Flutter Analysis of The Sunda Strait Suspension Bridge

M. Suangga1*, K. Subali1, I. Hidayat1, H. Irpani2

1Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia 11480
2Ministry of Public Work and Housing, Jl. Pattimura No. 20 Jakarta Indonesia

*Corresponding author: suangga@binus.edu

Abstract. Economic movements in Indonesia and the logistics and distribution systems that accompany them are highly dependent on road transportation modes. On the other hand, the islands of Sumatra and Java are the centers of concentration for the Indonesian economy where the number of people inhabiting the two islands reaches 80% of the total population of Indonesia. In order to accelerate development and increase the economic integration of Java and Sumatra, it is necessary to build the Sunda Strait Bridge. The main bridge considered includes the long span suspension bridge. At present, the planning and construction of the long bridge including suspension bridge was greatly affected by the failure of the Tacoma Narrow Bridge on 7 November 1940. Due to the wind load, the bridge structure shook until it finally collapsed. Although the cause of the collapse was not immediately known, it is currently concluded that it was caused by a single degree of freedom torsional flutter caused by self-excited wind load. This phenomenon is classified as an aerodynamic phenomenon on long span bridges. The flutter analysis performed on the Sunda Strait Suspension Bridge using the Direct Flutter Analysis method will be presented in this paper.

Keywords: long span bridge, suspension bridge, aerodynamic, flutter

1. Introduction

Economic movements in Indonesia and the logistics and distribution systems that accompany them are highly dependent on road transportation modes. On the other hand, the islands of Sumatra and Java are the centers of concentration for the Indonesian economy where the number of people inhabiting the two islands reaches 80% of the total population of Indonesia so that the mode of transportation on the two islands is very important. The economic route of the North Coast of Java (PANTURA) and Jalan Lintas Timur Sumatra (JALINTIM) which are also part of the Trans Asian and Asean Highways are the main economic routes on the islands of Java and Sumatra which are the lifeblood of the economy and the main route to support the national logistics system which for several decades has contributed more than 80% of the national economy. The two main crossings of the national road are currently connected by ferry crossings across the Sunda Strait. In order to accelerate development and increase the economic integration of Java and Sumatra, it is necessary to build the Sunda Strait Bridge.

Figure 1 shows the alternative location of the Sunda Strait Bridge based on Study conducted in 2014 by The Ministry of Public Work. The Selected alignment of the bridge is presented in Figure 2.
Considering the bathymetry at the bridge location at the selected bridge alignment, there are two major suspension bridges required, The East Bridge with main span of 2016 meter and The West Bridge with main span of 1224 meter.

2. Objectives

The objectives of the research are to develop a dynamic model of the Sunda Strait Bridge for flutter analysis, analyze the bridge performance against flutter by analytical method and compare the analysis results with the flutter speed obtained from the wind tunnel test.

3. Methodology

The methodology of this research is as follows.

a. This research is conducted at The East Bridge of The Planned Sunda Strait Bridge
b. The 3-Dimensional Finite Element Method has been developed for the East Bridge for flutter Analysis purposes
c. The dynamic parameter of the model in term of the natural frequencies then compared with the dynamic parameter of the bridge adopted in the design.
d. The aerodynamic derivatives extracted from the wind tunnel test is used for flutter analysis
e. Direct Flutter Analysis with Mode Tracing method is applied to the 3-Dimensional Finite Element Method of the East bridge to obtain the critical flutter speed.
f. The result of the flutter analysis then compared with the result of wind tunnel test

4. Theory

4.1 Wind Effect on Structures

Even though the oscillation of the bridge under wind loads has been observed in many cases during the early history of the suspension bridge and some of the failures of bridges have also been experienced, the answer to such problems was still unclear until the collapse of the Tacoma Narrow
Bridge by a moderate wind load. Although the causes of the failure were unclear at the moment of the accident, it is now understood that the failure was due to a single degree of freedom of torsional flutter caused by wind driven self-excited force. Since then, new criteria for long span bridge have been introduced. The failure of the Tacoma Narrow Bridge shows that the criteria previously considered for stiffness against static loads do not apply in the analysis of flexible bridges under wind forces. It has become the starting point of the studies on bridge aeroelasticity, which involves significant mutual interaction between structural motions and aeroelastic forces. The design of flexible bridges must assure that the structure is stable under dynamic effect of wind loads as given in Table 1.

Table 1. Classification of wind effect on structures [2] [3].

| Static           | Dynamic                | Effect of time-average wind pressure, wind force |
|------------------|------------------------|--------------------------------------------------|
| Static instability | Dynamic Instability     | Galloping                                        |
|                  |                        | Divergent Amplitude Response                      |
|                  |                        | Lateral Buckling                                 |
|                  |                        | Torsional flutter                                 |
|                  |                        | Coupled Flutter                                   |
|                  |                        | Vortex excitation / low speed flutter             |
|                  |                        | Limited amplitude Response                        |
|                  |                        | Turbulence response (gust, buffeting)             |

When a structure is exposed to wind, the fluctuating wind velocity translates into fluctuating pressure, which in turn produces a time-variable response of the structure. Buffeting is defined as the unsteady loading of a structure by velocity fluctuations in the oncoming flow. The buffeting response is caused by wind turbulence. It may lead to structural fatigue and an inconvenient effect on the vehicle.

Flutter is a phenomenon that may occur when a structure is subjected to aerodynamic forces. It occurs not only in aircraft but also in buildings, power lines, road signs and bridges. Flutter is an oscillation caused by significant mutual interaction between structural motions and aeroelastic forces. When the wind speed increases, the energy added in each oscillation to the structure by the aerodynamic forces increases. At some speed, the damping of the structure may be insufficient to absorb the energy increase from the aerodynamic load and the amplitude of the harmonic oscillations will grow until the structure collapse.

4.2 Direct flutter analysis with mode tracing method

There are two existing main methods of flutter analysis, which have been proposed and applied to actual projects. The first is the subspace approach, which utilizes mode shape coordinate system as the modal flutter analysis method. The second is based on FEM bridge model, which was called Direct Flutter Analysis [4].

In Direct Flutter Analysis method, introduced by Miyata and Yamada, the bridge structure is modeled as a 3-D frame on which the flutter analysis is performed directly. The aeroelastic effects by means of self-excited forces are modeled by a set of unsteady coefficients of flutter derivatives. These self-excited forces are incorporated directly into the bridge matrices. As these forces are in complex form, complex eigen analysis is required during the analysis process.

4.2.1 Complex Eigen Analysis

The equation of motion of a full bridge model in the presence of aeroelastic phenomena can be expressed as

\[ [M] \ddot{\mathbf{u}} + [K] \mathbf{u} = F_{ae} \]  

(1)

Where \( M \) and \( K \) are the mass and stiffness matrices formed by finite element method, \( \mathbf{u} \) is the displacement vector, and \( F_{ae} \) is the self-excited forces, which depend on the reduced frequency \( k \).
In which $L_{ae}, D_{ae}, M_{ae}$ are the lift, drag and moment forces respectively and contain a set of unsteady coefficients which depend on the reduced frequency only, $w$ is the displacement vector in local coordinate.

By assuming harmonic free vibration response of $w$ with complex frequency $\omega$.

$$w = Ae^{i\omega t}$$  \hspace{1cm} (3)

We can easily obtain

$$\omega^2 w = -\ddot{w}$$ \hspace{1cm} (4)

$$\omega \dot{w} = -i \ddot{w}$$ \hspace{1cm} (5)

Substituting these equations into Equation 3.12, the following equation can be obtained

$$F_{ae} = \begin{bmatrix} L_{ae} \\ D_{ae} \\ M_{ae} / B \end{bmatrix} = \rho \pi B^2 \omega \begin{bmatrix} L_{yl} & L_{zl} & L_{al} \\ D_{yl} & D_{zl} & D_{al} \\ M_{yl} & M_{zl} & M_{al} \end{bmatrix} \ddot{w} + \rho \pi B^2 \omega^2 \begin{bmatrix} L_{yr} & L_{zr} & L_{ar} \\ D_{yr} & D_{zr} & D_{ar} \\ M_{yr} & M_{zr} & M_{ar} \end{bmatrix} w$$ \hspace{1cm} (2)

From the above equation, it is evident that the right-hand side vector is the nodal acceleration; therefore these forces, $F_{ae}$, can be considered as an additional complex aerodynamic mass. Equation 3.2 then becomes

$$[M - F_w] \ddot{\mathbf{u}} + [K] \mathbf{u} = F_{ae}$$ \hspace{1cm} (7)

This equation, which looks like the classical form of the dynamic equation of mechanical system, is actually a set of equation, which depends on the reduced frequency $k$.

The solution of the flutter equation is

$$[K - M_F(k) \lambda^2] = 0$$ \hspace{1cm} (8)

$$k = \frac{\omega B}{U}$$ \hspace{1cm} (9)

Equation 8 is the eigen value problem with complex matrix $M_F$ that is a function of $k$. The real frequency $\omega$ is $\sqrt{\lambda}$, the square root of the complex eigen frequency, and can be regarded as the complex modal frequency.

By assuming a certain $k$ value, complex eigen analysis of Equation 8 can be carried out. The results of analysis are $n$ sets of complex eigen values and complex eigen vectors. The circular frequency and the aerodynamic logarithmic decrement damping can be obtained by these following equations.

$$\omega_m = \sqrt{\lambda_{rm}^2 + \lambda_{im}^2}$$ \hspace{1cm} (10)
\[ \delta_m = 2\pi \frac{\lambda_{lm}}{\sqrt{\lambda_{Rm}^2 + \lambda_{Im}^2}} \]  

(11)

Once the frequency is obtained the corresponding wind speed \( U \) can be calculated. By successively assuming the \( k \) value and performing complex eigen analysis the critical condition can be found by plotting the relation between aerodynamic dumping and wind speed. The critical flutter speed is the point at which the total damping equal to zero. A more sophisticated method that allows for the change of flutter derivatives along the span has been developed and used herein. In particular, it was desired that the effect of the main cables on the flutter stability be represented, as is the case with change of angle of attack due to the deck rotation from the wind loading.

As the bridge is modeled more accurately the number of equations also increases significantly. Solution by Direct Finite Element method for such a large system would require a lot of computing time. Development of Direct Flutter analysis is proposed by Dung, which was called Mode Tracing Method to reduce the computing time for a large system. This method considers only one mode at a time and then traces the revolution of modal properties, with step-by-step increase of wind speed [5].

5. Bridge Data

5.1 Bridge Configuration and Dimension

The Bridge Configuration and Dimension is as follow

- Length of the Bridge : 3600 m
- Main Span : 2016 m
- Vertical Clearance : 85 m
- Pylon Height : 320 m
- Mass of the Deck : 8 050 kN/m

![Figure 3](image-url) The East Bridge [1]
5.2 Static Wind Coefficient

The Wind Tunnel test has been conducted at TJ-1 Boundary Layer Wind Tunnel of the State Key Laboratory for Disaster Reduction in Civil Engineering of Tongji University. TJ-1 Boundary Layer Wind Tunnel. The Static Wind Coefficient and the Flutter Derivatives are presented in Figure 6 and Figure 7, respectively.

5.3 Flutter Derivatives

Flutter Derivatives $H^*$ and $A^*$ are presented in Figure 7 and Figure 8. Flutter Derivatives $P^*$ was not measured at the time of the test and is a very important parameter as the bridge span increases. $P^*$ i is very influential on long span bridges so that the absence of this parameter will cause the results of the flutter speed to be too high.

6. Results and Discussion

6.1 3-Dimensional Finite Element Method Model for Flutter Analysis

Figure 9 shows the 3-Dimensional Finite Element Method Model for Flutter Analysis.
The comparison of the natural frequency values obtained from the flutter analysis model and the design data is presented in Table 2.

| Analysis Stage | Horizontal (Hz) | Vertical (Hz) | Torsional (Hz) |
|----------------|-----------------|---------------|----------------|
| Flutter Analysis | 0.0338          | 0.06913       | 0.1581         |
| Design          | 0.0354          | 0.0691        | 0.1434         |

6.2 Flutter Analysis Result

From the 3-dimensional finite element modeling carried out using static load coefficients and aerodynamic coefficients with the help of a flutter analysis program, a logarithmic decreament dumping curve of wind speed is obtained for 15 vibration patterns with wind speeds of up to 200 m/s.

From Figure 10, it can be seen that at wind speeds between 180 m/s, there is a decrease in logarithmic decreament until it passes through 0. Thus, from the analysis carried out the flutter speed of the Sunda Strait bridge is 180 m/s.

This figure is very high and very much different from the results of the wind tunnel test where the critical Flutter Speed is more than 95 m/s [6]. The high flutter value of the bridge can be caused by the weight of the bridge deck that is too large and also because the aerodynamic derivative $P_i$ is not taken into account in this analysis. Previous study conducted for the Akashi Kaikyo Bridge, it is known that for a long span bridge, the results of the Flutter analysis are strongly influenced by the value of the derivative $P_i$.

7. Conclusion
Based on the results of the analysis of the research conducted it can be concluded that:

a. The bridge deck adopted in the Preliminary Design Stage is still relatively heavy, this causes the critical wind speed of the flutter to be relatively high so that in the future optimization is necessary.

b. Flutter analysis performed without using the $P^*i$ parameter gave far different results from the wind tunnel test results. For bridges with long spans such as the Sunda Strait Suspension Bridge, these parameters will greatly play a role in determining the flutter wind speed of the bridge.

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