Temperature Effect on Tension Force of Stay Cable of Cable-Stayed Bridge

Made Suangga, Hendy Candra, Irpan Hidayat, Yuliastuti

Abstract*: *Cable is the main element of cable-supported bridge, such as suspension bridge, cable stayed bridge and arch bridge. For the cable-stayed bridge, the cable receives the load from the bridge deck and transfer it to the pylon. As the ambient temperature change, the internal force in bridge element including stayed cable will change. This research investigate the ambient temperature effect to the tension force of stayed cable of cable-stayed bridge by comparing the result of finite element model analysis with the field measurement form electromagnetic sensor data. The finite element model of Merah Putih Cable-Stayed Bridge has been developed based on detailed engineering design data. The finite element model is validated using the natural frequency data from dynamic load test of the bridge. The ambient temperature and bridge elements temperature were measured for 24 hours. The finite element analysis were conducted based on field measurement data and the contribution of pylon and girder temperature to the cable tension forces variation was investigated. The output of finite element analysis then compared to the actual cable tension as measured by an electromagnetic sensor. It was found that the ambient temperature will affecting the magnitude of tension force at stay cable and the variation of cable tension has similar pattern of both from the finite element model and electromagnetic data. As the temperature of bridge element increases or decreases, the bridge will experience a deformation. Since the stay cable connected to the pylon at one side and to the girder at the other side, its will make the stay cable elongated or contracted which in turn will affecting the tension force at stay cable. When evaluating the bridge condition based on the tension force at stay cable, the effect of temperature variation need to be considered.

Keywords: cable, cable-stayed bridge, cable tension, electromagnetic sensor, finite element method, temperature.

I. INTRODUCTION

Cable-stayed bridges are widely used as a solution for long span bridges due to their simple and beautiful structure. On cable-stayed bridge, stayed cables are the main element of the bridge as they receives most of the load that works on the bridge deck and transfer it to the pylon. The stayed cable of cable-stayed bridge is a structure element that works based on the principle of tensile force. Stayed cables are made of high tensile strength steel and the stiffness of the cable element depends on the magnitude of the applied tension force.

Due to its importance, monitoring activity for the tension force at the stayed cable is necessary to be done, as it can provide an indication of the structural condition of the bridge. Cable tension forces should not exceed their allowable value. One of the methods that can be used to measure real time tension force at stay cable is an electromagnetic sensor. The bridge can be considered safe as long as there is no major power change in the cable system [1]

Cable tension forces may vary with time due to load and ambient temperature variations at bridge location. Since the stayed cable is made of steel, ambient temperature variation is one of the important parameters which can affect the tension forces on cable [3]. However, the thermal effect is not only influenced by temperature variations, but also influenced by the existing structural conditions [6]. This is due to expansion and shrinkage of the cable itself and also due to temperature effect on the other elements of the bridge that could make the bridge deforms. Cables with the natural length close to the chord distance reveal the highest sensitivity to temperature [4] and temperature changes have a global negative effect on the tension forces as in [5].

The variation of cable tension due to temperature is affected by the articulation of the bridge and assumption that the temperature of bridge element (pylon, girder and cable) similar with the ambient temperature is not accurate [3].

From past research project, it was found that there is a strong dependence of thermal effects on the cable's inclination, on its reference stress level, as well as on the magnitude of the stress variation induced by live loads acting on the supported structure, highlighting also the role of the stiffness of the supported structure [2].

This study aims to investigate how the temperature variation affects the tension force at the cable. A better understanding of the effect of ambient temperature variation on tension force of the stay cable will take advantage of the process of monitoring the condition of the bridge based on data measured by sensors from the bridge structural health monitor system.

To investigate the effect of ambient temperature variation, Merah Putih Cable-Stayed Bridge is used as a case study. The bridge is located at Ambon, Moluccas, Indonesia and it stretches the Bay of Ambon Island which connects Rumah Tiga Village (Poka) with Hative Kecil Village (Galaga). The Bridge located at Ambon Bay and has three spans, 75 m + 150 m + 150 m as presented in Fig. 1, Fig. 2 and Fig. 3.

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Fig. 1. Merah Putih cable-stayed bridge

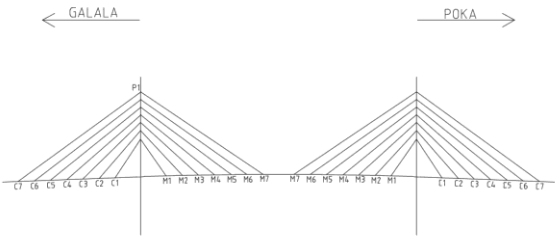

Fig. 2. Stay cable nomenclature of Merah Putih cable stayed bridge

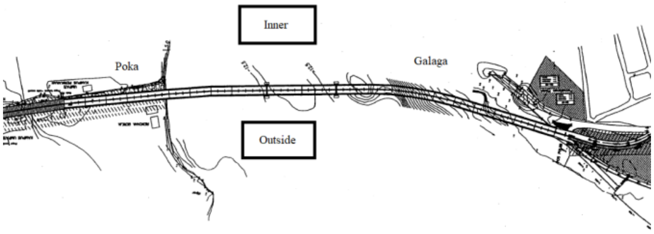

Fig. 3. Merah Putih cable-stayed bidge - plan

II. METHODOLOGY

Based on the available data, three-dimensional (3D) finite element model of Merah Putih Bride has been developed. Modification has been made from the previous study [3] by adding concrete deck element to the finite element model. To calibrate the finite element model of the bridge, dynamic properties of the three-dimensional model is compared with the dynamic properties of the actual bridge based on dynamic load test.

The ambient temperature and bridge elements temperature will be measured for 24 hours. Once the three-dimensional model has been calibrated, the variation of cable tension force based on bridge element temperature will be analyzed using a three-dimensional finite element model. Furthermore, the study on the contribution of pylon, cable, steel girder and concrete deck temperature variation to the cable tension forces variation will be investigated. Finally, the output of finite element analysis will be compared with actual cable tension obtained from an electromagnetic sensor attached at the bridge.

III. THEORY

A. Temperature Effect on Simple Cable Structure

The temperature will affect the change of cable structure, both in size, shape, or form. When a simple cable structure undergoes a temperature change, it either elongates or contracts depends on whether temperature is increased or decreased. If the end of a simple cable structure is released, then the elongation is not restricted. However, if the end of a material is fixed, elongation is restricted and will experience stress. [3] That stress will cause the force change formula to be negative, as seen in Fig. 4.

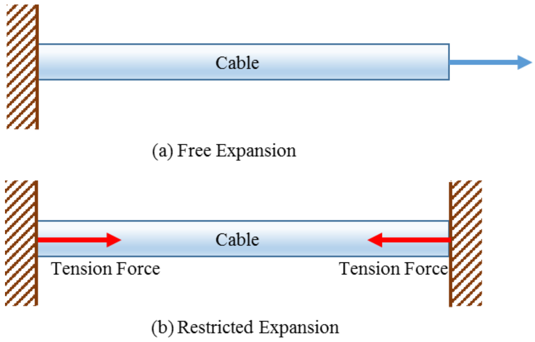

Fig. 4. Free expansion and restricted expansion

Thermal stress produces the same effects in a material similar to mechanical stress. When the temperature rises, compressive strength will produce in the material. When the temperature decreases, the tensile stress is developed. The force change equation is expressed as:

$$\Delta P_c = E \cdot A \cdot \alpha \cdot \Delta T \qquad (1)$$

Where ΔP_c is variation of axial force due to temperature, E is modulus of elasticity, A is sectional Area, α is coefficient of thermal expansion and ΔT is temperature change.

B. Temperature Effect on the Stay Cable of Cable -Stayed Bridge

Stayed cables of cable-stayed bridge connected to the pylon at one side and to the girder at the other side. Because of the fact that both pylon and girder could deflect, both end of the cable not fixed nor released. Stay cables will follow the deflection of pylon and girder that make the stay cable elongated or contracted.

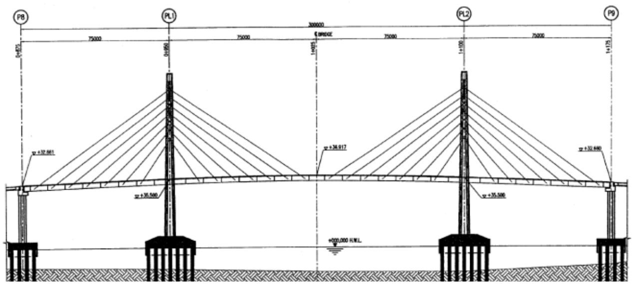

Fig 5. Stay Cable and its connection to pylon and girder

The tension force change due to elongation or contraction of stay cable caused by deformation of pylon and girder is expressed as:

$$\Delta P = E \cdot A \cdot \frac{\Delta L}{L_0} \qquad (2)$$

Where ΔP is variation of axial tension force, E is modulus of elasticity, A is sectional Area, L_o is initial length of the stay cable and ΔL is elongation or contraction of the stay cable due to deformation of pylon and girder.

IV. RESULT AND DISCUSSION

A. Validation of Finite Element Model of the Bridge

Fig. 6 and Fig. 7 show the 3-dimensional finite element model of the bridge for both without concrete bridge deck and with concrete bridge deck. Validation of the model has been made by comparing the dynamic parameter in term of natural frequencies of the model with the dynamic data of the actual bridge from dynamic field testing.

Table-I shows the comparison of natural frequencies between finite element model and the actual measured during dynamic load test. Addition of concrete bridge deck has improved the natural frequency closer to the actual natural frequencies.

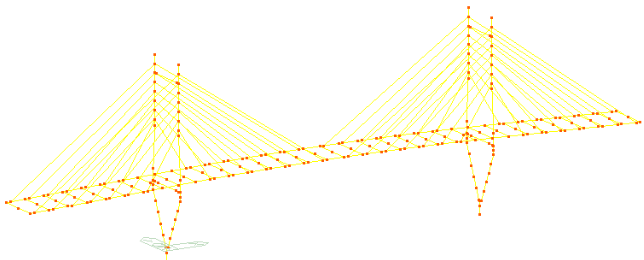

Fig. 6. Finite element model of the bridge without concrete deck [3]

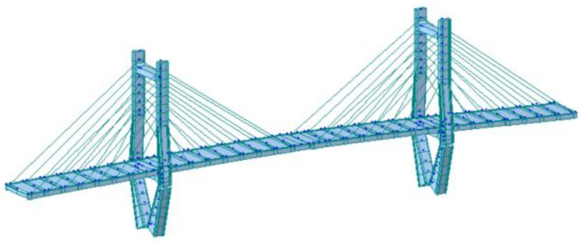

Fig. 7. Finite element model of the bridge with concrete deck

Table- I Merah Putih cable-stayed bridge frequency (Hz)

Tipe	Field Measurements Frequency	Modeling Frequency Without Deck [3]	Modeling Frequency With Deck
Longitudinal	0.370	0.323	0.351
Lateral	0.440	0.459	0.434
Vertikal	0.660	0.646	0.654

B. Ambient Temperature and Bridge Elements Temperature Data

Temperature data retrieval is conducted on the 20th and 21st of August 2019 for 24 hours where the data was taken every 1 hour. The location of data collection for bridge deck, pylon, girder and cable is presented in the Fig. 8, Fig. 9, and Fig. 10.

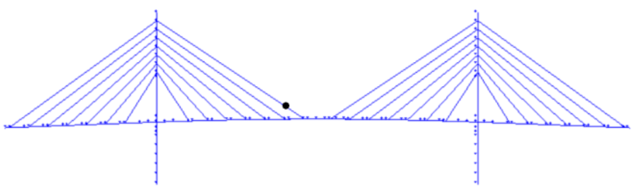

Fig. 8. Cable temperature measurement location

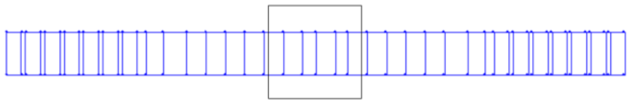

Fig. 9. Steel girder and concrete deck temperature measurement location

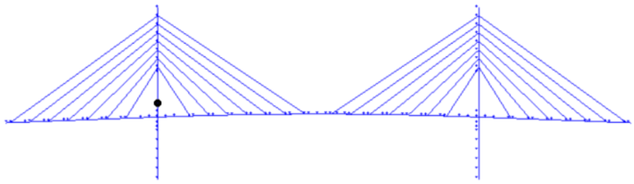

Fig. 10. Pylon Temperature measurement location

Ambient temperature and bridge elements temperature data based on field measurement are presented in Fig. 11, Fig. 12, Fig. 13, Fig. 14 and Fig. 15.

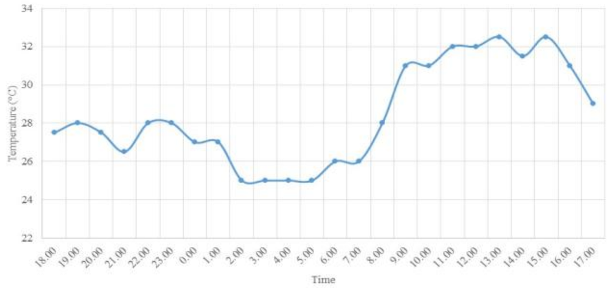

Fig. 11. Ambient temperature

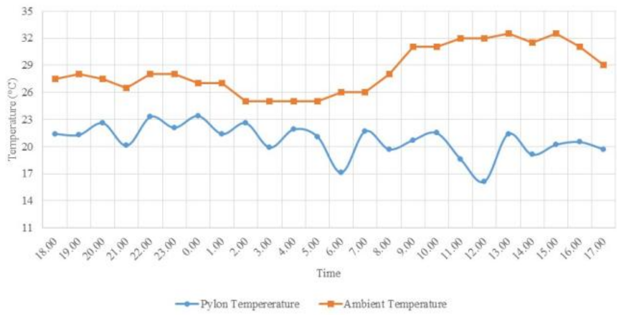

Fig. 12. Pylon temperature

It can been seen that the temperature of bridge element is correlated with the ambient temperature, however the temperature of bridge element is not equal to the ambient temperature

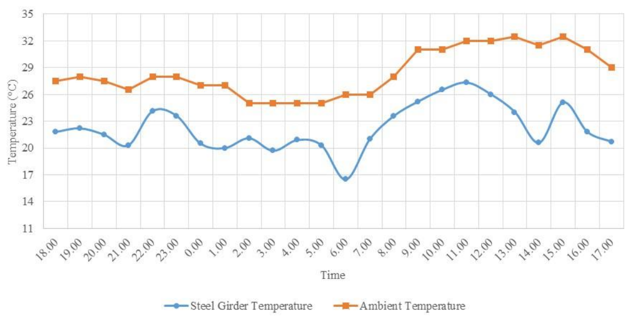

Fig. 13. Steel girder temperature

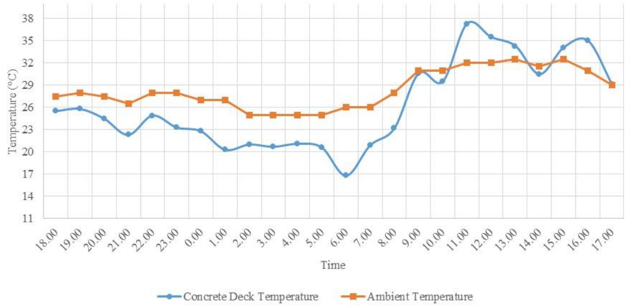

Fig. 14. Concrete deck temperature

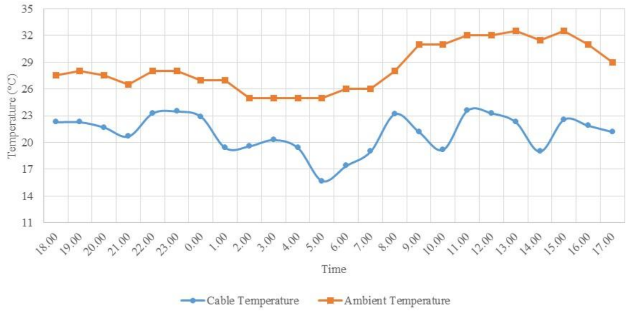

Fig. 15. Cable temperature

C. Stay Cable Tension Forces Data from Electromagnetic Sensor

Merah Putih Bridge has been equipped with Structural Health Monitoring System (SHMS) to monitor bridge condition in real time. The sensors installed including Electromagnetic Sensor to measure the cable tension. There are 24 electromagnetic sensors on Merah Putih Bridge as shown in Fig. 16.

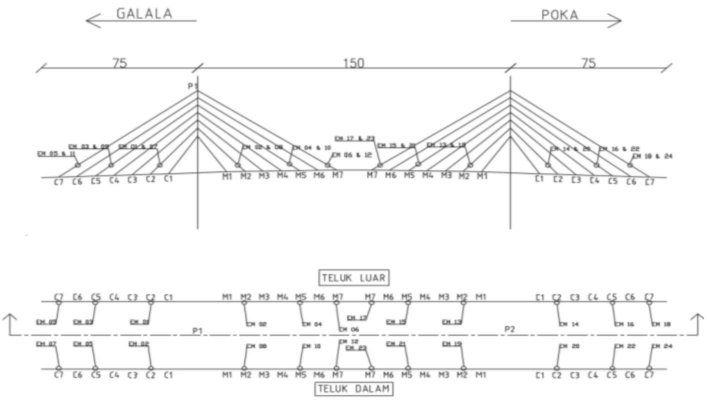

Fig. 16. Electromagnetic sensors position

Electromagnetic Sensor data on the 20th and 21st of August 2019 for C5 and are presented in Fig. 17 and Fig. 18. The Electromagnetic Sensor data are recorded every 10 minutes.

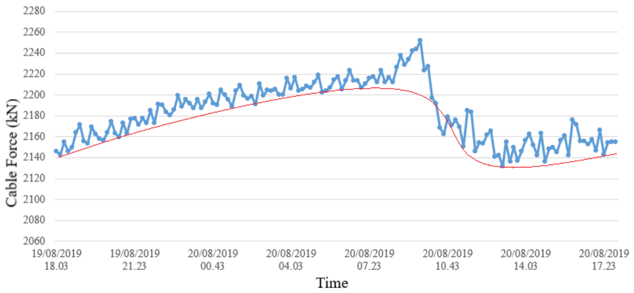

Fig. 17. Cable force EM3 (Cable C5 Galaga - outer bay)

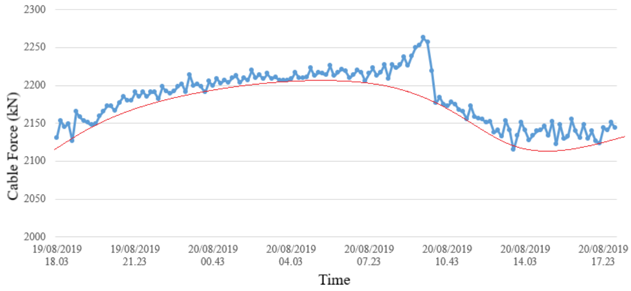

Fig. 18. Cable force EM9 (Cable C5 Galaga – inner bay)

D. Contribution of Pylon Temperature to the Cable Tension Force

The contribution of pylon temperature variation to the cable tension force was investigated by activating the temperature expansion coefficient (α) of the pylon only while others member type are made zero. The temperature expansion coefficient (α) of the pylon is 11 x 10^{-6} /^{o}C and the temperature at 00.00 was used as a reference. The result of analysis at 14.00 o'clock is presented in Table-II.

Table-II Contribution of Pylon Temperature to the Cable Tension Force at 14:00 o'clock

Galaga			Poka		
	Outer	Inner		Outer	Inner
No Cable	ΔPp (kN)	ΔPp (kN)	No Cable	ΔPp (kN)	ΔPp (kN)
C1	-21.565	-25.137	C1	-21.565	-25.140
C2	-9.721	-11.248	C2	-9.721	-11.250
C3	-5.127	-6.054	C3	-5.129	-6.057
C4	-3.387	-4.403	C4	-3.392	-4.409
C5	-3.716	-5.401	C5	-3.725	-5.411
C6	-5.154	-7.943	C6	-5.167	-7.959
C7	-8.051	-12.446	C7	-8.072	-12.470
M1	-20.448	-24.357	M1	-20.442	-24.340
M2	-8.664	-10.355	M2	-8.662	-10.333
M3	-3.412	-4.133	M3	-3.418	-4.137
M4	0.832	-1.108	M4	0.849	-1.133
M5	0.066	0.111	M5	0.036	0.160
M6	0.039	0.237	M6	0.011	0.317
M7	-1.319	-1.938	M7	-1.308	-1.929

As the temperature of pylon increases or decreases, the bridge will experience a deformation. Since the stay cable connected to the pylon at one side and to the girder at the other side, it will make the stay cable elongated or contracted which in turn affecting the tension will force at stay cable.

Cable C1 – Galala at inner side of the bay has original length L_o = 28.28107 m. From finite element analysis, due to bridge deformation caused by temperature variation of the pylon, its length reduced to L = 28.28005 m. By applying (2) with E = 1,9995 x 10-5 kN/m^2 and A = 0.0032 m^2, the tension variation due to pylon temperature can be calculated as

$$\Delta P = E \cdot A \cdot \frac{\Delta L}{L_0} = -21.564 \quad kN$$

It can be concluded that the contribution of pylon temperature to the tension force of stay cable mainly caused by deformation of the bridge which make the cables elongated or contracted.

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E. Contribution of Steel Girder and Concrete Deck Temperature to the Cable Tension Force

The contribution of steel girder and concrete deck temperature variation to the tension force of the cable is investigated by activating the temperature expansion coefficient (α) of the steel girder and concrete deck only others member type were made zero. The temperature expansion coefficient (α) of the steel girder is 12 x 10^{-6} /^{o}C, the temperature expansion coefficient (α) of the concrete deck is 11 x 10^{-6} /^{o}C. The temperature at 00.00 was used as a reference. The result of analysis at 14.00 o'clock is presented in Table-III.

Table-III Contribution of Steel Girder and Concrete Deck to the Cable Tension Force at 14:00 o'clock

Galaga			Poka		
	Outer	Inner		Outer	Inner
No Cable	ΔPGP (kN)	ΔPGP (kN)	No Cable	ΔPGP (kN)	ΔPGP (kN)
C1	-4.829	-5.413	C1	-4.833	-5.448
C2	-12.636	-13.417	C2	-12.621	-13.422
C3	-20.719	-21.908	C3	-20.638	-21.837
C4	-23.149	-24.600	C4	-22.967	-24.417
C5	-21.112	-22.775	C5	-20.775	-22.428
C6	-10.730	-12.384	C6	-10.181	-11.812
C7	13.683	12.511	C7	14.524	13.391
M1	-2.696	-2.341	M1	-2.919	-2.315
M2	-4.830	-4.816	M2	-4.916	-4.283
M3	-6.909	-6.453	M3	-6.696	-6.109
M4	-6.901	-6.373	M4	-6.278	-5.774
M5	-5.139	-4.608	M5	-3.945	-3.444
M6	-1.418	0.959	M6	0.550	1.037
M7	4.981	5.272	M7	4.932	5.214

As the temperature of steel girder and concrete deck increases or decreases, the bridge will experience a deformation. Since the stay cable connected to the pylon at one side and to the girder at the other side, its will make the stay cable elongated or contracted which in turn will affecting the tension force at stay cable.

Cable C1 at Galala Side at inner side of the bay has an original length (L_o) of 28.28107 m. From finite element analysis, due to the bridge deformation caused by temperature variation at steel girder and concrete deck, its length expanded to 28.28079 m. By applying (2), the tension variation due to pylon temperature can be calculated as

$$\Delta P = E \cdot A \cdot \frac{\Delta L}{L_0} = -4.828 \quad kN$$

It can be concluded that the contribution of steel girder and concrete deck temperature to the tension force of stay cable mainly caused by deformation of the bridge which make the cables elongated or contracted.

F. Contribution of Cable Temperature to the Cable Tension Forces

The contribution of cable temperature variation to the cable tension force was investigated by activating the temperature expansion coefficient (α) of the cable only others member type are made zero. The temperature expansion coefficient (α) of the stay cable is 12 x 10-6 /^{o}C. The temperature at 00.00 o'clock was used as a reference. The result of analysis at 14.00 o'clock is presented in Table-IV.

Table-IV Contribution of Cable Temperature to the Cable Tension Force at 14:00 o'clock

Galaga			Poka		
	Outer	Inner		Outer	Inner
No Cable	ΔPK (kN)	ΔPK (kN)	No Cable	ΔPK (kN)	ΔPK (kN)
C1	11.329	8.524	C1	11.331	8.523
C2	5.988	4.621	C2	5.991	4.622
C3	5.347	3.944	C3	5.356	3.951
C4	7.007	4.729	C4	7.025	4.745
C5	11.281	7.179	C5	11.313	7.208
C6	17.833	11.005	C6	17.885	11.054
C7	27.186	16.538	C7	27.267	16.612
M1	10.409	7.339	M1	10.381	7.328
M2	4.079	2.877	M2	4.068	2.890
M3	1.196	0.848	M3	1.219	0.872
M4	0.409	0.337	M4	0.481	0.393
M5	1.451	1.193	M5	1.591	1.299
M6	4.381	3.489	M6	4.611	3.664
M7	9.973	7.811	M7	9.943	7.779

As the temperature of stay cables increase or decrease, the bridge will experienced deformation. Since the stay cable connected to the pylon at one side and to the girder at the other side, its will make the stay cable elongated or contracted which in turn will affecting the tension force at stay cable.

Cable C1 at Galala Side at inner side of the bay has original length of 28.28107 m. From finite element analysis, due to the bridge deformation caused by temperature variation at stay cables, its length was reduced to 28.28282 m. By applying (2), the tension variation due to cable temperature can be calculated as

$$\Delta P = E \cdot A \cdot \frac{\Delta L}{L_0} = 41.460 \quad kN$$

Stay cable itself will elongates or contracts due to temperature as indicated in (1). Therefore, the variation of the cable tension force must be added with additional cable force due to the expansion of the cable itself.

$$\Delta P_{total} = \Delta P + \Delta P_c = 41.460 + (-30.132) = 11.328 \quad kN$$

It can be concluded that the variation of the tension force at stay cable caused by elongation or contraction of cable due to deformation of the bridge and by the thermal expansion of the cable itself

G. Comparison with Electromagnetic Sensor Data

Bridge element temperature data retrieval on the 20th and 21st of August 2019 for 24 hours has been applied to finite element model of the bridge to obtain cable tension force variation. The results then compare with the stay cable tension force variation measured by electromagnetic sensor. The comparison for cable C5 Galala at inner side of the bay and outer side of the bay are presented in Table-V and Fig. 19 and Fig. 20.

Table-V Comparison of Cable Tension Force Variation

Time	Variation of Cable Tension Force (kN)			
	C5 Galaga - outer side of the bay		C5 Galaga - outer side of the bay	
	Electromagnetic Sensor	Finite Element Analysis	Electromagnetic Sensor	Finite Element Analysis
18:00	-40	-1.97	-70	-15.43
19:00	-30	-2.01	-55	-12.80
20:00	-25	2.57	-40	-10.48
21:00	-20	5.33	-25	-4.43
22:00	-10	5.50	-20	-6.37
23:00	-5	7.30	-10	-7.67
0:00	0	0.00	0	0.00
1:00	5	13.87	7.5	10.28
2:00	10	16.49	12.5	6.40
3:00	15	9.04	13	-2.92
4:00	20	15.95	15.5	3.53
5:00	25	23.72	20	21.55
6:00	30	16.06	17.5	2.57
7:00	35	17.84	12.5	4.87
8:00	35	5.68	10	-5.06
9:00	20	-2.82	0	-22.04
10:00	-10	10.30	-15	-9.02
11:00	-40	-24.96	-40	-34.38
12:00	-45	-24.88	-50	-37.00
13:00	-50	-19.17	-60	-40.17
14:00	-50	-13.55	-75	-21.00
15:00	-45	-17.21	-75	-36.48
16:00	-42.5	-30.08	-70	-31.64
17:00	-40	-14.12	-65	-26.21

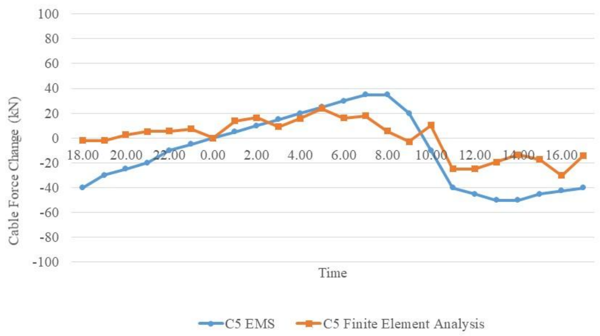

Fig. 19. Comparison of cable tension force variation at cable C5 Galaga - outer side of the bay

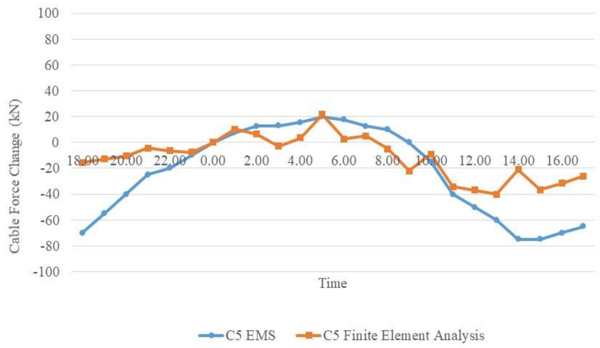

Fig. 20. Comparison of cable tension force variation at cable C5 Galaga - inner side of the bay

It can be concluded that the pattern of cable tension force variation obtained from finite element analysis similar pattern with the variation obtained from field measurement using electromagnetic sensor.

V. CONCLUSION

Based on the result analysis, it can be concluded that

a. Cable tension force will vary with temperature because of
   - the thermal expansion properties of the cable itself
   - the temperature variation of bridge element that make the bridge deform which in turn affecting the length of the cable.

b. Cable tension force variation obtained from finite element analysis has similar pattern with the variation obtained from field measurement using electromagnetic sensor.

c. The ambient temperature will affecting the magnitude of tension force at stay cable and therefore, when evaluating the bridge condition based on the tension force at stay cable, the effect of temperature variation need to be considered.

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