# Stability Study of Cable Stayed Bridge under Wind Load

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**Abstract- In this paper the response of Stonecutters Cable-Stayed Bridge under static wind load is investigated using finite element based softwarevizABAQUS. The natural frequencies and the vibration modes were validated against the data available in the literature at first.Secondly, the effect of the mean wind loading for wind speeds between 35 m/s and 211 m/s were determined. The vertical and horizontal displacements andthe torsional angle at mid-span are indicated to determine the bridge performance under mean wind load.**

**Keywords: Cable-Stayed Bridge, Stonecutters Bridge, Static analysis, lumped mass, Frequency.**

## I. INTRODUCTION

As a kind of cable-stayed system, cable-stayed bridge has a relatively greater crossover capability than other ordinary bridges. A cable-stayed bridge is composed of the tower, the cables and girder. Box-shaped pre-stressed concrete section is most frequently used in cable-stayed bridge. Cable-stayed bridge belongs to the composite structure system, as the beam and girder are supported by stayed-cables fix on the tower. The stayed-cables are anchored in the girder directly and under a great pressure. The horizontal force of the cable leads to girder pressured; hence, the girder and the tower are under compression, this is the main difference between cable-stayed bridge and suspension bridge. Because the girder of the cable-stayed bridge is directly connected to the tower by pre-tensioned cables, the bending stiffness and the torsional stiffness of the main girder increase, so, it is better resulting in dynamic characteristics, than the suspension bridge. The maximum value of the internal force and deformation of the structure with the closest connection to the natural frequency of vibration and mode of vibration, are intrinsic dynamic characteristics of the vibration system. In a dynamic calculation and analysis of the structure, we often need to calculate the natural frequency of vibration or the period first. The vibration of cable-stayed bridge is simple harmonic vibration either on vertical or lateral, so, when solving this kind of problem, the bridge should be divided into a number of units or elements, and then it is contribute to further analysis.

The current study has been developed to investigate the aerodynamic performance of the already constructed Stonecutters Cable-stayed Bridge which has a total length of 1,596 m with a main span of 1,018 m. The geometrical details of the dimensions of the bridge and the cross-sections of the bridge decks are represented in Figure 1 and Figure 2. The Stonecutters Bridge was the second longest cable-stayed bridge in the world at the time of its completion in 2008, and was the first major bridge with a twin-box girder superstructure. The most notable feature of this bridge is the slender twin-box deck girder, with two main box decks for the vehicular traffic, connected between them every 18 m with separated stabilizing beams, thus forming the main span of the bridge deck. Such twin-deck configuration increases the complexity of the numerical modelling and finite element analysis required for the structural verification of the bridge response to dynamic loadings. The overall deck is 53.3 m wide and only 3.91 m deep, composed of two trapezoidal steel boxes with curved bottom panels, 19.5 m wide. The boxes are joined by heavy cross-beams spaced longitudinally at 18.0 m centre to centre providing a 14.3 m gap between the boxes. The towers of the bridge are 300 m tall and they were built with a tapered circular cross-section. The towers were designed as a reinforced concrete structure up to 175 m and as a steel concrete composite from 175 m to 293 m. The tower section and dimension details are shown in the Figure 3.

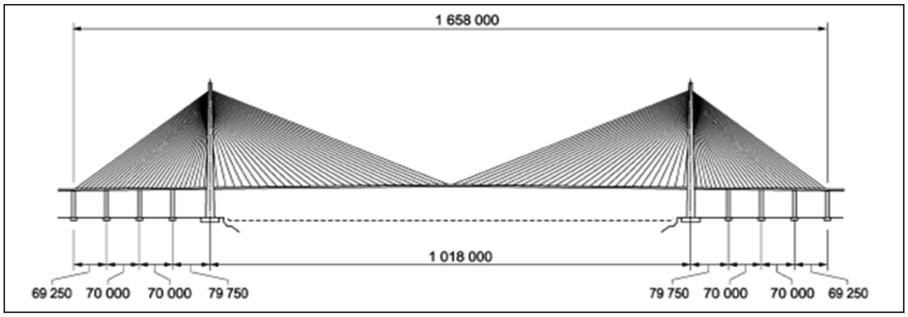


Figure 1: Side view of the Stonecutter Bridge.

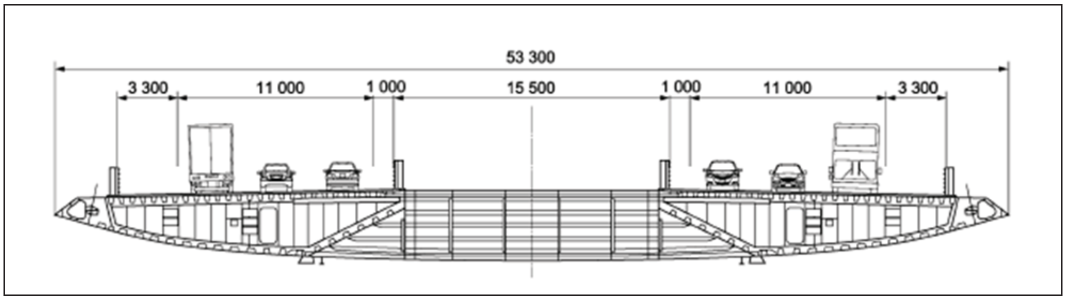


Figure 2: Cross-section of the bridge deck.

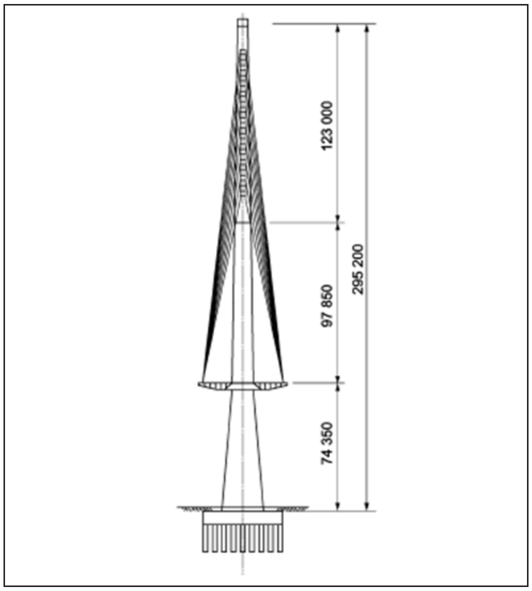


Figure 3 Tower cross-section details.

## II. BRIDGE AERODYNAMIC ANALYSIS METHODOLOGY

There are three main options for performing the bridge aerodynamic analysis; the theoretical development and the formulation of the aero elastic investigation, the experimental procedure involving wind tunnel tests for verifying the critical flutter wind speed and the numerical simulations performed for simplified finite element models of long-span bridges subjected to static, dynamic and self-exited motion conditions in order to simulate the flutter instability of the structure. Aerodynamic principles will be used in the theoretical analysis, mainly employed for developing different kinds of mathematical models for wind loadings, and then by combining these with the basic theory of structural dynamics, solutions for the wind-induced vibrations and the structural stability problems will be determined. Theoretical methods play a critical role in wind engineering. Wind tunnel experiments represent an irreplaceable verification method in the aerodynamic study of long-span bridges and they are commonly accepted as a procedure to test the aerodynamic characteristics of a bridge. Open or closed circuit wind tunnel facilities can simulate the atmospheric boundary layer and can reproduce a natural wind pressure environment induced to the investigated structure or model of a structure placed in the wind tunnel, based on the response of the model used in the experiment, the response of the real structure is predicted. Along with the development of information technology and popularization of the computer, the numerical simulation procedure has developed rapidly. This method relies on computer capacities and the available structural software which combines with the finite element theory, and according to numerical calculation performed on the given structure attempt to achieve the critical responses of the long-span bridge structures and to deliver solutions for engineering problems and optimum structural design. Currently there is a number of engineering software, such as ABAQUS, ANASYS, SAP, etc. and these can simplify the complicated structural problems involving high number of degrees of freedom and complex loading histories which can be employed. All of these software are conveniently and widely used in structural design, response analysis and load simulation.

## III. ANALYSIS

For the analysis, the model was run in various stages. The stages are as follows:

1. Initial step with constraints, boundary conditions and pre-tension forces in cables.
2. Dead load of bridge defined in general static analysis.
3. Eigen-frequency and mode-shape analysis.
4. Static response of the bridge model due to the mean wind velocity.

Dead loads play an important role in the final stiffness of the bridge (and thus a major role in the final natural frequency and vibration modes of the bridge). To include the geometric stiffness when calculating the natural frequencies of the bridge, the first step accounts for the self-weight of the structure. Non-linear geometry is switched on in this step. In ABAQUS, a static analysis step named “Static, General” is used as the first step. To include the self-weight of the bridge, a “gravity load” must be defined in the general static step with a 9.81 m/s2 acceleration value as the load component. In addition, the pre-tension forces aredefined for every individual cable in the first analysis step.

The frequencies of the Eigen modes of a cable-stayed bridge are important when the dynamic response is studied. Therefore, in the second step, the first 30 natural frequencies and the corresponding vibration modes are calculated. The subspace method was used in the frequency analysis. The advantage of the subspace method is in its ability to achieve rapid convergence to the eigenvectors in full space.

## IV. NATURALFREQUENCIES

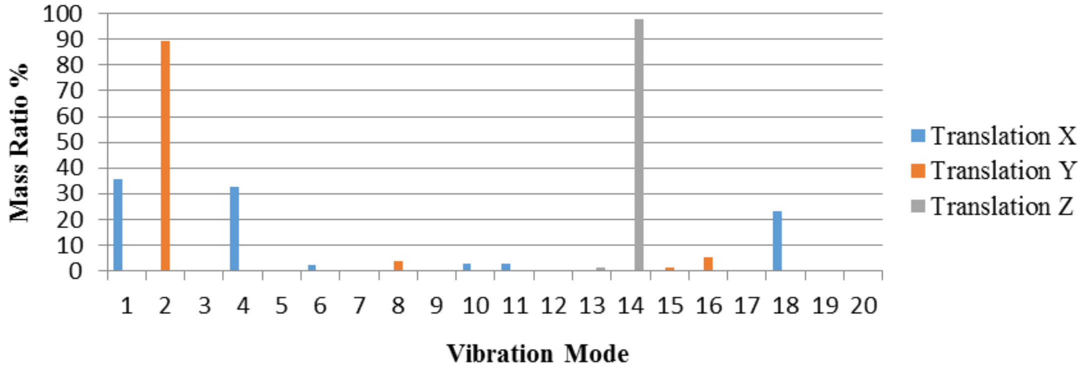
The natural frequencies and the mode shapes of the bridge can be successfully employed for analysing the dynamic characteristic so flexible structure effectively. Hence, determining the frequencies (Eigen-values) of the Eigen-modes of a cable-stayed bridge is vital for the current study, which focuses on studying the dynamic response of the Stone cutters Cable-stayed Bridge model under different wind loading scenarios. Several vibration mode shapes were identified through the frequency analysis, which was performed following the static response of the bridge under the self-weight. The dominant horizontal,vertical and torsional vibration mode sand also the coupling between them were reported for the bridge deck and for the tower.

Table 1: Natural Frequency of Stonecutters Bridge

| Mode No. | Eigenvalue | Frequency | | Generalized Mass |
|---|---|---|---|---|
| | | Rad/sec | Cycles/sec | |
| 1 | 0.82898 | 0.91048 | 0.14491 | 1.51 e+07 |
| 2 | 1.1714 | 1.0823 | 0.17225 | 1.94 e+07 |
| 3 | 1.4549 | 1.2062 | 0.19197 | 1.45 e+07 |
| 4 | 2.5355 | 1.5923 | 0.25343 | 0.924 e+07 |
| 5 | 2.5916 | 1.6098 | 0.25621 | 0.882 e+07 |
| 6 | 4.1401 | 2.0347 | 0.32384 | 2.50 e+07 |
| 7 | 5.0682 | 2.2513 | 0.3583 | 1.64 e+07 |
| 8 | 5.9227 | 2.4337 | 0.38733 | 1.38 e+07 |
| 9 | 7.086 | 2.662 | 0.42366 | 1.79e+07 |
| 10 | 13.331 | 3.6512 | 0.58111 | 2.20e+07 |

As it can be noticed from Table1,the first 10 natural frequencies of the Stone cutters Bridge model were situated between 0.9 rad/secand 3.65 rad/sec, however the generalized mass of the deckha da higher contribution towards the vibration modes 6,10,15and 29, representing a higher involvement of the structural deck elements in the se specific modes. Therefore, in order to clarify the type of the vibration mode and the response of the structuretowardsthedominantmodes,theeffectivemassdistributionandtheparticipation factorswere analysed.

The mass fraction expresses the mass participation in percentages for the specific vibration mode. The participation factors are summarized in Figure 5 the participation factors of a particular vibration mode demonstrates the importance of that specific mode. The vibration mode classification can be identified by observing the effective mass distribution and the participation factors for each vibration mode.The mass distribution and the participation factors aim at characterizing the vibration modes in terms of pure horizontal, vertical and torsional modes of vibration.As shown in Figure 4 and Figure 5, the effective mass and the participation factors along the three translational and rotational directions are represented.



(a)

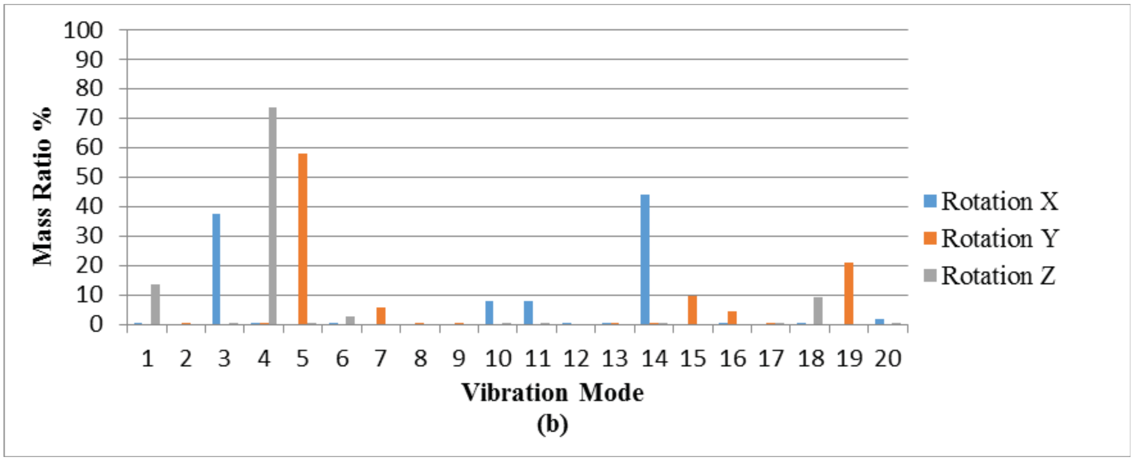


Figure 4: Effective mass ratio for the Stonecutters Bridge model. (a) Translations on X, Y, Z axes. (b) Rotations around X, Y, Z axes.

But normally for a bridge structure, only three of them are considered which are the translations in X and Y-axis, and the rotation in Z axis, because it is improbable for a long span bridge to rotate in X and Y directions.

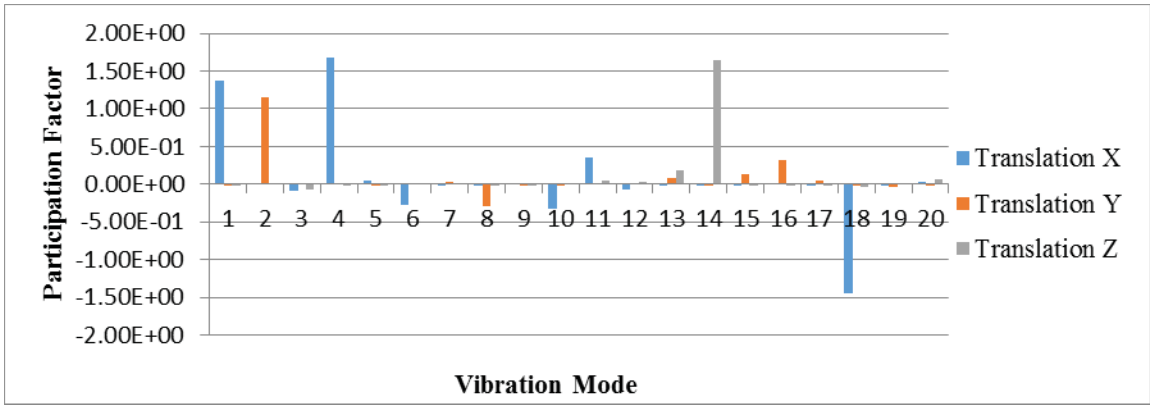


Figure5(a):ParticipationfactorsfortheStonecuttersBridgemodel.(TranslationsonX,Y,Z axes.)

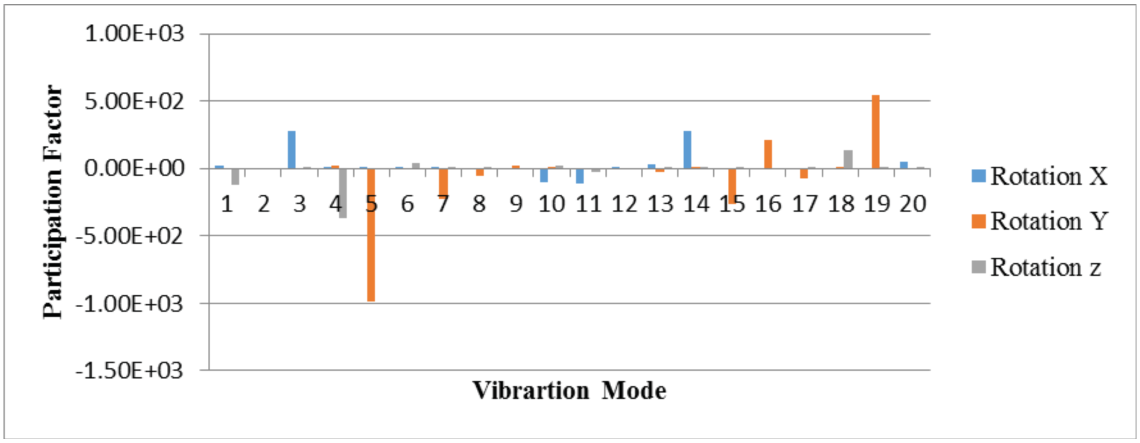


Figure5(b):Participation factors for the Stonecutters Bridge model.(rotations around X,Y,Z axes.)

In general, the participation factors are a measure of how much a vibration mode could participate in the dynamic structural response of the structure, excited with a dynamic loading on a given direction. In general, if the modal mass ratio contributing to a certain direction/rotation is not considerably high, then no vibration mode would develop, even if the participation factors might register a higher value for that specific direction/rotation.

## V. STATICANALYSIS

At the beginning of the analysis, a general static step was performed under the mean wind load without time history step. This was necessary for extracting the static response of the Stone cutters Bridge under the queasy-steady wind loading. It can be noticed that, the vertical, horizontal and torsional deformations registered the maximum values at the middle of the main span; when comparing with the results reported by Diana (Diana,etal.(2013)[13]. It can be found that the overall evolution was similar, namely the horizontal, vertical and torsional deformations of the bridge deck increased with the wind velocity, and the most critical position under the mean wind load was at the mid-span. It can be observed that all the deformations at mid-span a long the three directions are increasing gradually with wind velocity. The maximum reported values, a sexpected are for 211m/s wind velocity where the vertical displacement is 3.36m, the horizontal displacement is 7.39 mand the torsional angle is 1.53 degrees. For the Messina Bridge, at the maximum wind speed of 60 m/s,the vertical, horizontal and torsional displacements were 0.43 m, 11.45 mand 0.62 degrees, respectively.

## VI. CONCLUSIONS

Based on above results and discussions following conclusions are drawn,

1. Due to the Eigen-mode sof the bridge, it was observed that usually one dominant mode is coupled with other modes; thus pure vibration modes along one direction are seldom encountered.
2. The dominant mode shapes of the Stonecutters Cable-stayed Bridge in the lower frequency range are mainly the horizontal deck and the tower modes, but they still coupled with the torsional modes.
3. The coupled vibration shapes can be clearly observed in the higher modes.This reveals the fact that the cable-stayed bridge investigated is more flexible than the other type of bridges.
4. The responses at the mid-span location under a time history mean wind loadwere investigated and found that the torsional vibration mode may be the main vibration mode shape excited by high wind speeds, and may be coupled with the vertical vibration at the same time. This kind of torsional-based, vertical supplemented mode shape can even lead to permanent damage of the bridge structure when reaching a critical wind velocity.

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