Wind & Earthquake Response in Very Long Span Cable-Stayed and Suspension Bridges

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Very long span suspension bridges are flexible structural systems. The introduction of these cable suspended structures has been profoundly enhanced by the development of new structural materials and computer methods of analysis. Cable suspended systems comprise both categories of suspension bridges and cable stayed bridges. These flexible systems are susceptible to the dynamic effects of wind and earthquake loads.

Wind loads and earthquake loads make up what we call the lateral forces on a structure. A fundamental problem in dealing with these lateral forces is the computation of the magnitude of the wind load and the earthquake load. The structural effects, the response of the structure to such random lateral loads, and the subsequent design of an efficient lateral load resisting system, dictate very sophisticated methods of analysis and design. Such methods include but are not limited to classical methods of structural analysis, computer methods of structural analysis, experimental methods, as well as other validation and verification methods.

The finite element methods present the engineer with a powerful structural analysis technology reliant on modern digital computers. Preprocessors and postprocessors are available to facilitate the input and output data of such advanced computers. The art in all this technology is to present the engineer with results that can predict reliably the response of such complicated structural systems. Linear as well as nonlinear response, aerodynamic performance, structural stability, the choice of light materials for the superstructure, and other design considerations constitute the essence of the problem.

Wind tunnels are available to help us understand the aerodynamic problem associated with the structural vibrations of long span suspension bridges subject to wind loads. Shaking table experiments also can help us understand the dynamic behavior of long span suspension systems.

A structural designer is concerned with both aspects of strength and serviceability through out the expected service life of the structure. The engineer needs a proper understanding of the following items to address this problem:

1. The structural system and its characteristics,
2. The nature of wind forces,
3. The nature of earthquake forces,
4. The computer modeling process,
5. The limitations of the commercial software utilized,
6. Wind tunnel experiments,
7. Shaking table instrumentation, and
8. Reconciliation of the numerical and experimental results.

Suspension Bridges

Suspension bridges are a viable structural solution to spanning long distances. It is imperative that the cable system proposed would be capable of supporting its own weight in addition to the imposed loads of the superstructure. The weight of the cable is assumed to be distributed uniformly along the arc length of the cable. The choice of an optimum sag to span ratio is related to aesthetics as well as to aspects of minimizing the total weight of the main cable.

The main structural elements of a suspension bridge are:

1. The main cable system,
2. The towers or pylons,
3. The anchorage, and
4. The stiffening girder.

Very long suspension bridges require external anchorage to massive concrete foundations. This is called external anchorage. There are many studies that have shown that coupling of cable stays with a suspension system do not serve to reduce the deflections of the bridge structure. The presence of these inclined cable stays serves the purpose of enhancing the torsional rigidity of the structure. Modern suspension bridges do not utilize cable stays in conjunction with a suspended system. However, there are bridges were such combination is displayed.

An example of that is the San Marcos Bridge in El Salvador, with a system of inclined cable stays in the form of a network of cables. Such a concept is referred to as a cable-truss configuration. The Brooklyn Bridge, built by John Roebling, shows inclined cable stays in addition to the conventional suspension cable and hangar system. The German engineer Dischinger proposed the addition of inclined cable stays to reduce the deflection suspension bridges. However as Leonhardt points out, such systems are not very effective in reducing the deformation of suspended systems. The current longest suspension bridge in the world is the Akashi-Kaikyo Bridge in Japan. This bridge is designed for an earthquake of magnitude 8.5 on the Richter scale and a wind speed of 80 miles per hour. The main span of this bridge is 6529 feet long. Almost all of the existing suspension and cable stayed bridges are made of structural steel cables.

A recent development points out to the advantages of carbon-fiber-reinforced-plastic cables. These are superior to steel cables when it comes to strength and corrosion resistance. Such composite cables provide the engineer with an equivalent elastic modulus comparable to that of steel cables.

Current technology points out to the fact that for bridge systems of 1100 feet suspended span a cable stayed system provides the engineer with an optimal solution. For longer spans a suspension system should be considered. The cable stayed bridge system however, provides the engineer with additional stiffness since the cables are taut. This mechanism of prestressing the cables allows us to decrease the flexibility of a suspended span. This reduction in system flexibility reduces the vibrations of the bridge structure under the effects of wind loads. Gimsing, Menn, Mallick, Starossek, and others have addressed the problem of a very long span suspension bridge in the literature.

There are proposed systems for very long span suspension bridges:

1. The hybrid cable stayed suspension bridge system,
2. The hybrid double cantilever suspension bridge system, and
3. The Spread-Pylon cable stayed bridge system.

Very long span suspension bridges have been proposed by various consultants. One example is to connect the continent of Africa to Europe by a bridge that spans from Morocco to Spain. The proposed length of the bridge is 8.5 miles. A series of suspension bridges is considered for this design. Another proposed bridge is to connect Italy to the Island of Sicily. A great bridge is proposed to link the United States to Russia through the Bering Straits. The depth of the water at various points across the proposed path of the bridge present the engineer with technological hardships. Crossings beyond 10,000 feet require innovative technologies in materials and structural systems. As Menn points out, extrapolation of existing technologies does not present the engineering profession with innovative solutions.

Wind Effects on Suspension Bridges

Wind can produce the following effects on suspension bridges:

1. Wind lift and drag forces,
2. Aeroelastic effects (torsional divergence or lateral buckling),
3. Oscillations induced by vortex effects,
4. Flutter phenomena,
5. Galloping effects, and
6. Buffeting caused by self-excited forces.

All of the above effects require wind tunnel tests. It is very important to understand here that studies are needed for the partially complete structure as well as the completed structure. The performance of the structure under the effect of wind loads should be investigated during the various construction stages of the suspension bridge. The construction period of large suspension bridges should be wisely planned for seasons where no serious storm conditions are anticipated. Proper prediction of the weather for extended time periods is important. If the construction is contemplated for seasons with predicted storm activities, energy dissipating devices and dampers should be used to reduce the magnitude of the vibrations on the partially completed structure.

There are 3 types of wind tunnel tests on a suspension bridge:

1. Models of the entire bridge,
2. Taut strip models, and
3. Sectional models.

The first category of wind tunnel models provides the engineer with the advantages of similitude between model and prototype. These models are expensive to build and constitute a large initial capital expenditure. Experience from previous designs indicates that a scale of 1 to 300 is desirable. Other scales are also possible. The distribution of the mass in such complete scale models is identical to the mass distribution of the real life structure or prototype.

The second category, or the taut strip model, consists of 2 wires that are stretched across the wind tunnel. The response of such models to applied fluid flows in the wind tunnel is similar to the response of the center section of the suspension structure.

The third category is made up of sections of the bridge deck in the span-wise direction. The ends of these sections are supported on spring type foundations to allow motion in the vertical direction as well as the rotational sense. The usual scales for such deck sections are within the 1/50 to 1/25 range. These sectional models are very important in determining the aeroelastic stability of the proposed deck system. These models allow us to further investigate the steady state coefficients for drag, lift, and moment.

These 3 quantities are fundamental characteristics of the suspension bridge deck. These coefficients are a function of the air density, the deck width of the bridge, the mean wind speed at the height of the deck, as well as the drag, lift, and moment per unit span length. The science of aerodynamics is very important here since various plots of these functions are usually done versus the angle of attack of the oncoming wind flow. It is also possible from a study of these sectional models to determine the aerodynamic coefficients attributed to the self-excited forces acting on the vibrating structure.

Finally these models allow us the determination of a very important number in fluid mechanics, the Strouhal number. The Strouhal number is associated with vortex shedding. This non-dimensional number is defined as the product of the frequency of full cycles of vortex shedding and the dimension of the body projected on a plane perpendicular to the mean velocity of the flow, divided by the velocity of the oncoming fluid flow. It is very important to note here that the fluid flow is presumed laminar in this formulation. The Reynolds number is very important in this type of analysis. Vortex shedding had been experimentally observed for cylinders and other bluff body shapes. Research continues on the topic of periodic vortex shedding for very large Reynolds numbers.

The Tacoma Narrows Suspension Bridge

The Tacoma Narrows suspension bridge in the State of Washington had a span of 2800 feet. The bridge experienced large amplitude vibrations causing the suspender cables to fail and the roadway to fall in the water. This bridge had a large span-to-width ratio. It had been noticed earlier that this structure experienced smaller amplitude vibrations. The bridge designer was Leon S. Moisseiff, who had designed many earlier bridges. In the design of the Manhattan Bridge in 1909, Moisseiff applied the deflection theory to the design of suspension bridges. The longitudinal stiffening element was a girder.

Great uplift forces were introduced into the structure causing large vertical and torsional vibrations. At the time of the disaster the wind speed was approximated at 40 miles per hour. The vibration amplitudes for the Tacoma Narrows suspension bridge were estimated at 15 feet. This structural failure caused a lot of concern for long span suspension bridges and from that time on many engineers recognized the importance of aerodynamic studies as applied to long span suspended systems. The wind tunnel became a primary research and investigation tool for such bridges. The stability issues of such bridges under wind loading became very important ever since. Today in addition to the wind tunnel tests performed in a laboratory, engineers resort to analytical means like Computational Fluid Dynamics (CFD) type techniques to study the flow patterns around a long span suspension bridge. Computational Fluid Dynamics has become an accepted discipline in fluid mechanics, the aerospace industry has almost perfected this process.

Aerodynamics of Long Span Bridges

Wind loads and earthquake loads constitute the lateral forces applied on a typical Civil Engineering structure. Wind loads constitute what many engineers call environmental loads on a structure. One of the most important design considerations for bridges against wind is a proper understanding of the exposure at the site. Severe wind loads can be generated in areas involving a bay or mountain topography. The higher the bridge, the more severe is the wind loading. Many parameters affect the design consideration for bridges including but not limited to wind speed, angle of attack of the wind, the shape of the bridge, the size of the bridge, the natural topography or terrain features, as well as gust conditions at the site. Simiu and Scanlan have published a book on Wind Effects on Structures. Dr. Robert Scanlan, of the Johns Hopkins University in Baltimore, Maryland, is a world class researcher on the topic of wind effects on various types of structures including buildings and bridges.

There are profound differences between wind effects on buildings and wind effects on long span bridge structures. There are basically 3 effects related to wind loads on bridges:

1. The effect of the static wind pressure,
2. The dynamic effect known as the oscillatory effect, and
3. The buffeting effects.

Our concern with long span bridges is related to the aerodynamic effects of wind on long flexible cable-stayed and suspension type bridges. A steady wind type of fluid flow can bring about aerodynamic instability if amplification of vibrations can develop with time. These vibrations can become very damaging to a long span suspended structure and cause structural failure. In a process of generating lift not much different than what happens on an aircraft wing, many problems can develop on a long span; thin deck, suspended type structure. These effects are dynamic in nature and should be distinguished from aerostatic effects.

Dynamic wind forces much lower than those forces it was designed for destroyed the Tacoma Narrows Bridge. A cable-stayed bridge, or a suspension bridge, has the ability to vibrate in the low frequency domain with multiple modes or shapes. Davenport, Scanlan, and Wardlow reported these research findings. Modern commercial software like ADINA developed at the Massachusetts Institute of Technology, in Cambridge, Massachusetts, SAP-2000, developed by Computers and Structures, of Berkeley, California, and other programs, can plot the modal shapes of long span suspension bridges. Buffeting is related to dynamic effects of bridge structures in close proximity to each other. Suspension bridges have aeroelastic effects. Buffeting is associated with long span cable-stayed bridges and suspension bridges. Lift and drag forces are generated on long span suspended structures. The cross section of a bridge structure is not much different than a thin airfoil when it comes to analysis.

Aerodynamics Stability of Long Span Suspension Bridges

Many studies have been conducted to understand fluid flow past objects of different shapes. The problem of fluid flow around a cylinder is documented very well in the literature. A suspension bridge deck is basically a non-streamlined object. It is similar to an airfoil. The classical theory of aerodynamics tells us that when a fluid flows past a cylinder, a region of wake turbulence develops close to the trailing edge of the airfoil. A similar phenomena, is generated around the trailing edge of a suspended deck. This is what is known as the Von Karman vortex.

Vortices are shed from both sides of the cylinder in the fluid flow stream and these vortices are periodic. The presence of these vortices gives rise to dynamic fluctuating forces. These vortices are a function of the Reynolds number. If we were to simulate the bridge deck with a thin plate type structure similar to an airfoil, we would observe that the oncoming flow changes directions at the edges of the plate. At low Reynolds numbers the vortices flow patterns are symmetric and as the Reynolds number increases this symmetry disappears. Scanlan and Simiu have shown that at large Reynolds numbers, cyclic alternating vortices are generated.

At very high Reynolds numbers the wake is turbulent in nature. The Strouhal number is used to describe these phenomena, and the value of this non-dimensional parameter is dependent on the cross-sectional shape of the bridge deck. Scanlan and Simiu have presented diagrams for low separation and wake regions for square and rectangular plates. The vortex shedding process on a bridge deck is not much different than that for an airfoil. The varying pattern of the wake presents the bridge deck with a vertical force applied to the deck of the superstructure.

The real problem comes in when the natural frequency of vibration of the bridge deck becomes close to the frequency of the vortex shedding. The frequency of the vortex shedding is dependent on the wind speed. If these 2 frequencies become close, a possibility exists that the bridge will vibrate in resonance. Wardlow refers to that as galloping. Galloping is basically vibration with large amplitude characteristics. The vibration excitation activates the bending mode in a plane that is perpendicular to the direction of the wind. The large amplitudes bring about instability of the structure. The key parameter to ensuring a stable design is to come up with a design for the deck where the vibration frequency of the bridge deck is not close to the frequency of the vortex shedding. In an actual scenario of a vibrating bridge, as the wind speed becomes larger, the tendency of the bridge structure would be to exhibit reduced vibration amplitudes. The reason for this is the fact that we are now away from the resonant vibration environment.

The combination of two or more modes of vibration can cause oscillation of the bridge structure. The increase in the value of the wind speed can cause the combination of a bending mode and a torsional mode of vibration. A proper investigation of the wind speed profiles at the bridge site is very important. Flutter is very complicated and is dependent on the elastic characteristics of the bridge as well as its dynamic properties. In a flutter type scenario, there is a rapid magnification of the amplitude of vibration in a very few number of cycles.

There is evidence that points out to the fact that the angle of attack of the wind can profoundly affect the velocity of flutter on a bridge. A small change in the direction of the wind can lead to a great reduction in the value of the critical flutter speed. Such change in angle of attack can be caused by the nature of wind as attributed to gusting effects and turbulent flows. It is imperative to point out the issues of rigidity in a long span suspension bridge. John Augustus Roebling, builder of the world famous Brooklyn Bridge, pointed out to issues pertaining to aerodynamic stability of bridges back in 1869. The massive stiffening truss serves the purpose of introducing rigidity into the bridge structure. As an outcome of the failure of the Tacoma Narrows Bridge in the State of Washington, modern suspension bridges utilize trapezoidal box type sections and not solid girders. The torsional stiffness of trapezoidal deck sections is well presented in the literature. The structural design of the bridge should be aimed at increasing the critical flutter velocity to very large value. Steinman has done a lot of work on this topic. This issue is clearly one pertaining to aerodynamics of modern suspension bridges.

Structural engineers are concerned with the stability of long span suspended bridges subject to wind loading. There are 3 main items that need attention here:

1. The geometry of the bridge deck,
2. The vibration frequency of the bridge, and
3. The installation of damping systems on the bridge.

The shape of the deck of the bridge is very important. Bluff cross-sectional shapes can cause instability. A close look at the wing of an airplane can provide us with what constitutes a streamlined shape. Closed box sections are very good for torsional stiffness. Providing a design whose torsional natural frequency of vibration is high compared to its natural bending frequency can enhance the aeroelastic stability of a cable-supported bridge. Active and passive damping systems have been used on long span bridges to enhance the aeroelastic stability of the structure.

The key parameter in all long span bridge design, is the uncertainty associated with the behavior of the wind. The true nature of wind is something we need to model properly in a wind tunnel as well as using modern Computational Fluid Dynamics tools. A study of the science of CHAOS might be in order here since the nature of wind forces is characterized by randomness. Research work on the nature of wind is well documented in the literature. Wind tunnels suited to civil engineering type structures are available at many universities and research centers around the world. There are many such wind tunnels in the United States, Canada, Japan, and Europe.

Current Record Holders

Currently the Akashi Kaikyo Bridge is the longest suspension bridge in the world. It has a central span of 6529 feet and a total length of 11828 feet. The Tatara Bridge is the longest cable-stayed structure in the world with a central span of 2760 feet. Both of these bridges are world records and are located in Japan. The next world record holder shall be the Messina Straits Bridge connecting Calabria in Southern Italy to Sicily. The crossing demands a central span of 2.1 miles. Innovative systems are needed for such a crossing, extrapolation of current design technologies and the use of modern digital computer programs is not necessarily the path to a good solution. What is needed is more innovative structural systems. John Augustus Roebling, the designer and builder of the Brooklyn Bridge stated: " No Man is Great by Imitation ". The Messina Straits Bridge, or the connecting of Spain to Morocco, or the crossing of the Bering Straits in Alaska, are problems that demand an innovative approach to challenging Civil Engineering structures.

Recent Work

A comprehensive Civil Engineering senior project team was formulated at Cal Poly Pomona to address the finite element computer modeling of such a long span bridge. We intend to use the commercial software package SAP-2000 to perform the static and dynamic analysis of this bridge structure. We are currently addressing issues relevant to a proposal by Dr. Christian Menn of the Swiss Federal Institute of Technology Zurich to study the feasibility of such a daring structural system. An architectural model of this concept as well as a computer rendering shall be available at the time this project is presented to the University community and the Industry Action Council of the Department of Civil Engineering.

Figure 1 is a schematic of the proposed concept.