Temperature effect on cable tension forces of cable-stayed bridge

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Abstract. Cable is the most important element of cable-stayed bridge because it sustains most of the loads that work on the bridge deck and transfer the load to the pylon. The purpose of this research was to determine the effects of temperature on stayed cable of the bridge, to analyze the contribution of pylon and girder stiffness to the cable tension forces variation due to temperature effect. The result of the analysis using Finite Element Method then compared with the available field measurement data. To validate the finite element model, the dynamic finite element model of the bridge will be compared with the dynamic properties of the bridge from dynamic testing of actual bridge. It was found from the finite element model that he effects of temperature on the cable force is linear and the girder and pylon stiffness has significant contribution to the variation of cable tension force due to temperature change. The different between field measurement and finite element model has been found due to assumption on the temperature behavior of bridge deck, pylon and cable

Keywords: cable-stayed bridge, cable, temperature, finite element method

1. Introduction

On cable-stayed bridge, cable is the most important element because cable sustain 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. Generally, the cable is composed of small diameter steel (strand) combined into one (tendon) to have a higher tensile strength.

As the cable is an important element in cable-stayed bridges, monitoring the tension force of the cable is very important. It can be used to indicate the structural condition of the bridge and has to be ensure that the tension forces not exceeding their allowable value. Cable tension forces may varies with time due to variation on the load acting on the bridge. Temperature is one of the important parameter which can change the tension forces on cable. This is due to expansion and shrinkage of the cable its self and also due to temperature effect on the other element of the bridge such as pylon and bridge girder.

This research will analyses the influence of temperature to cable forces on cable-stayed bridge using 3-dimensional finite element model of the bridge. Merah Putih Bridge in Ambon, Moluccas is considered in the analysis. The contribution on temperature change in pylon and girder also investigated. The result then compared with the field data of cable tension forces.

2. Methodology

As a starting point, the temperature effect on simple cable system will be analysis using analytical method and finite element method. The results then compared before applied to the 3-dimensional model of the actual cable stayed bridge. Merah Putih Cable Stayed bridge is used for this analysis. 3-dimensional model of the bridge will be built. To calibrate the finite element model of the bridge, dynamic properties of the 3-dimensional model will be compare with the dynamic properties of the actual bridge based on dynamic test.

Once the 3-dimensional model calibrated, the study on the variation of cable tension forces will be conducted by varying the temperature of the bridge element on 3-dimensional finite element model. The temperature different at Ambon between the maximum and the minimum is 10°C. The effect of temperature change in stay cable, bridge girder and pylon then investigated to understand the contribution of temperature variation at bridge components to the variation of cable tension forces. The result of finite element analysis then compared with the available record of the cable tension forces

This research was conducted at Merah Putih Bridge, Ambon, Moluccas, Indonesia. The bridge has 150 m main span and two 75 m side spans.

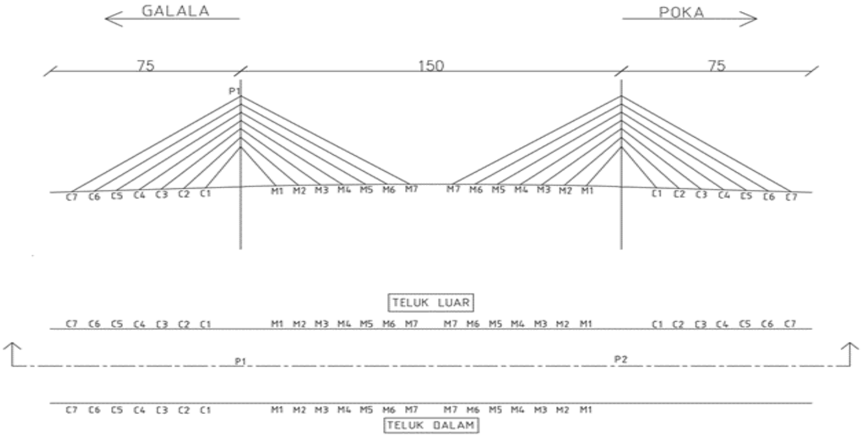

Figure 1. Merah Putih Bridge layout

Table 1. Merah Putih Bridge cables data

Cable	Strand Amount	Cable Amount	Length (m)	Diameter (mm)
C1	23	4	30,63	64,03
C2	23	4	39,52	64,03
C3	25	4	48,81	66,76
C4	25	4	58,32	66,76
C5	27	4	67,95	69,37
C6	30	4	77,66	73,13
C7	35	4	87,42	78,99
M1	23	4	29,74	64,03
M2	23	4	38,28	64,03
M3	25	4	47,29	66,76
M4	25	4	56,56	66,76
M5	27	4	65,98	69,37
M6	30	4	75,51	73,13
M7	35	4	85,11	78,99

Merah Putih Bridge has been equipped with Structural Health Monitoring System (SHMS). The sensors installed including Electromagnetic Sensor (EMS) to measure the cable tension. There are 24 EMS sensors on Merah Putih Bridge.

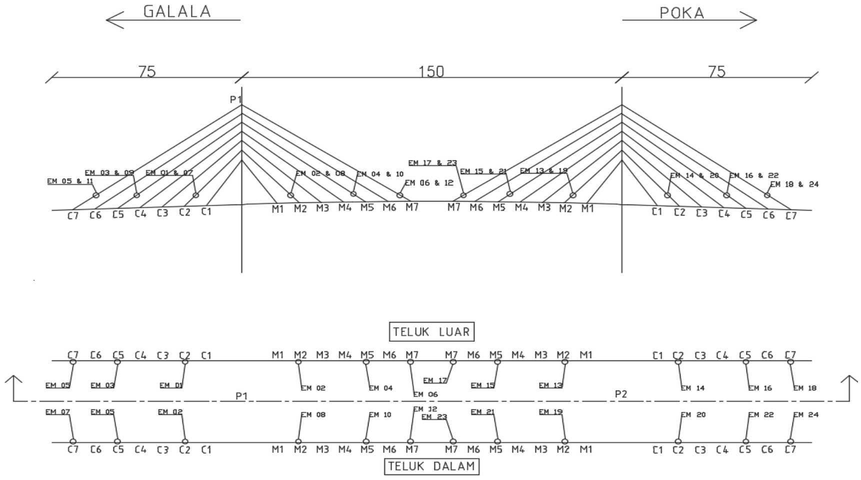

Figure 2. Electromagnetic sensor position on Merah Putih Bridge

3. Results and Discussion

3.1 Temperature effect on simple cable structure by theoretical and finite element analysis

The temperature will affect the change of objects, both in size, shape, or form. When a material undergoes a temperature change, it either elongates or contracts depends on whether temperature is increased or decreased. If the end of a material is released, then the elongation is not restricted. However, if the end of a material is fixed, elongation is restricted and will experience stress. That stress will cause the force change formula (Equation 1) to be negative.

(a) Free Expansion

(b) Restricted Expansion

Figure 3. Free expansion and restricted expansion

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

$$\Delta P = E \, . \, A \, . \, \alpha \, . \, \Delta T \qquad (1)$$

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

The analysis result of simple cable system theoretically (ΔP_T) by using Equation 1 and Finite Element Analysis (ΔP_{EK}) for 10°C temperature variation is presented in Table 3. Both methods give similar value

Table 2. Temperature effect on simple cable structure by theoretical and finite element analysis

Cable	ΔP_{EK} (kN)	ΔP_T (kN)	Difference (%)	Cable	ΔP_{EK} (kN)	ΔP_T (kN)	Difference (%)
C1	-75,329	-75,329	0,0009	M1	-75,329	-75,329	0,0009
C2	-75,329	-75,329	0,0009	M2	-75,329	-75,329	0,0009
C3	-81,879	-81,880	0,0005	M3	-81,879	-81,880	0,0005
C4	-81,879	-81,880	0,0005	M4	-81,879	-81,880	0,0005
C5	-88,430	-88,430	0,0001	M5	-88,430	-88,430	0,0001
C6	-98,254	-98,255	0,0020	M6	-98,254	-98,255	0,0020
C7	-114,632	-114,631	0,0001	M7	-114,632	-114,631	0,0001

3.2 Finite element model of the bridge and the validation

Based on the available data, 3-dimensional finite element model of Merah Putih Bride has been developed. Figure 4 show the 3-dimensional finite element model of the bridge. To obtain representative model, validation of the model has been made. The dynamic parameter of the model has been compared with the dynamic data of the actual bridge from dynamic testing. The natural frequencies of the finite element model of the bridge have been compared with the measured natural frequencies of the bridge.

Table 3 show the comparison between finite element model and the actual measured. The natural frequencies are not much different and therefore the 3-dimensional finite element model of the bridge is valid.

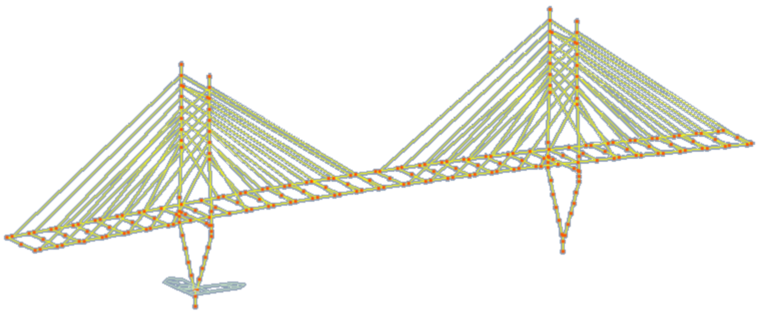

Figure 4. 3-Dimensional finite element model of Merah Putih Bridge

Table 3. Calibration of finite element model of the bridge

Mode	Design Frequency (Hz)	Type	Information	Field Measurement Frequency (Hz)	This Study Frequency (Hz)
1	0,341	Longitudinal	*Deck*	0,370	0,323
2	0,475	Lateral	*Cable*	0,440	0,459
3	0,611	Vertikal	*Deck*	0,660	0,646

3.3 Variation of cable tension forces due to 10°C temperature increase

Table 4 shows variation of cable tension forces due to 10°C temperature (ΔP_M) compared with the variation for simple cable system (ΔP_T). There are significant different of the variation of cable forces. This is because for simple cable system, the effect of pylon and girder deflections due to temperature change are not considered.

Table 4. Variation of cable tension forces due to 10°C temperature increase by simple cable system and 3-d finite element model

Galala			Poka		
Cable	ΔP_M (kN)	ΔP_T (kN)	Cable	ΔP_M (kN)	ΔP_T (kN)
C1	5,815	-75,329	C1	5,815	-75,329
C2	2,319	-75,329	C2	2,319	-75,329
C3	0,018	-81,880	C3	0,018	-81,880
C4	-3,578	-81,880	C4	-3,578	-81,880
C5	-9,868	-88,430	C5	-9,868	-88,430
C6	-19,764	-98,255	C6	-19,764	-98,255
C7	-33,242	-114,631	C7	-33,277	-114,631
M1	4,643	-75,329	M1	4,643	-75,329
M2	-1,512	-75,329	M2	-1,512	-75,329
M3	-4,139	-81,880	M3	-4,139	-81,880
M4	-4,993	-81,880	M4	-4,993	-81,880
M5	-5,404	-88,430	M5	-5,404	-88,430
M6	-5,304	-98,255	M6	-5,304	-98,255
M7	-3,811	-114,631	M7	-3,811	-114,631

3.4. The effect of temperature change to individual cable tension

The Effect on temperature change to individual cable tension is presented in Figure 5. The temperature change is varied from -10°C to 10°C. There is linear relation between temperature change and cable tension change. For most of the cables it is decrease with increase in temperature except for cable C2.

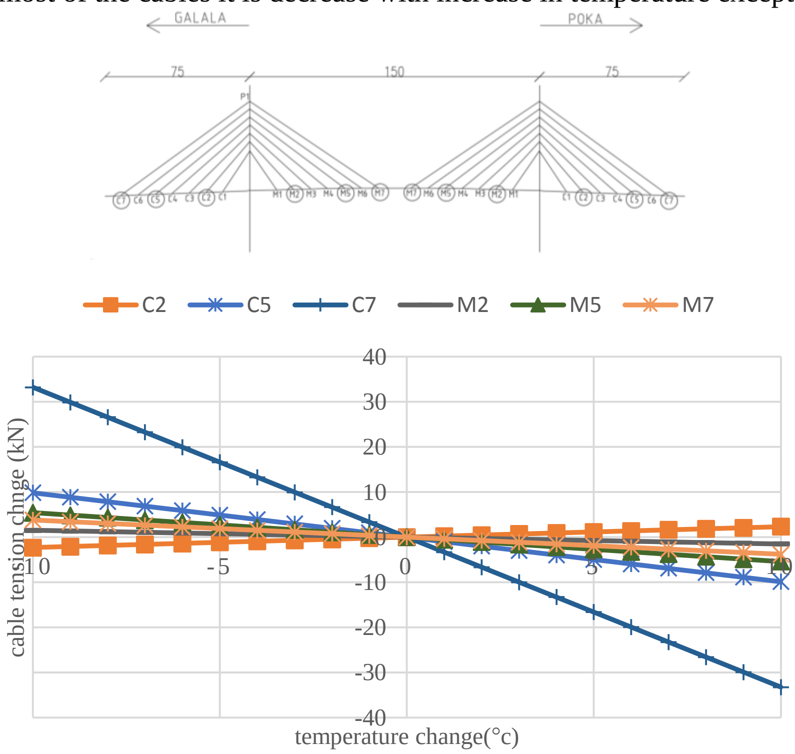

Figure 5. The Effect on temperature change to individual cable tension

3.5 The effect of bridge articulation on variation of cable tension force due to temperature

Two types of bridge articulations are considered. Type 1 (Figure 6) is the actual bearing of Merah Putih Bridge, and type 2 (Figure 7) is a case where the connection between pylon and girder are released or free. In type 2 bearing, all the right and left ends of the bridge are assumed to be fix.

For 10°C increase in temperature the cable force is variation due to type 1 (ΔPM) bearing is smaller than type 2 (ΔPP2) bearing. This is due to the right and left ends of the Type 2 bridge articulation are fixed. Therefore the effect of temperature on cable tension is affected by the articulation of the bridge

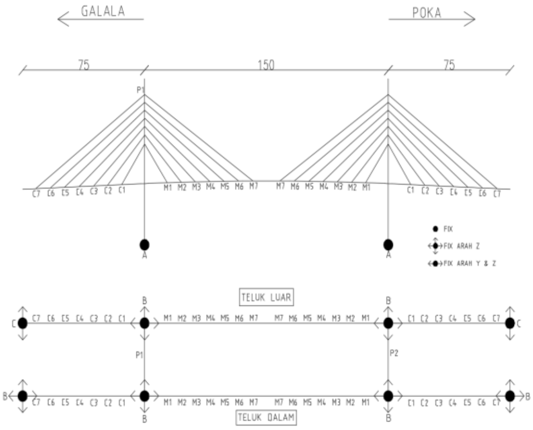

Figure 6. Type 1 bearing configuration

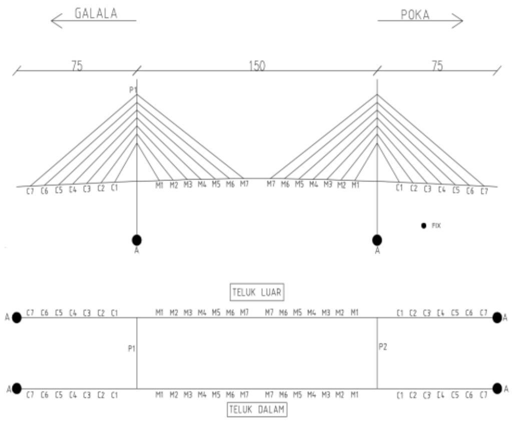

Figure 7. Type 2 bearing configuration

Table 5. Bearing detail

Code	X Axis	Y Axis	Z Axis
A	*Fix*	*Fix*	*Fix*
B	*Free*	*Free*	*Fix*
C	*Fix*	*Free*	*Fix*

Table 6. Comparison of cable force change due to type 1 and type 2 bearing

Galala			Poka		
Cable	ΔP_M (kN)	ΔP_{P2} (kN)	Cable	ΔP_M (kN)	ΔP_{P2} (kN)
C1	5,815	0,175	C1	5,815	0,175
C2	2,319	-0,136	C2	2,319	-0,136
C3	0,018	-5,376	C3	0,018	-5,376
C4	-3,578	-14,489	C4	-3,578	-14,489
C5	-9,868	-28,263	C5	-9,868	-28,263
C6	-19,764	-45,498	C6	-19,764	-45,498
C7	-33,242	-63,800	C7	-33,277	-63,800
M1	4,643	-26,857	M1	4,643	-26,857
M2	-1,512	-23,570	M2	-1,512	-23,570
M3	-4,139	-22,473	M3	-4,139	-22,473
M4	-4,993	-21,244	M4	-4,993	-21,244
M5	-5,404	-23,307	M5	-5,404	-23,307
M6	-5,304	-28,210	M6	-5,304	-28,210
M7	-3,811	-38,456	M7	-3,811	-38,456

3.6 The effect of expansion coefficient of pylon, girder, and cable to the cable tension forces

Aside from bearing, pylon, girder and cable also affects the cable tension force. To investigate the effect of expansion coefficient of pylon, girder, and cable to the cable tension forces three cases are considered,

a. The thermal coefficient on girder and cable is 0 so that the temperature only works on the pylon (ΔP_{Py})
b. The thermal coefficient on pylon and cable is 0 so that the temperature only works on the girder (ΔP_G)
c. The thermal coefficient on pylon and girder is 0 so that the temperature only works on the cable (ΔPK)

The result for 10° C temperature different then compared with the result of 3D finite element model (ΔP_M).

Table 7. Thermal coefficient cases

Thermal Coefficient	Pylon Effects	Girder Effects	Cable Effects
Pylon (α_P)	$\neq 0$	$= 0$	$= 0$
Girder (α_G)	$= 0$	$\neq 0$	$= 0$
Cable (α_K)	$= 0$	$= 0$	$\neq 0$

Table 8. The effect of expansion coefficient of pylon, girder, and cable to the cable tension

Cable	ΔP_{Py} (kN)	ΔP_G (kN)	ΔP_K (kN)	ΔP_M (kN)
C1	29,299	-1,384	-22,100	5,815
C2	8,008	-0,450	-5,239	2,319
C3	1,270	0,121	-1,372	0,018
C4	0,710	1,012	-5,300	-3,578
C5	3,464	2,605	-15,937	-9,868
C6	8,434	5,134	-33,332	-19,764
C7	16,298	8,740	-58,280	-33,242
M1	29,987	-2,615	-22,729	4,643
M2	7,942	-4,771	-4,682	-1,512
M3	0,336	-7,271	2,796	-4,139
M4	-1,837	-8,003	4,846	-4,993
M5	-1,881	-6,638	3,115	-5,404
M6	-0,833	-0,888	-3,583	-5,304
M7	2,227	12,187	-18,225	-3,811

Table 8 shows that each bridge element contributes to the temperature effect on cable tension however the effect of expansion coefficient of pylon and cable is in opposite direction and the girder in between.

3.7 The effect of pylon stiffness on cable tension forces due to temperature

Table 8 indicates that the stiffness of pylon affects the cable tension. For this analysis, the stiffness of the pylon increased by 25%, 50%, 75%, and 100% and the cable tensions for 10°C temperature different are compared.

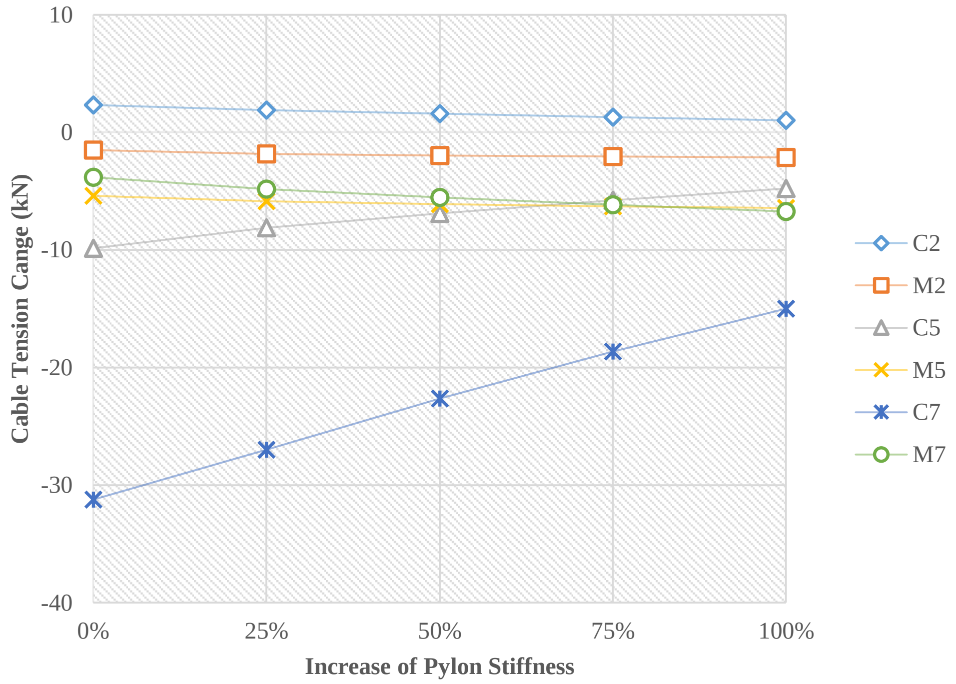

Figure 8. The effect of pylon stiffness on cable tension forces due to temperature

From Figure 8 can be seen that variation of cable tension forces due to variation of pylon stiffness is almost linear for all cables. In general, as the pylon become stiffer the variation of cable tension due to temperature at outer cable decrease and relatively constant for middle cables.

3.8 The effect of girder stiffness on cable tension furce due to temperature

Table 8 indicates that the stiffness of girder affects the cable tension. For this analysis, the stiffness of the girder increased by 25%, 50%, 75%, and 100% and the Cable tensions for 10°C temperature different are compared.

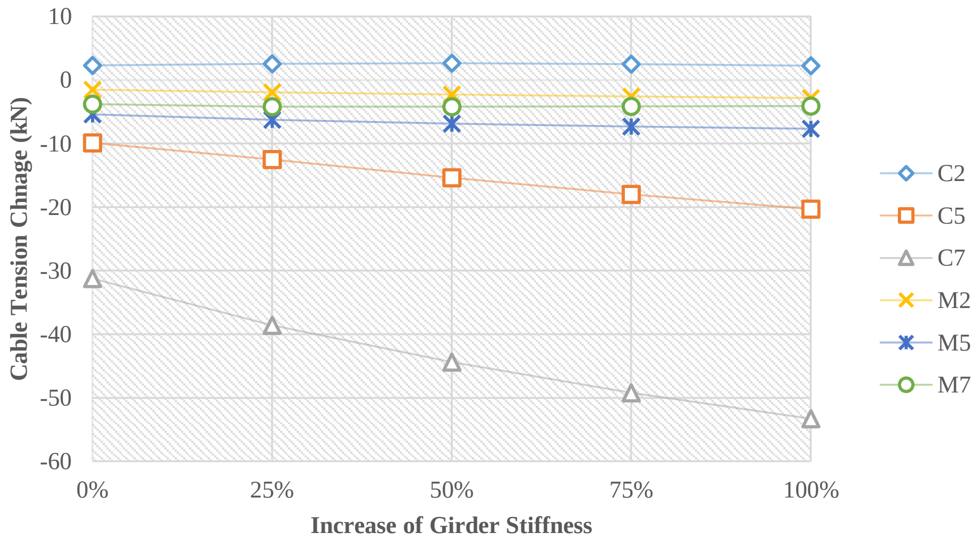

Figure 9. The effect of girder stiffness on cable tension due to temperature

From figure 9 can be seen that cable force change due to girder stiffness is almost linear for all cables. In general, as the girder become stiffer the variation of cable tension due to temperature at outer cable increase, and relatively constant for middle cables.

3.9 Comparison with Electromagnetic Sensor (EMS) Reading

The result of analysis is compared with the EMS measurements data on June 28, 2017 - June 29, 2017, where the highest temperature at the time was 30°C and the lowest was 23°C. Table 9 shows the comparison between EMS and 3-dimension finite element model and Table 10 shows the comparison between EMS and simple cable system.

Table 9. Comparison of EMS and 3-dimensional finite elemen model

Galala				Poka			
Cable	ΔP_{EM} (kN)	ΔP_M (kN)	Difference (kN)	Cable	ΔP_{EM} (kN)	ΔP_M (kN)	Difference (kN)
C2	-65,000	-3,667	61,333	C2	-73,000	-3,667	69,333
C5	-70,000	-11,156	58.844	C5	-66,000	-11,156	54.844
C7	-50,000	-40,796	9,204	C7	-80,000	-40,796	39,204
M2	-55,000	-3,278	51,722	M2	-65,000	-3,278	61,722
M5	-65,000	2,180	62,180	M5	-52,000	2,180	52,180
M7	-86,000	-18,561	67,439	M7	-103,000	-18,561	84,439

Table 10. Comparison of EMS and simpel cable system

Galala				Poka			
Cable	ΔP_{EM} (kN)	ΔP_T (kN)	Difference (%)	Cable	ΔP_{EM} (kN)	ΔP_T (kN)	Difference (%)
C2	-65,000	-52,730	12,27	C2	-73,000	-52,730	20,270
C5	-70,000	-61,901	8,099	C5	-66,000	-61,901	4,099
C7	-50,000	-80,242	30,242	C7	-80,000	-80,242	0,242
M2	-55,000	-52,730	2,270	M2	-65,000	-52,730	12,72
M5	-65,000	-61,901	3,099	M5	-52,000	-61,901	9.901
M7	-86,000	-80,242	5,758	M7	-103,000	-80,242	22.758

Table 9 and Table 10 indicates that the variation of cable tension due to temperature of EMS is closer to the simple cable system rather than 3-dimensional finite element model. This is because the assumption that the temperature of bridge element (pylon, girder and cable) similar with the ambient temperature. In reality the temperature of concrete pylon can be lower but the temperature of cable element can be higher. It is make the result of 3-dimensional finite element model not accurate

4 Conclusion

Based on the results of this study, it can be concluded that

a. Theoretical method and finite element model of simple cable system give similar result
b. There is linear relation between temperature change and cable tension change
c. The outer stay cable has the most significant effect of temperature
d. The variation of cable tension due to temperature is affected by the articulation of the bridge
e. As the pylon become stiffer the variation of cable tension due to temperature at outer cable decrease and relatively constant for middle cables
f. As the girder become stiffer the variation of cable tension due to temperature at outer cable increase, and relatively constant for middle cables
g. Assumption that the temperature of bridge element (pylon, girder and cable) similar with the ambient temperature the results of simple cable system provide closer result to the EMS measurement

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