STRENGTH OF A BRIDGE

An Explanation, Without Mathematics, as to How It Is Calculated.

IT is the habit of the public to accept without question the conclusions of qualified and reputable experts on every subject which is necessarily outside of popular knowledge. The engineer builds a bridge and the people cross it with rarely a thought as to its stability. They assume that it is strong enough for the purpose for which it is designed. So the engineer assumes also, or he would not allow it to be opened for use.

The difference between the two assumptions is that one is wholly on faith, and the other is the result of the most painstaking and laborious calculation. This is natural and proper. In all the relations of life we are compelled to accept on faith the opinions of those who are rated as experts. If we are curious as to the composition of matter we ask the chemist, whose analysis is accepted with confidence. If we want to know if a building is strong enough to carry the weight of machinery or merchandise we desire to put in it, or a bridge strong enough to carry the loads to which it is subjected in use, we ask the engineer, who covers quires, or it may be reams, of paper with calculations we could not follow if we would, and gives us results in the shape of an opinion which we accept with entire confidence. It may not be correct, but it is the nearest approximation to truth we have opportunity to make, and on it we must "take the chances." That professional opinion is infallible no one assumes. None knows this better than the engineer, and against dangerous and misleading errors of judgment he endeavors to guard himself and those who rely upon his judgment by allowing what he calls the "factor of safety." He might with equal propriety and a great deal more truth call it the factor of ignorance, and no doubt he would if the term were not likely to be misunderstood by those not initiated in the mysteries of the drawing board and the yellow pad.

It is because the engineer, however wise, is to a great extent ignorant of the materials he is dealing with that he prescribes a strength in construction which shall be two, three, four, or more times as strong as is theoretically necessary. His admitted ignorance also explains why it is that when an increased load, more or less obvious deterioration, or the "general flavor of mild decay" which comes with age, intrudes upon the margin of allowance which he calls the factor of safety, he becomes nervous and distrustful and urgently recommends that measures be taken to strengthen the structure so that it may again be made two, three, four, or more times as strong as it apparently needs to be, or else that the loads it is expected to carry be reduced so that the relation originally aimed at may be restored. Experience has shown that anything just strong enough for its normal work is not strong enough for the casual and unexpected strains to which it is subjected from time to time from natural or artificial causes. The proneness of the unexpected to happen is a phenomenon which the engineer forgets at his peril.

Recently a commission of experts undertook the examination of the Brooklyn Bridge for the District Attorney, and made a report which the average reader doubtless found in part unintelligible and in part unsatisfactory. He looked in vain for a definite statement as to whether the bridge in its present condition and under the loads it carries is or is not safe. The reason he did not find it is that the question is not one to which it is possible to give a categorical answer. The engineer does not live who could give such answer and demonstrate it with less preparation than the work of half a year. To reach the conclusions he feels warranted in expressing he exhausts the resources of the higher mathematics, but inasmuch as his data must be to a great extent assumed, he naturally hesitates to declare himself sure of anything he cannot see, measure and test to destruction. His inability to do this leaves a great many X's in his equation for which he has to assume arbitrary values.

To follow and verify the calculations which the bridge engineer must make to determine the safe working load and ultimate strength of a structure would be neither interesting nor instructive, but both interest and instruction may be found in a hasty sketch of what a conscious engineer, with a full realization of his moral and legal responsibilities, has to consider and allow for in order to form an opinion upon which he is willing to rest his professional reputation.

It must be understood at the outset that strength and weakness are relative terms. In the case of a bridge, they are relative to the loads to be carried and the stresses and strains to be resisted. The first consideration of the bridge designer is that his structure shall hold itself up. To dispose a number of hundreds or thousands of tons of iron or steel in the air and make it self-sustaining is by no means as easy a problem as it may appear. The collapse of bridges during construction by reason of the fact that at a critical moment their weight exceeded their structural strength is not unheard of in engineering experience. If the key piece drops out the whole puzzle collapses, and it is the rule that the bridge which will hold itself up is strong enough to carry a considerable load as well. There are anxious days in the bridge engineer's work when he does not know whether before night he will see it all drop to the bottom of the river, or at least a part of it. To guard against such an accident is almost always difficult, and sometimes impossible, and that it sometimes happens does not necessarily impeach the intelligence of the engineer. The foreman of the construction gang may be at fault, or the apparatus for raising the parts may be defective and break. This, however, brings us into another phase of the subject.

Bridge designing begins with a sketch of the structure, which gradually develops into a working drawing. Thus far the engineer depends upon rules and formula which crystallize experience and give him a general approximation to accuracy in roughing out his construction. The three chief problems with which he has to deal are susceptible of classification as follows:

Dead weight, which includes everything which is a part of the structure and which tends to pull it down by static pressure.

Live weight, which includes every form of moving loads.

Wind strains, which include every result of atmospheric disturbance from a zephyr to a hurricane.

In the simplest construction of its class, the ordinary highway bridge, the calculation of these various strains, if properly done, taxes the knowledge of a very capable engineer. That a great many bridges are not calculated at all, but are built by "rule of thumb," explains why accidents occur from time to time which dump innocent citizens into rivers or precipitate trains into gullies. In the case of a railroad bridge with long spans, it becomes much more difficult, and when a suspension bridge is reached, it is easier to calculate the transit of Venus than to verify its strain sheet.

The differences found to exist in materials must all be taken into account. Wood is measurably constant. The strength of a pine, spruce, white oak, or other timber of given dimensions, free from wind shakes, large or loose knots, decayed or sap wood, worm holes or other defects impairing its strength or durability, is measurably constant, and may be safely taken from the standard tables. The same is true of methods of framing, which have been worked out through the centuries. Of stone, however, the engineer cannot safely take very much for granted. He must test the crushing strength of any stone he purposes using, and ascertain for sure whether it disintegrates or decomposes when subjected to the action of the weather. If any uncertainty exists on these subjects he must insure an excess of strength by using an amount of material far in excess of his theoretical requirements.

In the domain of iron and steel construction he enters a new sphere of mathematics. All tension members are now of steel, which in general terms is 33 1-3 per cent. stronger and 25 per cent. cheaper than trustworthy iron. Where dead weight must be limited to the least amount consistent with massiveness and strength, he should prescribe the formula by which the steel is to be made. He must make sure that the phosphorus does not exceed 0.06 of 1 per cent. in steel made by the so-called acid process, as in the Bessemer converter, nor over 0.04 of 1 per cent. in steel made by the basic method in the open-hearth process. In important bridge work it is usual for the company or municipality for which the work is ordered to have an inspector, and sometimes several inspectors, at the mill where the work is made, to watch every step of the process and promptly reject all material which does not come up to specifications. Tensile strength, elasticity, and ductility are determined by samples cut from the finished material after rolling, which are tested to destruction in a machine which records the elastic limit, elongation, and ultimate strength. Care must be taken that no work is put upon steel between the temperature of boiling water and that at which hardwood sawdust sprinkled on the metal will ignite. Somewhere within this range, which constitutes blue heat in the color scale of steel, lies the "critical temperature" at which steel becomes brittle under manipulation. All medium steel must have an ultimate strength of 60,000 to 69,000 pounds per square inch, an elastic limit of not less than half the ultimate strength, and a minimum elongation of not less than 22 per cent. in 8 inches. After heating to redness and quenching in water it must be able to stand bending to a curve with an inner radius one and a half times the thickness of the material without cracking. Soft steel must have an ultimate strength of 54,000 to 62,000 pounds, and an elongation of not less than 25 per cent. in 8 inches. In good bridge practice, steel castings must show in test an ultimate strength of not less than 67,000 pounds. In fact, everything which enters into a bridge in the way of metal must conform to the most exact specifications, and the conscientious engineer will not assume that it does if there is any way of finding out whether it does or not.

With such materials and a sharp inspection in the mill, as well as on the ground, it would seem that he could make his design with a great deal of confidence, even though impelled by considerations of economy to hew as close as practicable to the line of absolute strength. As a matter of fact, however, the only thing he can be sure of is that his materials are not as strong practically as they are theoretically. He is warranted in assuming that there are concealed flaws and defects which the most conscientious care in manufacturing and inspecting will not find. This is so demonstrably a matter of universal experience that he usually considers it necessary to take four as his factor of safety—that is, he makes everything four times as strong as would carry the load without fracture if everything was as strong as it appears to be. This, however, is not so excessive as it appears. Elastic limit is what he must consider, and a factor of safety of four calculated from the ultimate strength is only about a factor of safety of two calculated from the elastic limit. Theoretically, the elastic limit is about 60 per cent. of ultimate strength in the case of steel, but it is well to keep well within 50 per cent. of this in designing a bridge. All of this would be necessary if the only function of a bridge was to hold itself up.

In dealing with loads the engineer has to assume that the bridge will at all times be under the greatest strain it is capable of bearing. As a matter of fact, he knows it will not be, but as he does not know when it may be, he cannot take any chance of there ever occuring a moment when it will not be. This is probably intelligible, though it is somewhat suggestive of the language in which the Irishman disclaimed a former acquaintance: "No, I don't know you, and if, when I did know you, I had known you as well as I do now, I'd never have known you at all."

The dead weight has his first consideration. Bridges seem so strong that there is a constant tendency to overload them. We find them carrying water and gas mains, trolley tracks, telegraph, telephone, and electric light and power wires, which were no part of the designer's calculation. Sometimes, also, we find them carrying snow enough to represent an increase in dead weight amounting to more than the live weight at any time of use. Once in a while, during a cold Winter storm, they will become covered with ice, and the weight of this is sometimes great enough to strain every member far beyond the absolute danger point. At such times the live load is liable to be as great as at other times. All of these normal, if infrequent, happenings, must be taken into account, and when they are overlooked the bridge is liable at any moment to become unsafe.

Live loads are variable through so wide a range that everything like close margins must be avoided. They are more apt to be constant in a railroad bridge than in a highway bridge, where a physician's gig may be followed by a bronze group of heroic proportions on the heaviest truck made. The passing of such a group from New York to Brooklyn probably strained the East River suspension bridge more severely than anything in its history. Such loads do not pass every day, but it is fair to assume that every day witnesses the passage of something which never crossed before and probably never will again, and which at the moment of passing develops strains far greater than the bridge designer ever contemplated.

In calculations of live loads, allowance must be made for jar, shock, and vibration. The way a live load moves makes a vast difference in its effect upon the bridge over which it moves. I remember one day at Niagara seeing the highway suspension bridge subjected to a greater strain than it had probably ever before known. A steer, becoming frightened, escaped from a drove on the American side and started across the bridge. He struck a rhythmical trot, so that his considerable weight was thrown first on one side and then on the other. Before he had gone a hundred feet the bridge took up the motion and began to swing, with increasing violence, straining at the guy ropes and menacing the whole structure with collapse. Fortunately the steer was stopped before he reached the middle of the bridge, and in a few seconds the swinging ceased. Soldiers in crossing the bridges are always required to break ranks and wander over, every man for himself—what is, or used to be known in the manual as route step. The reason for this is that while the bridge may be many times stronger than is necessary to carry the weight of a regiment, it would be promptly destroyed by vibration if the body moved in step across it. Accidental happenings setting up violent vibration and oscillation must be counted on and provided for in bridge designing.

The usual rule for city highway bridges is to allow for a live load a strength of floor and its supports in the parts devoted to vehicles which will be safe under a load of twenty-four tons concentrated on two axles, ten feet centres. Footwalks are usually calculated for a load of 100 pounds per square foot. The rules of practice vary with different kinds of bridges intended for different kinds of service. To go into details on this subject would be tedious.

Wind strains are extremely variable. To provide for them it is necessary to give a bridge great lateral stiffness, which is secured by lateral bracing. To resist wind pressures, a bridge must be able to resist a lateral force equivalent to 300 pounds per foot of span, and half of this must be treated as a moving load.

Expansion and contraction are also of first importance in the calculations of the bridge engineer who deals with iron or steel. If everything staid where he put it and maintained the same relations at all times, his task would be much simplified. In point of fact, a constant movement is going on in his structure. Every piece is coming and going, so to speak, and the strains set up by this constant effort of readjustment are infinitely difficult of calculation. In the case of the main span of the Brooklyn Bridge, the crown of the arch is raised by the shortening of the cables by contraction and lowered by their expansion. Their change of length between 120 F and zero is 16.26 inches. Every other piece of steel in the structure lengthens or shortens in proportion. The average variation in length with each degree of temperature gained or lost is .007 of an inch in each 100 feet. Consequently, while at, say, 60 F every part of a bridge may bear the normal relation to every other part, every part begins to pull or push as it grows warmer or colder. The strains thus set up are irresistible, since they are exerted with a power greater than the strength of the material. If not accommodated they will accommodate themselves. Expansion and contraction are the most destructive forces with which the engineer has to deal.

In bridge building there are two divisions of work—the theoretical and the practical. So far as results are concerned, they are perhaps equally important. Erection demands constant care and supervision. Careless riveting may very well reduce the factor of safety to a minimum, and this is true of every detail of construction. The conscientious bridge engineer who can sleep well while construction is in progress is immune to insomnia.

This meagre outline will perhaps give some idea of the technical requirements in bridge engineering, as regards design and construction.

To even suggest what has to be done, and how, to inspect an old bridge and pass judgment on its actual condition and safe strength, would be impossible without going into the mathematics of the subject. In such work a great deal has to be assumed, for the reason that it cannot be accurately determined. What deterioration has taken place in members concealed from sight is a matter of conjecture. To verify the original strain sheet is impossible, and the closest approximation to accuracy which can be had leaves many things open to debate.

Suppose, for example, the engineer called upon to answer definitely yes or no to the question, Is the Brooklyn Bridge strong enough for the service to which it is subjected? should undertake to prepare himself by making tests. He would take out so and so many suspender rods and test them to destruction, but he could not possibly know that all the other thousands of suspender rods were as strong as the average of those tested. Some have doubtless suffered more deterioration than others from being in more exposed positions or experiencing greater strains in use. In the case of the cables he might retest some of the wire strands which went into them and by multiplication estimate their strength, but he could not possibly know whether every strand was still intact and unimpaired. In a word, he could only verify the original strain sheet by taking the whole structure to pieces and putting it together again, testing meanwhile as many samples as might be necessary to show what had happened to the material in twenty years.

From all of this it may appear that the knowledge of the bridge engineer is not knowledge at all, but good judgment based upon a wide and general observation of phenomena under various conditions. Well, this is just what it is. The physician cannot have access to the vital organs of the patient, but he is rarely at fault, if skillful, in deciding whether the heart is impaired or the lungs are imperfect or other and less accessible organs out of tune. Sometimes the autopsy contradicts his conclusions, but in a great majority of cases it confirms them. Bridge judgment is scientific diagnosis.

Encroachments upon the theoretical factor of safety due to deterioration and increased loads are danger signals, but when the actual point of imminent risk of collapse is reached, no one can certainly tell until the structure falls. The engineer is not omniscient. He deals with the unknown at every step, and that his work is so generally safe and satisfactory is largely because he recognizes the limitations of his knowledge and insists that the allowance for what he does not and cannot know shall be ample.

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