thrill of riding over a bounding, galloping roller-coaster. For four months the bridge did a thriving business, and apparently the authorities in charge were daily becoming more confident of the safety of the structure. It is even reported that the bridge officials were planning a week later to cancel the insurance policies on the bridge in order to save on the premiums by taking out new insurance in reduced amount.

During the four months of service, the vertical undulations of the bridge, produced by wind action, never exceeded a maximum of five feet. Movements of high amplitude were observed when the wind was blowing as little as four miles per hour.

From about 7 A. M. on the morning of November 7, 1940, the bridge had been persistently undulating for some three hours. A wind of 35 to 42 miles per hour was blowing, and the waters of Puget Sound were whipped into whitecaps. The segments of the span were heaving periodically up and down as much as three feet, with a frequency of about 36 cycles per minute. Alarmed at the persistent character of the wave motion in the span, the highway authorities stopped traffic over the structure. At 10 A. M., the last truck was passing over the span, when something seemed to snap and, suddenly, the character of the motion changed. The rhythmic rise and fall changed to a two-wave twisting motion, with the two sides out of phase. The main span was oscillating in two segments, with nodes at mid-span. As two diagonally opposite quarter-points were going up, the other two diagonally opposite quarter-points were going down. The frequency was 14 cycles per minute and, soon after, changed to 12 cycles per minute. With each successive cycle, the motion was becoming greater, until it had increased from three feet to 28 feet! At one moment, one edge of the roadway was 28 feet higher than the other; the next moment it was 28 feet lower than the other edge. The roadway was tilted 45 degrees from the horizontal one way, and then 45 degrees the other way. Lamp standards in one half of the span made an angle of 90 degrees with lamp standards in the other half. Fortunately, some amateur photographers were at the scene with motion picture cameras, and they have supplied us with a unique and unprecedented record of the action of the span in its dance of death. The motion pictures of the twisting span are unforgettable and the distortions they depict, in character and magnitude, are almost unbelievable. The span twists in gigantic waves, and it is difficult to realize that the girders were made, not of rubber, but of structural steel having a modulus of elacticity of 29,000,000 pounds per square inch. For a half-hour and more, the steelwork and the concrete slab took this terrific punishment. Something was bound to give way. At 10:30 came the first break: one floor panel at mid-span broke out and dropped into the water 208 feet below. The twisting, writhing motion continued. Spectators on the shores were herded to a safer distance away from the span. At 11 A. M. the real breaking up of the span occurred; 600 feet of the main span near the west quarter-point tore away from the suspenders, the girders ripping away from the floor like a zipper; part of the falling bridge floor turned upside-down before the entire falling mass hit the water, sending up spray to a great height. With a 600-ft. section of the bridge gone, the engineers of the bridge structure expected the motion to subside. But the heaving and twisting of the rest of the bridge continued, with the side spans now participating in the motions. Finally, at 11:10 A. M., nearly all the rest of the main span tore loose, and came crashing down. The 1100-foot side spans, now deprived of the counterbalancing weight of the main span, suddenly deflected about 60 feet, striking the approach parapet; then bounced up with an elastic rebound, only to drop again with a final sag of about 30 feet. This was the final gigantic convulsion in the death struggle of a great bridge.

The torn, tangled, twisted stub ends of steelwork sticking out from the towers were all that was left of the main span. It was a tragic, heart-rending spectacle—the helpless mutilated wreck of a great and beautiful structure. Into it men had built their faith and their hopes, only to have these shattered. Once more the elemental forces of Nature had conquered—but such victories are only temporary. After each such set-back, Man proceeds with more perfected knowledge, with greater resourcefulness, and with strengthened resolve, to strive again, to plan again, to build again, to achieve again—all toward renewed triumph and more enduring mastery over the obstacles and destructive forces of Nature.

Only one car was on the span at the time of the failure. It belonged to a newspaper reporter who had to abandon the car and its sole remaining occupant, a pet dog, when the span began its violent twisting motion. Crawling on hands and knees, and desperately clutching the curb, the reporter slowly and painfully made his way along the heaving span until, torn and bleeding, he finally reached safety. His dog went down with the car and the span—the only life lost in the disaster.

About a year earlier, recognizing the unusual proportions of the span, the authorities had appropriated $20,000 for dynamic model tests. These were under the direction of Professor F. B. Farquharson at the University of Washington at Seattle. The scale model was actuated not by wind but by electric solenoids, with circuit controls arranged to produce different modes of harmonic motion. Professor Farquharson succeeded in getting the laboratory model to duplicate all of the known modes of undulation of the bridge, with the main span moving up and down in one segment, two segments, and so on up to nine segments. The one type of motion that finally caused the failure of the structure, namely the twisting motion was, however, entirely unanticipated in these experiments. On the morning of the failure, the Professor was the last man on the span. Even then, with the span tilting more than 28 feet up and down and twisting through an angle of more than 90 degrees, the Professor was making scientific observations and recording notes of the new and unexpected mode of motion that had developed, with little or no anticipation of the imminent destruction of the bridge. When the motion increased in violence, he made his way safely to the side span by scientifically following the yellow line in the middle of the roadway. He was one of the most surprised men when the span he had left began to disintegrate to come crashing down into the Sound.

One of the chief construction engineers, overwrought by the tragic spectacle of the collapsing span, attempted to leap from the bridge after the falling steelwork, but was restrained by his friends.

After the catastrophe, the toll gate at the end of the bridge was barred with a sign marked "Closed". A large sign near the bridge approach advertised a local bank with the slogan "As Safe as the Tacoma Bridge"; the day after the bridge collapsed, that billboard was taken down.

One of the insurance policies covering the bridge had been written by a local agent who had pocketed the premium and had neglected to report the policy, in the amount of $800,000, to his company. When he later received his prison sentence, he pointed out that his embezzlement would never have been discovered if the bridge had remained up but another week, at which time the bridge authorities had planned to cancel all of the policies.

The amazing feature of the catastrophe was the confidence of the bridge authorities in the safety of the structure and their failure to apply adequate corrective measures before opening the bridge to traffic.

Two years earlier, a parallel situation had arisen when the phenomenon of aerodynamic undulations had been discovered on another bridge; in that case, however, prompt and effective corrective measures had been devised and applied before the bridge was opened to traffic, and the information had promptly been presented to the profession.

In the summer of 1938, when the Thousand Islands International Bridge over the St. Lawrence River was approaching completion, peculiar undulations of the 800-ft. suspension span were observed under certain conditions of a quartering wind. This was only a week or two before the date scheduled for the official opening of the bridge and its dedication by President Roosevelt and Prime Minister Mackenzie King. The engineers had to make a critical decision. To open the bridge to traffic without first curing the strange, unexplained undulations was to them unthinkable. There remained but two alternatives: One was to cancel the official dedication and keep the bridge closed until the problem could be solved, and the other alternative was to find a prompt solution of the problem and apply it before the opening date. Applying their analysis and resourcefulness under emergency conditions, the engineers devised corrective measures and promptly installed them. These corrective measures consisted of mid-span guys anchoring girder to cable at mid-span so as to stop relative longitudinal movement, and end-span cable stays running from the ends of the girder to cable bands near the quarter-points of the cable to check any building up of the critical oscillations of span and cables. These corrective devices were hurriedly fashioned in temporary form out of 3/4-inch hoisting rope borrowed from the contractor, and their installation was completed on the morning of the opening day. They proved effective in stopping the undulations of the span, and later were replaced with more rigid and permanent installations. The information on the aerodynamic phenomena discovered and on their successful correction was promptly made available to other bridge engineers through professional publications.

Shortly after the Tacoma Bridge was opened and its undulatory behavior was reported in technical periodicals, the engineers of the Thousand Islands Bridge communicated with the engineers of the Tacoma span, offering the availability of their services and patents to correct the undulations. This offer was not accepted. Three months later the Tacoma span was wrecked by its undulations.

At the time, it had not been disclosed that the corrective measures successfully applied on the Thousand Islands Bridge had been partially followed on the Tacoma Bridge to the extent of installing mid-span stays; but at Tacoma these mid-span stays were apparently inadequately proportioned, besides being made of ropes resisting tension only instead of being made of rigid braces, resisting both tension and compression, as in the permanent installation at Thousand Islands. Moreover, the mid-span stays at Tacoma, without supplementary end-span stays to check vertical motions and twisting, constituted only a half-way measure, not a complete correction. In addition, at Tacoma, hydraulic buffers were installed at the ends of the main span with the thought of damping longitudinal motion, but these apparently were of little efficacy in stopping the undulations of the span. Under the land spans vertical hold-down ropes were installed, and these served to hold the side spans relatively firm (until the main span collapsed). With all these staying and checking devices installed, but without the essential end-span stays, the main span continued to heave in periodic waves of formidable magnitude, and the traffic continued to be allowed over the structure. The mid-span stays served to keep the vertical undulations, with node at mid-span, from breaking into the more dangerous out-of-phase twisting oscillations; without the mid-span stays, the bridge probably would not have lasted as long as it did. On the morning of the failure, at 10 A. M., it appears that one of the mid-span stays at the south cable snapped, throwing double strain and duty on the corresponding connection at the mid-span point of the north cable; overloaded, the north cable band began to slip, and this permitted the prior vertical heaving to change suddenly into the catastrophic twisting motion that, during the ensuing hour and ten minutes, wrecked the structure.

During the weeks preceding the failure, Professor Farquharson had made some wind-tunnel tests on a small-scale model of the cross-section of the Tacoma span. The lift-graph obtained in these wind tunnel tests showed the downward or negative slope that is a characteristic of sections having "aerodynamic instability." From such lift-graph, as had been previously shown by Professor den Hartog, amplification of vertical undulations can be predicted. The point that was missed, however, was that the same wind-tunnel lift graph, by an extension of the analysis, also predicts the development and amplification of the more dangerous twisting oscillations. This would have been revealed even more clearly if a torque graph had been recorded in the wind tunnel tests.

In the same series of tests, Professor Farquharson studied various methods of modifying the Tacoma cross-section so as to reduce its vulnerability to the aerodynamic effects. One of these proposals was to cut rows of large holes in the webs of the stiffening girders so as to reduce their presented vertical area; but this would have involved weakening the section as designed. Another proposal was to affix circular fairing in front of the windward girder so as to deflect the wind. In fact, on the morning of the failure, the authorities were securing prices on the material for such streamlining of the bridge. This proposal, however, would have been of doubtful efficacy, especially if such fairing were to be affixed to both girders in order to provide for wind from either direction.

There are a number of economical ways in which the bridge could have been made safe prior to the day of its failure, also a number of emergency measures by which the structure could have been saved on the morning of the failure.

During the investigations that followed the disaster, one of the engineering experts retained by the insurance companies, Holton D. Robinson, 78 years old, calmly walked out over the 17½-inch cables, each 5900 ft. long and 450 feet high at each tower, to examine the condition of the wires and to cut out samples of the wire at mid-span. His feat was rendered more difficult and hazardous by the fact that the hand-ropes in the main span had been wrecked. In the subsequent conference he was asked how much it would have cost to equip the Tacoma bridge with cable stays such as had been used at Thousand Islands. "Much less than the money that was spent on the laboratory model studies," was his reply.

The Tacoma Narrows Bridge was perfectly safe for all the loads and forces for which it had been designed, namely dead load, live load, temperature, and *static* effect of wind load. In common with other bridges, however, it had not been designed for the *dynamic* effect of wind load. By this we mean the effect of a steady wind, acting on a flexible structure of certain types of cross-section, to produce a fluctuating resultant force automatically synchronizing in timing and *direction* with the harmonic motions of the structure so as to cause a progressive amplification of those motions to dangerous or destructive amplitudes.

On the morning of the Tacoma failure, the gale of 35 to 42 miles an hour meant a wind pressure of only about 5 pounds per square foot. The bridge had been designed for a wind pressure of 50 pounds per square foot, and was structurally safe for a *static* wind load of 50 pounds per square foot. It was destroyed however by the *cumulative dynamic* effect of a wind pressure of 5 pounds per square foot.

This aerodynamic behavior of a bridge was not entirely unprecedented. It had happened before, but the lesson had been missed by the profession.

In 1848, Charles Ellett completed his greatest work, the suspension bridge over the Ohio River at Wheeling with the record-breaking span of 1010 feet. It was, at the time, the world's longest span. Six years later, on May 17, 1854, that great bridge was destroyed by the wind. Technical publications recorded the disaster merely as another bridge wrecked by a powerful storm, and the lesson was lost to the profession. We find the complete story of the disaster, however, in an eye-witness account by a reporter, printed the following day in the "Wheeling Intelligencer" and reprinted four days later in the "New York Times". A remarkable parallel to the Tacoma catastrophe is revealed by the following excerpts from the original newspaper account (italics have been supplied):

> With feelings of unutterable sorrow, we announce that the noble and world-renowned structure, the Wheeling Suspension Bridge, has been swept from its strongholds by a terrific storm, and now lies a mass of ruins. Yesterday morning thousands beheld this stupendous structure, a mighty pathway spanning the beautiful waters of the Ohio, and looked upon it as one of the proudest monuments of the enterprise of our citizens. Now, nothing remains of it but the dismantled towers looming above the sorrowful wreck that lies beneath them.
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> About 3 o'clock yesterday we walked towards the Suspension Bridge and went upon it, as we have frequently done, enjoying the cool breeze *and the undulating motion of the bridge* . . . We had been off the flooring only two minutes, and were on Main street when we saw persons running toward the river bank; *we followed just in time to see the whole structure heaving and dashing with tremendous force.*

> For a few moments we watched it with breathless anxiety, *lunging like a ship in a storm;* at one time it rose to nearly the height of the tower, then fell, *and twisted and writhed,* and *was dashed almost bottom upward.* At last there seemed to be a *determined twist along the entire span, about one-half of the flooring being nearly reversed,* and down went the immense structure from its dizzy height to the stream below, with an appalling crash and roar.
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> For a mechanical solution of the unexpected fall of this stupendous structure, we must await further developments. We witnessed the terrific scene. The great body of the flooring and the suspenders, forming something like a basket swung between the towers, was *swayed to and fro like the motion of a pendulum. Each vibration giving it increased momentum,* the cables, which sustained the whole structure, were unable to resist a force operating on them in so many different directions, and were literally twisted and wrenched from their fastenings. . . .
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> We believe the enterprise and public spirit of our citizens will repair the loss as speedily as any community could possibly do. It is a source of gratulation that no lives were lost by the disaster.

The newspaper man who wrote the foregoing dramatic account unknowingly summarized the crux of the aerodynamic phenomenon he had observed when he used the significant phrase: *"Each vibration giving it increased momentum."* And when he stated that the mechanical solution of the failure "must await further developments," he wrote better than he knew. In those days bridge builders were not thinking in terms of aerodynamics, and the profession had to wait nearly 90 years for the further developments that finally gave them an understanding and mastery of the problem.

Even before the Wheeling Bridge disaster, a similar aerodynamic destruction of a span had been recorded. On November 30th, 1836, one of the spans of the Chain Pier at Brighton, England, was destroyed by a storm. This was about three years before the invention of photography; but a scientific eye-witness has left us sketches recording, with remarkable fidelity, the wave motions and the final collapse of the span. This was Lieut. Col. Reid of the Royal Engineers, who was distinguished for his researches on storms and who was later appointed Governor of Bermuda. In his two published drawings of the Brighton disaster the first sketch shows the sine-curve undulations of the span, in two segments with node at mid-span. The second sketch shows one half-span breaking and falling into the sea. These drawings reveal a striking similarity to the photographic views of the undulations and collapse of the Tacoma Bridge. The parallel between the two bridge disasters is further confirmed by the following excerpts from Col. Reid's account published in 1838 (italics supplied):

> The same span of the Brighton chain-pier (the third from the shore) has now twice given way in a storm. The first time it happened in a dark night . . . This time, it gave way half an hour after mid-day, on the 30th of November, 1836, and a great number of persons were therefore enabled to see it. The upper one of the two sketches annexed, shews the greatest degree of *undulation* it arrived at *before the road-way broke;* and the under one shews its state after it broke; but the great chains from which the road is suspended remained entire. . . . The second and fourth spans . . . also undulated greatly during the storm, but not in the same degree of undulation of the third span. *A movement of the same kind* in the roadway has always been sensibly felt by persons walking on it in high winds; but on the 29th of November, 1836, the wind had almost the same violence as in a tropical hurricane. . . . [Note: A. M. called November 29, P. M. called November 30—D. B. S.] For a considerable time, the undulations of all the spans seemed nearly equal. The gale became a storm about eleven o'clock in the forenoon, and by noon it blew very hard. Up to this period many persons from curiosity went across the first span, and a few were seen at the further end; but soon after mid-day the *lateral oscillations* of the third span increased to a degree to make it doubtful whether the work could withstand the storm; and soon afterwards *the oscillating motion across the roadway,* seemed to the eye to be lost in the undulating one; . . . the undulatory motion which was along the length of the road is that which is shown in the first sketch; but there was also an *oscillating motion* of the great chains across the work, though the one seemed to destroy the other. . . . At last the railing on the east side was seen to be breaking away, falling into the sea; and immediately the undulations increased; and when the railing on this side was nearly all gone, the undulations were quite as great as represented in the drawing.

In the *Transactions of the Royal Scottish Society of Arts,* Vol. I, 1841, John Scott Russell, vice president of the Society, published a paper entitled "On the Vibration of Suspension Bridges and other Structures; and the Means of preventing Injury from this Cause." In this paper, *published a hundred years ago,* the author discussed "the general nature of the vibrations that destroy suspension bridges and other slender structures"; he showed how the Brighton span failure confirmed his prior investigations and predictions; and he recorded in simple, logical form the elementary, fundamental principles of applying systems of stays to break up the natural modes of harmonic motion of a structure.

Thus, as far back as 1841, the basic, elementary principles involved were already analyzed, tested, and recorded. A century later, at great price, bridge engineers had to learn the lesson over again. Let us resolve that this time the lesson, in its full significance, will be clearly and emphatically impressed upon all future bridge engineers, so that this kind of bridge failure shall never occur again.

This narrative of the unfortunate Tacoma Bridge catastrophe would not be complete without a sincere tribute to the eminent designing engineer of that great span, and to his prior distinguished contributions to the science and art of suspension bridge design. The span failure is not to be blamed on him; the entire profession shares in the responsibility. It is simply that the profession had neglected to combine, and apply in time, the knowledge of aerodynamics and of dynamic vibrations with its rapidly advancing knowledge and development of structural design.

The Tacoma Narrows Bridge represents the culmination of a trend in bridge design. A century ago, bridge engineers began to realize that suspension bridges needed stiffening to reduce deflections under load and to prevent destruction by wind. Stiffening trusses and stays were introduced by John A. Roebling and his contemporaries. Subsequent stiffening trusses were made deeper and deeper, reaching a climax in the obviously excessive and clumsy proportions of the Williamsburg Bridge completed in 1903. Thereafter the trend was reversed. The introduction of the "Deflection Theory" for suspension bridge design revealed that prior spans had been proportioned with needlessly excessive depth and section, and placed a premium of economy on more flexible design. Increased emphasis on artistic appearance placed a further premium on grace and slenderness. Stiffening trusses were made of shallower and shallower depth. Towers were reduced to more and more slender and flexible design. Then, commencing about 1929, with such effective examples as the 1033-ft. span of the Cologne-Muhlheim Bridge over the Rhine, the use of stiffening girders instead of trusses acquired increasing application, resulting in maximum artistic simplicity of line. Thus improvement in analysis, the demands of economy, and considerations of aesthetics—all combined to accelerate the trend toward increased slenderness of proportions.

About 1935, considerable thought and study were given to developing a specification for the necessary minimum stiffness of suspension spans. Formulas and graphs were devised for rating the comparative rigidities, but there appeared to be no way of establishing a proper criterion of satisfactory stiffness. Where should the line be drawn to separate adequate from inadequate coefficients of rigidity? How far could we safely go? The answer to this question was lacking. *Now we have the answer.* Four bridges completed in 1938 and 1939 have rigidity coefficients below a certain value; these four spans have given some trouble under aerodynamic action, and have required stays to check their undulations. Then came the Tacoma Narrows Bridge completed in 1940; this span had a still lower coefficient of stiffness, and it succumbed to the effects of its extreme flexibility. Hence now we know where to draw the line: below a certain measure of stiffness, we may expect some difficulties requiring corrective measures; and if we go below a still lower indicated stiffness ratio, we may expect disaster.

Such is the price we pay for progress. The great advances of the human race have been won by those who showed the courage to go beyond the charted course. It is only in such manner that new knowledge can be gained—that new progress can be achieved. When progress is rapid, we may expect to stumble. The test of Man is that he profits by his experience and continues onward, with new wisdom and knowledge, toward still greater enterprise and achievement.