Vibration of Tayan Bridge’s Hanger in West Kalimantan, Indonesia

Made Suangga, Prasetyo Eko Junianto

Abstract*: *In November 2015, vibration has been detected at hangers of Tayan steel arch bridge just before its opening for public. The vibrations occurred at certain wind speed in the first asymmetric torsional mode. Vibration on the hanger is a phenomenon that often occurs especially if the hanger is I-shaped. There are 3 possible reason of the vibration including Vortex Induced Vibration (VIV), Galloping and Flutter.

To investigate the phenomena, a finite element analysis of the hanger was conducted by considering the effect of the axial force to the natural frequency of the hanger. The results of the analysis obtained in the form of the natural frequency of the structure in the first asymmetric torsional mode then compared with the frequency of vortex vibrations. It was found that the natural frequency of the structure corresponds to the vortex vibration frequency, and therefore, the hanger vibrated because of Vortex Induced Vibration (VIV).

Several alternative solutions to increase Vortex Induced Vibration (VIV) wind speed were considered including improving the shape of the hanger and increasing the hanger’s stiffness by using cable struts.

Index Terms*: *steel arch bridge, hanger, aerodynamic, vortex induced vibration, natural frequency.

I. INTRODUCTION

The Tayan Bridge is located 112 km from the city of Pontianak, on the South Link of Kalimantan, which connects West Kalimantan and Central Kalimantan Provinces. The total length of the bridge is 1,420 m with 11 m width. The approach bridge consists of a simple composite steel girder bridges with a span of 40 m. The main bridge is steel arch bridge with the main span of 200 m and vertical clearance of 13 m. The full shoring method was adopted for construction of the main bridge.

The Tayan Steel Arch Bridge has 35 hangers at one side with the length varies from 0.90 m to 26.80 m as shown in figure 2. The shape of the hanger is Web Flange (WF) with size of 450x150x12x15.

Revised Manuscript Received on April 25, 2019.

Made Suangga, Civil Engineering, Bina Nusantara University and Master Program in Civil Engineering, Tarumanagara University, Jakarta, Indonesia.

Prasetyo Eko Junianto, Master Program in Civil Engineering, Tarumanagara University, Jakarta, Indonesia.

Figure 1 Tayan Steel Arch Bridge

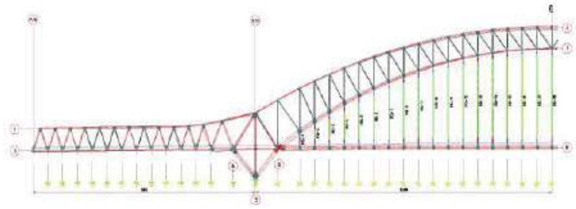


Figure 2. Hanger of Tayan Steel Arch Bridge

When the shoring removed, during final preparation for opening, an excessive vibration at hangers has been sought several times especially when the wind blew at certain speed level. To investigate the vibration, an anemometer was installed at the bridge to record both wind speed and wind direction from November 28, 2015 to December 8, 2015.

On December 1, 2015, a significant wind speed was recorded from 14:54 PM to 14:57 PM with wind speed ranging from 7.2 m/s to 7.6 m/s and the wind direction was between W-NW. No vibration on hangers has been found.

On December 2, 2015, two significant wind speeds were recorded from 17:13 PM to 18:28 PM, which were 6.3 m/s and 11.2 m/s and the wind direction was between W-SW. Visually, no vibration on Hanger H-1 to H-5 and hanger H-31 to H-35 has been found. Small vibration has been detected at hanger H-6 to H-10 and hanger H-26 to H-30, and excessive vibration was found at hanger H-11 to H-25 in first asymmetric torsional mode.

On December 6, 2015, other significant wind speeds were recorded from 14:15 PM to 15:11 PM with the magnitude of 6.3 m/s and 12.1 m/s and the wind direction was between W-SW. Another significant wind speeds were recorded from 17:24 PM to 17:35 PM with wind speed of 6.7 m/s and 7.2 m/s and the wind direction was between W-SW. Visually, there were no vibration on Hanger H-1 to H-5 and hanger H-31 to H-35 that can be observed. Small vibration was detected at hanger H-6 to H-10 and hanger H-26 to H-30, and excessive vibration was found at hanger H-11 to H-25 in first asymmetric torsional mode.

Based on the filed observations and wind speed recording, it can be concluded that the excessive vibration mode was the first asymmetric torsional, at wind speed between 8.9 m/s to 11.2 m/s with wind direction between W and SW (α = 15°) as shown in figure 3.

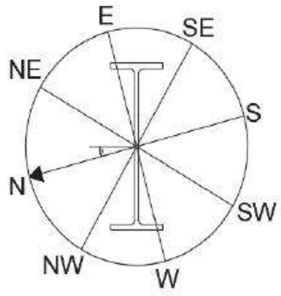


Figure 3. Direction of wind to the hanger

There are 3 possible reason of the hanger vibration, including Vortex Induced Vibration (VIV), Galloping and Flutter [2].

II. THEORY

A. Vortex Induced Vibrations (VIV)

When a field of fluid flow both water and air moves through an object, then the flow pattern will be disrupted from its original condition and adjusted to its new equilibrium condition. Separation of vortex flow through an object is called vortex shedding. The separation of flow highly depends on the speed of flow through the object At low flow velocities, flow separation occurs smoothly without local vortices (vortex), while at high flow speeds, the flow field that occurs causes the formation of vortex formation to form a mess with certain patterns [1] [3].

$$N_s = S_t \frac{U}{L_b} \tag{1}$$

The frequency of vortex shedding, symbolized as N_s, is proportional to the speed of the wind (U) that occurs and is inversely proportional to the dimensions of the structure perpendicular to the wind flow (L_b). The constant S_t is called the Strouhal Number. This value obtained is based on the cross-sectional shape of the structure or by the wind tunnel test.

As the wind speed increase, the value of vortex shedding frequency will continue to increase up to certain conditions, the N_s frequency of vortex shedding will approach the natural frequency of the structure so that resonance vibrations occur. After vibrations due to vortex, the structure tends to continue to vibrate due to the frequency of the N_s vortex shedding will be locked following the frequency of vibration rather than the structure. This causes the structure to continue to vibrate although the wind speed changes from the wind speed that causes resonance. This condition is called a lock-in phenomena.

B. Galloping

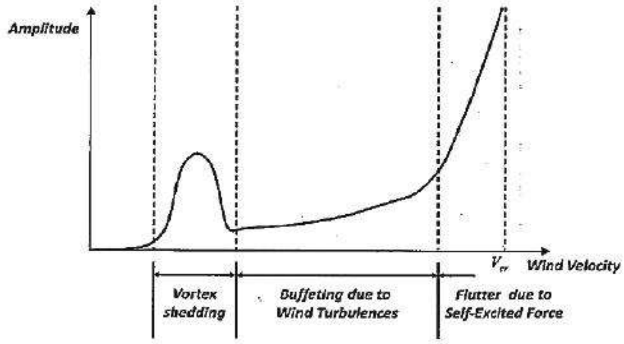
Dynamic instability due to galloping generally occurs in structures with long and slender elements. The term galloping is used to explain the large amplitude of vibrations that occur in the normal direction from the direction of the average wind velocity at lower frequencies than vibrations due to vortex shedding [1] [3].

Galloping instability will occur if the following equation is fulfilled:

$$\frac{d_{C_L}}{d_\alpha} + C_d = 0 \tag{2}$$

The above equation is used to check the occurrence of galloping instability in a flexible structure. The equation is called Glauert-Hartog Criterion [1].

C. Flutter



(a)Vortex Induced Vibrations (VIV) (b) Flutter Instability

Figure 4. Vortex Induced Vibration and Flutter Instability

Flutter is a vibration condition that is self-feeding (enlarged by itself) and when this aerodynamic vibration works together with the movement of the structure itself, they could have the potential to damage the structure. If the energy received by the structure due to gusts of wind is greater than the damping capacity of the structure, the amplitude of the vibration of the structure will continue to increase. The vibrations will further enlarge the aerodynamic force which will cause self-exciting forces and self-exciting oscillation [1] [3].

Vortex Induced Vibrations (VIV) only occurs at a certain wind speed and as the wind speed increase, the vibrations that occur will disappear, while the phenomenon of flutter occurs at high speeds speed, the greater the wind speed, the occurring vibration will also increase.

III. RESULT

A. The frequency of Vortex Shedding

The frequency of vortex shedding (N_s), is calculated using equation 1 where the vortex induced vibration wind speed (u) is 8.2 m/s, the dimensions of the hanger in the direction of perpendicular to the air flow (L_b) = 0.15 m and the Strouhal number (S_t) of H shaped hanger's cross section is 0.12.

$$N_s = 0.12 \frac{8.2}{0.15} = 7.12 \quad Hz$$

The excessive vibration of hangers can be concluded to be Vortex induced vibration if the natural frequency of the hanger for first asymmetric torsion mode similar to the frequency of vortex shedding (N_s).

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B. Natural Frequency of Bridge's Hanger

The natural frequency of the hanger is calculated for hanger no 18 as shown in figure 4. The length of the hanger is 26.8 m with tension force of 470 kN.

Several formulas have been introduced to calculate the natural frequency of the hanger. However, one of the limitations of the formulas that calculates the torsional frequency is that the formulas do not take the effect of the tension load into account. The effect of tension load is significant for Tayan Bridge's hanger vibration since the hangers in front of the parked truck did not vibrate, while the other hangers vibrated.

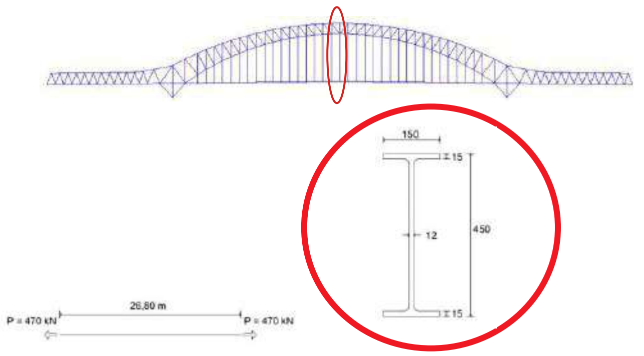

Figure 5. Parameter of Hanger no 18.

By using ANSYS software, the natural frequency of the hanger can be calculated by taking into account the axial load on the hanger. The finite element model of the hanger is presented in figure 6. The result of natural frequency analysis is presented in table 1.

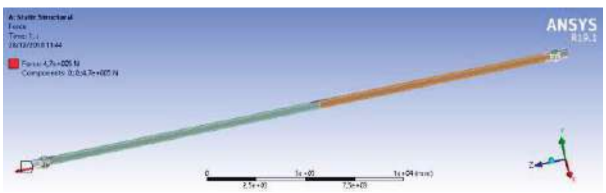

Figure 6. Hanger Modelling

Table 1. Natural frequency of hanger no 18

Mode	***Mode Shape***	**Natural Frequency (Hz)**
1	*1st Bending (x-dir)*	1,5657
2	*1st Bending (y-dir)*	3,2237
3	*1st Torsion*	3,2361
4	*2nd Bending (x-dir)*	3,3887
5	*3rd Bending (x-dir)*	5,5142
6	*2nd Torsion*	7,2631

From table 1, it is found that the natural frequency of the hanger for the second torsional mode is 7.2631 Hz. This natural frequency value is similar with the frequency of vortex shedding calculated using equation 1, where N_u is 7.12 Hz.

Therefore, it can be concluded that the vibration of Tayan Bridge's hanger is due to Vortex Induced Vibration.

C. The Effect of Tension Load to the Natural Frequency of Hanger

To investigate the effect of tension load to the natural frequency of the hanger, hanger no 18 was analyzed and various tension loads were applied to the hanger. The result of analysis conducted by using ANSYS software is presented in table 2 and figure 7.

From the results, it can be concluded that, the natural frequency of the hanger will increase as the tension load increases, except for the 1st torsional mode. The natural frequency value for 1st torsional mode was relatively constant.

This could explain why the hangers in front of the parked truck did not vibrate, while the other hangers did.

Table 2. Effect of tension load to natural frequency of hanger

Mode Shape	*Natural Frequency (Hz)*						
	P=0 kN	P=100 kN	P=200 kN	P=300 kN	P=400 kN	P=500 kN	P=600 kN
1st Bending (x-dir)	0,5057	0,86704	1,1047	1,2964	1,4613	1,6082	1,7418
1st Bending (y-dir)	3,0862	2,9288	3,0117	3,0921	3,1703	3,2464	3,3205
1st Torsion	2,651	2,957	3,0351	3,1111	3,1852	3,2576	3,3284
2nd Bending (x-dir)	1,6387	2,1377	2,5406	2,8855	3,1917	3,4696	3,7256
3rd Bending (x-dir)	3,4185	3,937	4,4229	4,8577	5,2545	5,6216	5,9648
2nd Torsion	5,4965	-	-	7,0166	7,1627	7,3057	7,4456

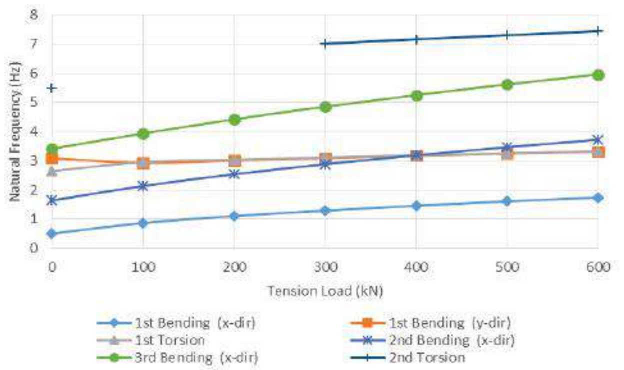

Figure 7. Effect of tension load to natural frequency of hanger

D. The Effect of Hanger's Length to the Natural Frequency of Hanger

To investigate the effect of hanger's length to the natural frequency of the hanger, the cross section of Tayan brideg's hanger, Web Flange (WF) with size of 450x150x12x15, was analyzed with various hanger's length. The result of analysis using ANSYS software is presented in table 3 and figure 7.

From the results, it can be concluded that, for the hanger that has a length of 19.8 m or more, the natural frequency of the hanger did not varies much.

This could explain why the vibration occur only at several hangers.

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Table 3. The Effect of Hanger's Length to the Natural Frequency of Hanger

Mode Shape	*Natural Frequency (Hz)*					
	L=7,07 m	L=14,33 m	L=19,80 m	L=23,70 m	L=26,04 m	L=26,80 m
1st Bending (x-dir)	10,706	2,6119	1,3684	0,9551	0,79117	0,74694
1st Bending (y-dir)	58,242	14,924	7,882	5,5165	4,5746	4,3201
1st Torsion	17,08	6,1947	4,1497	3,3601	3,0163	2,9193
2nd Bending (x-dir)	29,264	7,1934	3,7706	2,6322	2,1805	2,0586
3rd Bending (x-dir)	56,132	14,076	7,3869	5,1581	4,2734	4,0346
2nd Torsion	41,829	13,633	8,7931	7,0108	6,2521	6,0401

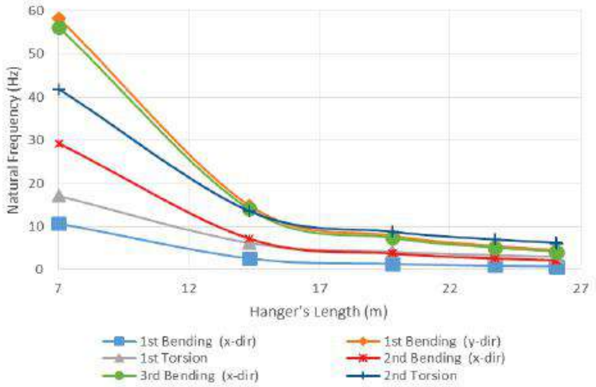

Figure 7. The Effect of Hanger's Length to the Natural Frequency of Hanger

E. The Effect of Hanger's Stiffness to the Natural Frequency of Hanger

To investigate the effect of hanger's stiffness to the natural frequency of the hanger, hanger no 18 was analyzed and various EI values were applied to the hanger. The result of analysis using ANSYS software is presented in table 4 and figure 8.

From the results, it can be concluded that, the natural frequency of the hanger will increase as the hanger's stiffness increases by an almost similar increment.

Table 4 The Effect of Hanger's Stiffness to the Natural Frequency of Hanger

Mode Shape	*Hanger's Stiffness (EI)*						
	70%	80%	90%	100%	110%	120%	130%
1st Bending (x-dir)	0.6249	0.66808	0.70861	0.74694	0.78339	0.81823	0.85164
1st Bending (y-dir)	3.6145	3.864	4.0984	4.3201	4.531	4.7324	4.9257
1st Torsion	2.4425	2.6111	2.7695	2.9193	3.0618	3.198	3.3286
2nd Bending (x-dir)	1.7224	1.8413	1.953	2.0586	2.1591	2.2551	2.3472
3rd Bending (x-dir)	3.3756	3.6087	3.8276	4.0346	4.2315	4.4197	4.6002
2nd Torsion	5.0536	5.4025	5.7302	6.0401	6.335	6.6167	6.8868

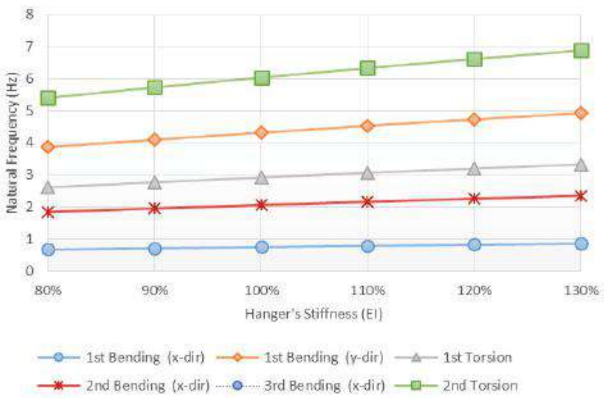

Figure 8. The Effect of Hanger's Stiffness to the Natural Frequency of Hanger

IV. SOLUTIONS

To overcome the excessive vibration of the hangers, several alternative to increase Vortex Induced Vibration (VIV) wind speed were considered and the alternatives can be categorized into two groups. The first group is by modifying the shape of existing WF and the second group is by increasing the stiffness of the hanger by using cable struts that connect the hangers.

A. Modification of hanger's shape

Modification of hanger's shape can be done by adding a non- structural material to transform the hanger's shape from I-shape into rectangular, circle and hexagonal shapes, as seen in figure 9.

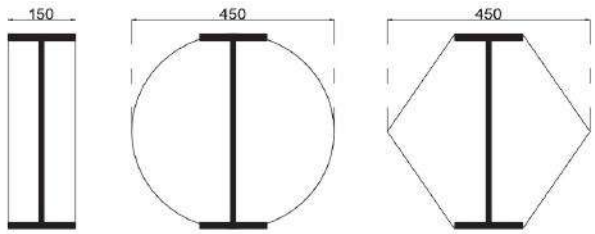

Figure 9. Modification of hanger's shape

The vortex induced vibration wind speed (U) can be calculated by using equation 1 and by applying the Strouhal Number for each shape. The result of analysis is presented in table 5

Table 5. Vortex shedding wind speed for various shape

No	*Hanger's Shape*	*Strouhal Number (S_t)*	*Hanger dimension perpendicular to wind flow (L_b) m*	*Vortex shedding wind speed (m/s)*
1	Rectangular	0.16	0.15	6.675
2	Circle	0.2	0.45	16.02
3	Hexagonal	0.16	0.45	20.025

It can be concluded that changing the hanger's shape from I-shape to rectangular shape does not improve the performance of the hanger to the vortex induced vibration, while changing the hanger's shape to circle and hexagonal shapes could significantly improve to the vortex induced vibration wind speed.

B. Modification of hanger's stiffness using cable struts.

Hanger stiffness was increased by installing cable struts connecting hangers so that the hanger's stiffness can increase. Two struts arrangements were considered, single struts at the middle of hanger's length and double struts at 0.25L and 0.75 L of hanger's length as shown in figure 10. The cable strut was modelled as a spring. By using ANSYS software, the natural frequency of the hanger can be calculated by taking into account the axial load on the hanger. The finite element model of the hanger is presented in figure 11 and figure 12. The result of natural frequency analysis is presented in table 6.

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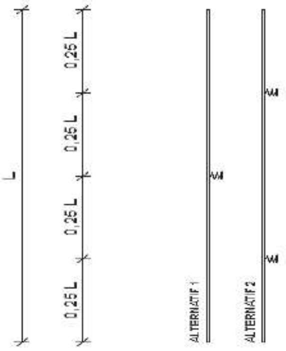

Figure 10. Modification of hanger's stiffness using cable struts

The stiffness of the cable struts was calculated using the following equation:

$$K_{strut} = \frac{E_{strut} A_{strut}}{L_{strut}} \quad (3)$$

Where the Modulus of Elasticity of cable strut, E_{strut} =199.950 MPa; The length of cable strut is equal to the distance between hangers L_{strut} =5 m, the diameter of the cable strut, Φ_{strut} =0,6 in and the section area of the cable struts, A_{strut} = 0,0001387 m^2.

$$K_{strut} = \frac{E_{strut} A_{strut}}{L_{strut}} = 5{,}546.613 \quad kN.m$$

From the calculation, it can be concluded that, the natural frequency of the hanger will significantly increase as the number of struts installed increases.

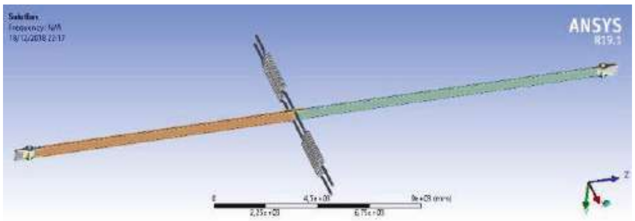

Figure 11. Modelling of Hanger with single strut

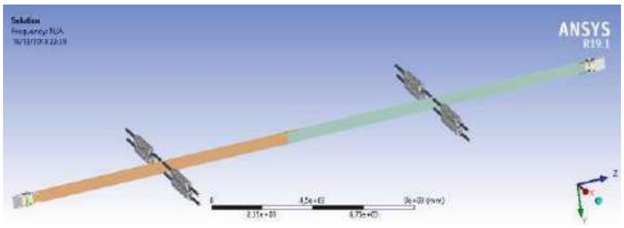

Figure 12. Modelling of Hanger with two struts

Table 6. The Effect of Cable struts to the Natural Frequency of Hanger

Mode Shape	*Natural Frequency (Hz)*		
	No cable strut	1 cable strut	2 cable struts
1st Bending (x-dir)	1.565	3.013	16.258
1st Bending (y-dir)	3.223	3.238	20.218
1st Torsion	3.236	6.931	38.228
2nd Bending (x-dir)	3.388	4.647	28.278
3rd Bending (x-dir)	5.514	7.267	42.618
2nd Torsion	7.263	8.580	142.600

The vortex induced vibration wind speed (U) can be calculated using the new natural frequency for first asymmetric torsional mode. The result of analysis is presented in table 7.

Table 7. Vortex induced vibration wind speed according to shape and number of struts

Shape of Hanger	*Number of cable strut*	*Strouhal Number (St)*	*Hanger dimension perpendicular to wind flow (L_h)*	*Natural Frequency of 1st asymmetric torsional (Hz)*	*Vortex shedding wind speed (m/s)*
WF - original	-	0.12	0.15	7.263	9,08
Rectangular	-	0.16	0.15	7.263	6,68
Circle	-	0.2	0.45	7.263	16,02
Hexagonal	-	0.16	0.45	7.263	20.03
WF - original	1 strut	0.12	0.15	8.580	10,73
WF - original	2 struts	0.12	0.15	142.600	178,25

C. The best alternative to improve Comparison of the vortex induced vibration wind speed Vortex

By comparing the improvement of vortex induced vibration wind speed by modifying the shape of existing WF and by increasing the stiffness the hanger by cable struts, it can be concluded that installing 2 struts to the hanger gives the highest vortex induced vibration wind speed

V. CONCLUSIONS AND FUTURE SCOPE

D. Conclusions

Based on this study on Vibration of the Tayan Bridge's hanger, it can be concluded that:

a. The phenomenon that causes vibrations in the hanger of the WF profile of the Tayan bridge is the result of Vortex Induced Vibration (VIV).
b. Tension force significantly affects the natural frequency value of hanger, and therefore, should not be neglected.
c. Installing 2 struts to the hanger gives the highest improvement on vortex induced vibration wind speed.
d. The recommended solution is to use struts-cable on the hanger so that the vortex speed increases.

E. Future Scope

Based on conclusions drawn from the results of data analysis it is recommended to avoid the use of WF shape for hanger due to its performance to Vortex Induced Vibration

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AUTHORS PROFILE

Made Suangga is a lecturer at Master Program in Civil Engineering, Tarumanagar University and Civil Engineering Bina Nusantara Univerity in Jakarta, Indonesia. He completed his undergraduate study at the Bandung Institute of Technology (1992), Master Program in Highway Engineering and System at the Bandung Institute of Technology (1995), and completed a doctoral program at Yokohama National University focusing on Wind and Bridge (2000).

Prasetyo Eko Junianto completed his undergraduate study program at Tarumanagara University (2017) and continued his master's program at Tarumanagara University (2019) with a focus on structural engineering

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