AEROELASTIC ANALYSIS OF SUSPENSION BRIDGE DECKS USING FINITE ELEMENT METHOD

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ABSTRACT:

The present study attempts to investigate suspension bridge deck response using finite element method. The Tacoma Narrow's (USA) and Great Belt East Bridge (Denmark) behavior under wind loads has simulated. The study shows that there is good agreement between the experimental wind tunnel tests results and simulated one. Wind tunnel tests, usually takes more cost and time. In primary design stage, the present study is attractive and saves money and time.

1) INTRODUCTION

Very long span suspension bridges are flexible structural systems. These flexible systems are susceptible to the dynamic effects of wind loads. The structural effects, the response of the structure to such random lateral loads, and the subsequent design of an efficient lateral load resisting system, dictates very sophisticated methods of analysis and design. As all scientists of wind engineering field know, The Tacoma narrows suspension bridge with a span of 1.087 km, was one of a such structures that experienced large amplitude vibration causing the suspender cables to fail and the roadway to fall in the water. This was due to large span-to-width ratio of the bridge. The wind velocity was almost 100 km/h in the accident. As has reported in literature, The bridge experienced torsional movement more than 45 degree and vibration amplitude about 8.5 m. This failure brought awareness to the designers around the world that wind can cause aerodynamic instability of bridges resulting in failure. Thus it becomes necessary and important to conduct sufficient aerodynamic studies of the bridge before construction so that the stability of the bridge against wind can be ensured.

Analysis of wind effects on a bridge structure are studied using wind tunnel experiments. It usually takes more cost and time (6-8 weeks). For example the design of the Great Belt East Bridge involved more than 16 box sections, as desired by Larsen and Jacobsen (1992). Each section model test would in average run over six weeks. In the initial design phase, this becomes time-consuming and expensive. Therefore now the shift is towards computer modeling of the wind induced effects on a bridge structure by using the principles of computational structural dynamics (CSD) and computational fluid dynamics (CFD). The numerical solutions are becoming increasingly attractive not only because they have become affordable, but also because they appear to offer increased insight into the complex processes involved in fluid structure interaction (FSI). This generates hope that the combination of quantitative predictions and improved understanding could lead to more efficient use of experimental facilities, saving expense and time during the design phase by reducing the number of physical model tests required.

2) WIND EFFECTS ON SUSPENSION BRIDGES

Wind can produce the following effects on suspension bridges:

1) **Static Effects**

In static case, the wind effects are overturning, excessive lateral deflection, divergence buckling and lateral buckling, usually, the static phenomena are not critical for the design of bridges. The issues related to static behavior can be checked by the aerodynamic force components like drag and lift forces and pitching moment. The issues are taken care of by the plot of the coefficients of drag, lift and moment against the angle of incidence of wind.

2) **Dynamic effects**

using Newton's second low, the motion of mass is described by the differential equation.

$$m\ddot{u} + c\dot{u} + ku = P_{(t)} \tag{1}$$

Where, $P_{(t)}$ is the time dependent load acting on the mass, k is the stiffness coefficient and c is the coefficient of damping. This equation can be rewritten in the form

$$\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = \frac{P_{(t)}}{m} \tag{2}$$

$\omega=(k/m)^{1/2}$

$\xi=c/(2m\omega)$

Where, ω is the natural circular frequency and $2m\omega$ is the critical damping coefficient. The cases arise based on ξ being less than, equal to or greater than unity resulting in under-damped , critically damped and over-damped responses due to vortex shedding excitation , self excited oscillations and buffeting by wind turbulence. Unlike the static behavior, the dynamic behavior is critical and important to be considered during design. Aeroelasticity is the discipline concerned with the study of phenomena wherein the aerodynamic forces and structural motions interact significantly. When a structure is subjected to wind flow, it may vibrate or suddenly deflect in the airflow. This structural motion results in a change in the flow pattern around the structure .if the modification of wind pattern around the structure by aerodynamic force is such that it increases rather than decreasing the vibration, there by giving rise to succeeding deflection is said to occur. The aeroelastic phenomena that are considered in wind engineering are vortex shedding, lock-in, torsional divergence, galloping, flutter and buffeting. Tacoma's narrows bridge failure was due to the flutter phenomenon. So it is necessary that the wind velocity should not exceeds the critical velocity for flutter and since the suspension bridge are prone to the aerodynamic instabilities, this becomes a prime criterion to be checked during the design and an acceptable flutter limit is one of the principal design criteria for long-span bridges.

3) The present study

The case studies are based around the Tacoma narrows (USA) and the Great Belt East Bridge (Denmark). Both bridges, i.e., Tacoma's and GBEB's main span is modeled and flutter critical velocity is computed. The analysis is performed for the bridge cross-section (2D) and finally the results are compared with the work done by other researchers and wind tunnel tests. Elastic characteristics, dynamic properties and geometric shape of the bridge's main span are illustrated in the figures 1&2. In the figures, C.G. & S.G. denote to the center of gravity and shear center of the bridge's cross-section, respectively.

TABLE 1. VERTICAL BENDING CHARACTERISTICS OF THE BRIDGE'S MAIN SPAN

Natural Frequency($f_{\alpha 1}$) Hz	**Torsional stiffness(G_a) N.m/m**	**Mass moment of inertia(I_m) Kg.m^2/m**	**Natural Frequency(H_z) H_z**	**Vertical stiffness(k_y) N/m^2**	**Mass(m) kg/m^3**	**Bridge Name**
0.27	94E10^6	2.051E10^6	0.097	8785.06	2.7E10^3	**GBEB**
0.2	44516	2.819E10^2	0.13	867	1.3E10^3	**Tacoma Narrows**

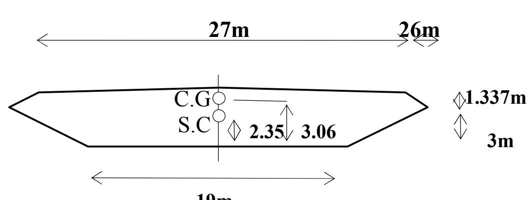

Fig1. GBEB Bridge cross-section

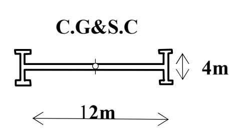

Fig2. Tacoma narrows Bridge cross-section

Based on elastic characteristics, dynamic properties and geometric shape of the bridge's main span, the bridge decks idealized, modeled and illustrated in the following figure.

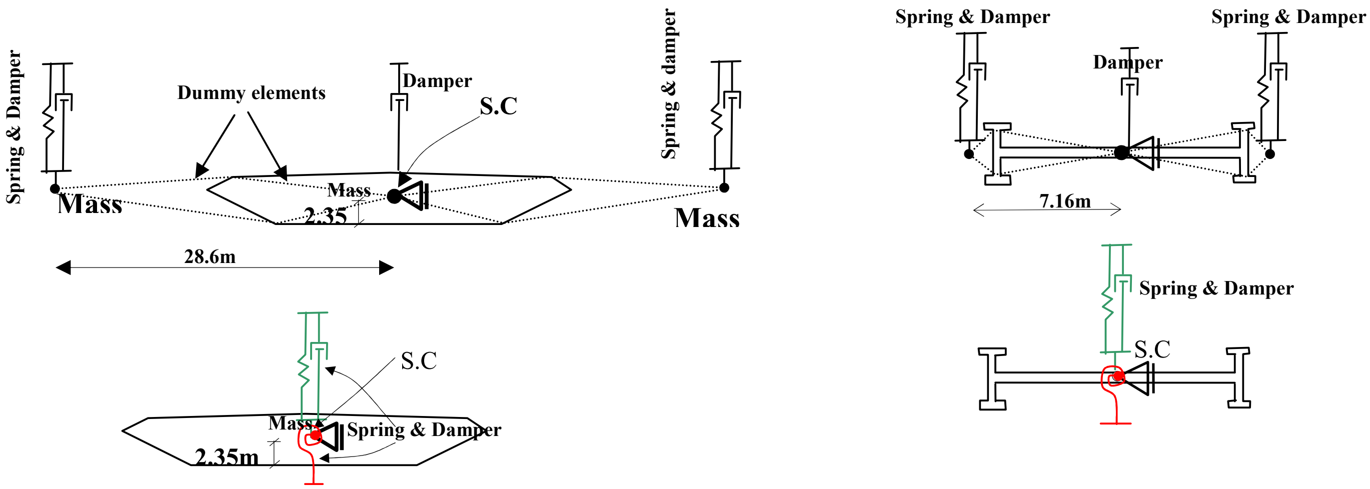

Fig 3. The Idealized and Modeled Bridge Decks

Structural equations are formulated in the Lagrangian co-ordinate system and the fluid equations are formulated in the eulerian co-ordinate system. The FSI modeling needs the solving of the equations of fluid and structure simultaneously. In the present work, both of the mentioned equations solved simultaneously using of sequential coupling analysis of finite element method. The moving interface between fluid and structure is modeled through the arbitrary Lagrangian-eulerian formulation (ALE). The bridge decks are assumed to be rigid. The computed critical velocity for flutter is in good agreement with the tunnel measurements. The fluid domain (3B*8B) is meshed with 4313 three-nodded triangular elements (irregular-unstructured) for Tacoma bridge and 5331 three-nodded triangular elements for GBEB bridge and a plane-strain condition is used to simulate the structural domain Ds.

Fig 4. Domain and fluid-structure interaction boundary conditions

Samples of the wind velocity contour around the simulated model and displacement of flutter condition are shown in the following figures.

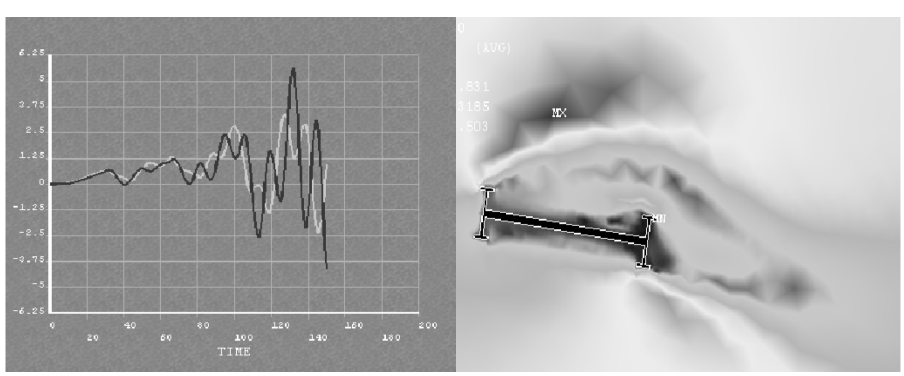

Fig 5. Flutter condition and wind velocity contour around simulated bridge deck

As it can be seen from the following table, there is very good agreement between the result of the present study and wind tunnel tests which have been made by scientists an engineers.

TABLE2. Comparison of the Present Study By Others Work(GBEB's bridge)

Jenssen & Kvamsdal (1999)	Selvam et.al.(2002)	Wind Tunnel Tests	Enevoldsen et. al. (1997)	Larson et. al. (1997)	Present work	Modeled GBEB's bridge deck
70	69	73	70-80	74	70	U(m/s)

TABLE3. Comparison of the Present Study By Others Work(Tacoma narrow's Bridge)

Estimated wind velocity in the accident	Present work	Modeled Tacoma narrow's Bridge deck
29	27	**U(m/s)**

4)Conclusions:

The outcome of the present study are as flow:

1- The shape of the deck of bridge is very important and as an outcome of the failure of the Tacoma narrow's Bridge, modern suspension bridges utilize trapezoidal box type sections(or sharp leading edges sections) and not solid girders. Experimental testing also reveals a great sensitivity of the bridge behavior to minor changes in leading edge geometry.

2- The risk of flutter-induced vibrations is significant when the torsional natural frequency is only slightly larger than vertical natural frequency, which is often the case of slender long-span bridge decks. Closed box sections are very good for torsional stiffness providing a design whose torsional natural frequency of vibration is high compared to its bending natural frequency can enhance the aeroelastic stability of a cable-supported bridge.

3- Numerical bridge flutter models usually are 2D without attempts to include a turbulence model formulation. A laminar flow assumption and two-dimensional flow solutions, on an irregular unstructured grid in this work, predicted a flutter limit in good agreement with wind tunnel experiments.

4- Numerical models with increased mesh density and less load step size presents more accurate flutter prediction but the optimized mesh and load step appears to present the same accurate results saving time during the solution. Flutter numerical models are also less sensitive to boundary layer effects compared to the other aeroelastic analysis.

Selective References:

1.Bower; S.N.A. (1940), “Taccoma Narrwos Bridge Wretched By Wind ”, Engineering News Record,Vol,**125**..

2.Dowel; E.H. (1975), ”Aeroelastcity of Plates and shells”,Noordhoff International Publishing , the Netherland.

3.Hoffman Klaus A.& Chiang Steve; T.(1996), "Computational fluid dynamics for engineers", University of vitchita,

4.Novak;M.(1973)“Aeroelastic Galloping of Prismatic Bodies", Wech. Div., ASCE,98, NO. EMI.

5.Paneer; S. & govindaswamy; S. (2001), ”Aeroelastic Analysis of Bridge Girder Section Using Computer Modeling"**, Ph.D. Thesis**, University of Arkansas, USA.

6.Scanlan; R.H.& Wardlaw; R.l.(1970) “Reduction Of Flow-Induced Structural Vibration”, AMD vol.1, Sect.2 ASME,New York.

7.Scanlan; R.H.& Budiong; K.S. (1972),”Flutter and Aerodynamic Response considerations for Bluff objects in smooth flow”, Springer-verlag, berlin, Germany.