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Defining Appropriate Temperature for Perfect Erection Time of Steel Arch Bridge Closure to Minimize the Effect of the Thermal Stress. *Case Study: The New Kutai Kartenagara Bridge, Indonesia*.

H Sugihardjo[1,3], Tavio[1], D Prasetya[1], and N I Achmad[2]
[1]Department of Civil Engineering, Institute Teknologi Sepuluh Nopember (ITS), Kampus Sukolilo, Surabaya, Indonesia.
[2]PT. Pembangunan Perumahan (Persero) Tbk, Indonesia
[3]Member of Committee for Bridge and Road Tunner Safety, Indonesia

Corespondence E-mail: hidajat.sugihardjo@gmail.com

Abstract. The impact of temperature change could govern the final stress of structural elements in the long-span steel bridges. The study was conducted to investigate the effect of temperature change during the construction of a new steel arch bridge, namely the Kutai Kartanegara Bridge. The main bridge has a total spanning length of 470 meters. The erection method of the bridge was the cantilever method with temporary towers, mast cranes, and stay cables. The deflections and internal forces of the steel elements were analyzed using the Midas Civil software. The study focuses on the effort to find the perfect erection time for the closure with regards to the temperature. By measuring the temperatures of the steel elements during the construction, it was found that they varied between 19 and 64 degrees Celsius. From the results of the analyses with various temperatures, it can be concluded that the recommended temperature for the closure erection was 44.6 degrees Celsius. This temperature is similar with the air temperature between either 6 AM and 12 noon or 12 noon and 6 PM. During this periods of time, the effect of thermal stress on the final internal forces in the bridge elements was found much lesser than those obtained during any other period of time.

1. Introduction

On November 26th, 2011 the Kutai Kartanegara suspension bridge, called as the Indonesian Golden Gate Bridge, collapsed. The bridge used a closed steel truss system for the stiffening girder with a through deck system. It has a left-hand end span of 100 meters, a main span of 270 meters, and a right-hand end span of 100 meters as shown in Figure 1. It was publicly opened to traffic since 2002. To replace the collapse bridge that connected Samarinda and Tenggarong cities, a new half-through steel arch bridge was constructed and it had been publicly opened to traffic on December 8th, 2015, while it is still using the strengthened existing foundations as shown in Figure 2.

Many investigations on the effects of temperature changes on the bridge structures have been conducted in various methods through the laboratory tests, and the theoretical and experimental investigations. In 1893, it was reported the site experiments conducted on an arch bridge structure at Lyons, France [1]. Parts of the structure that exposed to the direct sunshine had a temperature of 54°C (130°F) and the coldest winter temperature recorded was –26°C (–15°F). An investigation in Austin, Texas-USA, concluded that the effect of temperature contributes approximately 10 percent of the design due to live load on the structure [2]. An investigation on a composite steel bridge summarized that the environmental influences such as solar radiation, site temperature, and wind speed are crucial variables [3]. A health monitoring was conducted on a Little Mystic Truss Bridge, Massachusetts-USA. It was found that the increase of temperature has caused a camber and the compressive strains in the lower chords, while the decrease of temperature has caused a deflection and the tensile strains in the lower chords [4]. The investigations on the closure erection of a concrete-filled steel tube arch bridge concluded that only by selecting an appropriate erection and temperature of the closure can significantly reduce the thermal stress occurred in the arch bridge elements [5].

Figure 1. The Old Kutai Kartanegara Suspension Bridge in 2007, before Collapsed (Courtesy of Hidajat Sugihardjo).

Figure 2. The new Kutai Kartanegara steel arch bridge in 2015 (courtesy of Hidajat Sugihardjo).

The Forward Assemblage Analysis (FAA) method using a stay-cables or temporary supports and derrick cranes (mast cranes) has been implemented for the erection of many bridges, such as Strömsund Bridge-Sweden, Batman Bridge-Australia, Kniebrücke Bridge-Germany [6], Rainbow Bridge-USA and Lewiston-Queenston Bridge-USA [7] and Gustav Lindenthal New York City's Hell Gate Bridge-USA [8]. Normally, for girder bridges, the roadway of a derrick crane is located on the deck, meanwhile for the arch bridge, it is located on the top of the arch.

On the basis of the previous investigations, this study focused on the prediction of defining the field temperature for erection of the closure. The analysis was performed at the time before the closure was attached by imposing its selfweight and construction load and after closure was mounted due to the live load and superimposed dead load. The paper is the modified and developed the study of the undergraduate thesis conducted by [9]. By obtaining the appropriate temperature, the bridge responses are evaluated against temperature changes of the coldest and hottest temperatures. The effect of thermal stress on the final internal forces in the bridge elements are also evaluated due to the thermal load when the closure is erected during the extreme temperatures.

2. Theoretical Background

A bearing system is one of the structural components that influences the bridge movements. The phenomenon experienced by an arch bridge due to the temperature change are as follows: if the arch is a three-hinged structure (i.e. statically determinate structure), the frame revolves about each hinge, resulting no temperature stress. However, if the arch is a two-hinged structure (i.e. statically indeterminate structure), the frame deflects upward or downward, thus the frame elements slightly bend and further induce the thermal stresses in the frame elements [1]. An increase of temperature causes the compression in the lower elements (intrados) and tension in upper elements (extrados) of the arch crown as illustrated in Figure 3 [1, 10].

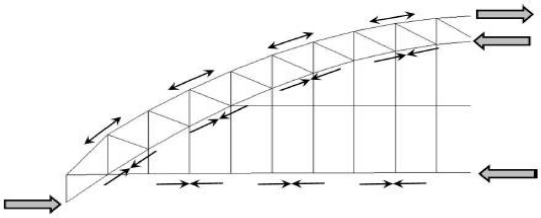

Figure 3. Distributions of thermal forces due to increasing of temperature [1, 10].

From the phenomena of temperature changes on the bridge structures as mentioned above, the axial thermal stress can be calculated by Equation (1). On the basis of this formula, then the bridge structural responses regarding the temperature change during construction is investigated.

$$\sigma_t = E\varepsilon_t = E\alpha(\Delta T)L \quad (1)$$

where:
ε_t = thermal strain; α = coefficient of thermal expansion; ΔT = temperature change; L = original length of element; E = modulus of elasticity of material

3. Bridge Descriptions

The bridge data obtained from the design including the geometry, material properties, cross-sections of the main truss, hangers and bearings are as follows [9, 11]:

- Type: half-through truss arch
- Span: 99.831 + 269.614 + 99.985 meters
- Rise: 57.84 meter; Rise/Span = 1 : 4.7
- No. of lanes of traffic: 2 + sidewalks 2×1.30 meter
- Width: 10.75 meter; Width/Span = 1:25
- Sections of arch truss: box and plate girders
- Materials: SM490YA/YB JIS G 3106
- Hangers: steel wire strands with tensile strength of (1570 ~ 1630) MPa
- Supports: pot bearings of fix-, unidirectional sliding- and multidirectional sliding types
- Loading specification: SNI T-02-2005 [12]

4. Results and Discussion

4.1. Construction Stage

The elevation view of the bridge is shown in Figure 4. The construction stage of the bridge using temporary supports and pylons, stay-cables and mast cranes with a weight of 5 tons is illustrated in Figure 5. The truss elements of the bridge which were erected from the both end spans have been divided into 15 consecutive stages as shown in Figure 6. The erection of the bridge elements in Stages 1 to 6 used the mobile pontoon cranes from both end spans, whereas in Stages 7 to 15 it used the mast cranes. The analysis carried out focused on Stage 11 (see Figure 6(k)), shortly before the closure was connected. In this stage, the bridge could be provided as a structure with fewer redundant than those after the closure was erected [9].

To analyze the temperature impact on the final stress of the bridge structure, the four sides of steel section were measured by four thermocouples during one week in July 2014. Normally, during these months (June to August) in Indonesia, the hottest and coldest temperatures occur during the daytime and the night time or early morning, respectively. The positions of the thermocouples for observations of a steel section element are shown in Figure 7. From the observations, it was found that the temperature change varied between 19° and 64°C [13]. Having the maximum and minimum temperatures of 64° and 19°C during the daytime and the night time or early morning, respectively, thus it can be assumed that the temperature change is approximately 45°C for the analysis. The value was much greater compared with the temperature change according to the Indonesian code, i.e. 25°C [12].

With the measured temperature ranging between 19° and 64°C for the respective minimum and maximum element temperatures, the closure should ideally be erected at a temperature that gives the lowest impact to the expansion and shrinkage of the bridge structural elements, i.e. 19 + (64 – 19)/2 = 41.5°C. However, the ideal temperature still depends on the two end nodes (nodes 29 and 177 at downstream and upstream, respectively) of the left cantilever, shortly before it converges with the right cantilever at the mid-points of the bridge. The superimposed loads at this stage are the gravity load and the thermal load due to the temperature changes during Stage 11 shown in Figure 6(k).

The erection time proposed in this study was begun with the assumptions that the bridge elements were erected at the extreme temperatures in the morning, at noon, and afternoon of 19°, 64°, and 24°C, respectively. These values were set as the initial and final temperatures of any stages in the Midas software [14]. The erection time was assumed to be started in early morning, at noon, and afternoon. For example, if the initial erection of the elements is set in the morning, the temperature change (temperature at noon – temperature in the morning) is assumed as ΔT_1 and then followed by temperature change ΔT_2 (temperature in the afternoon – temperature at noon) as shown in Figure 8.

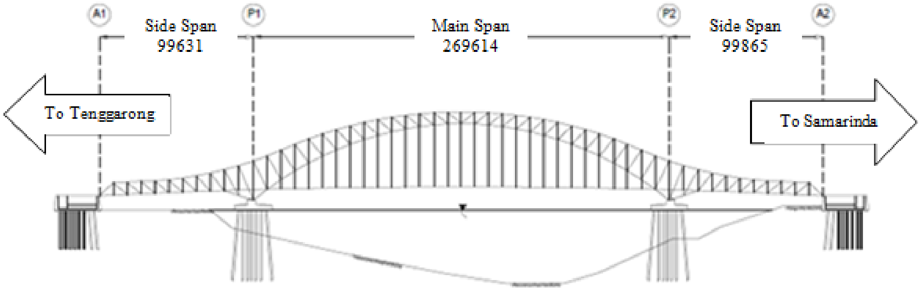

Figure 4. Elevation view of the new bridge.

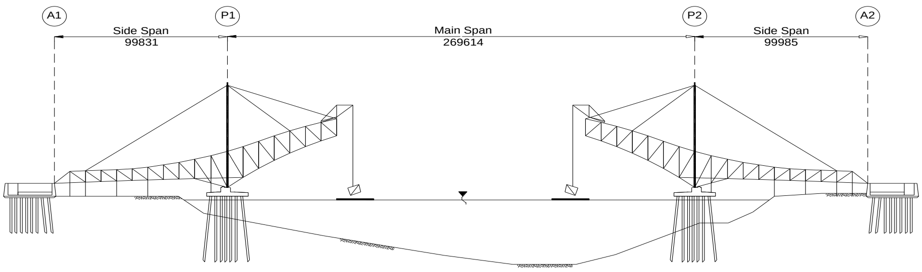

Figure 5. Schematic of erection of the bridge elements.

To illustrate the element responses during the construction of the bridge, an evaluation was conducted on four elements located near the supports, which are BA11, BB3, DG13, and TG11, and four elements at the mid-span, namely BA25, BB17, DG27, and TG27 as shown in Figure 9. The sections and related dimensions of the structural steels used in the bridge structure are listed in Table 1. It can be seen from the table that all the structural steels have the same cross-sectional width of 750 mm to ensure that they can be connected easily. The axial force history of the upper chord BA11 during the construction is given in Figure 10. It can be seen that the forces occured in the elements were still less than their capacities, either in compression or tension.

The evaluations were conducted from Stages 1 to 15 which include the observations of element forces, node deflections, and pretensioning loads of the temporary cables. The imposed loadings were selfweight of the bridge, the mast crane loads, and the load from the temperature changes. As shown in

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Table 2, Stage 7 of the FAA's method sequence in the MIDAS software, for instance, which starts using the mast crane, can be elaborated as follows:

a) Stage 7: Pretensioning and temperature load, ΔT_2, is given, the previous stages are not activated.
b) Stage 7a: The selfweight is activated, followed by temperature load ΔT_1.
c) Stage 7b: Temperature load ΔT_2 is activated simultaneously by deactivating temperature load ΔT_1.
d) Stage 7c: The mast crane is imposed simultaneously by deactivating temperature load ΔT_2.

The deflection history of Node 53 during construction as illustrated in Figure 6(j) is shown in Figure 11. From the figure, it can be seen that the maximum deflections occured when the positions of the mast cranes are all at the cantilever ends. The pretensioning loads applied to Cables Numbers 1 to 6 during Construction Stages 7 to 14 are shown in Figure 12.

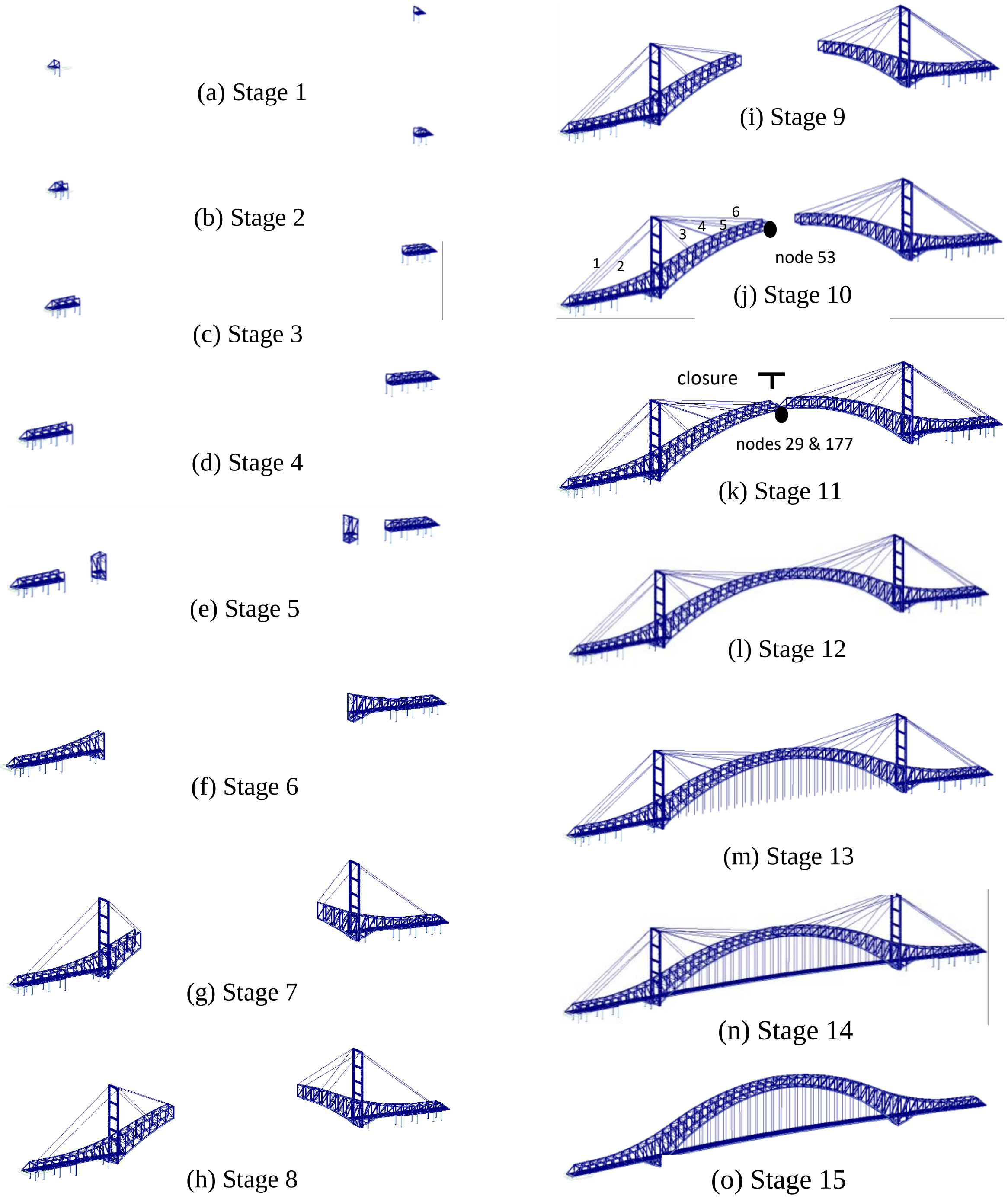

Figure 6. Modelling of construction stages [9].

The figure depicts the additional (+) and reducing loads (-) that should be applied during the construction stages and they normally do not exceed 50 percent more than the minimum breaking strength of the wire cables [6].

4.2. Closure Erection

The closure was erected at Stage 12. At the end of Stage 11, when the last element was attached, the displacement of Nodes 29 and 177 should be as small as possible or still in the tolerable value. Nodes 29 and 177 are located at the mid-span of the bridge. By obtaining the small displacements of Nodes 29 and 177, it is possible to attach the closure as shown in Figure 6(k). To obtain this ideal condition, it can be done by using the temperature interval ΔT = (64 – 19)/4 = 11.25°C, resulting the elevated temperatures of 19°C, 30.25°C, 41.5°C, 52.75°C, and 64°C for the analytical purpose. In the analytical modelling, the temperature variations were assumed as the final temperatures, while the initial temperatures were 19°C, 64°C, and 24°C, measured in the morning, at noon, and afternoon, respectively.

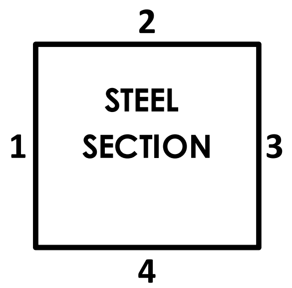

Figure 7. Positioning of four thermocouples on a steel section.

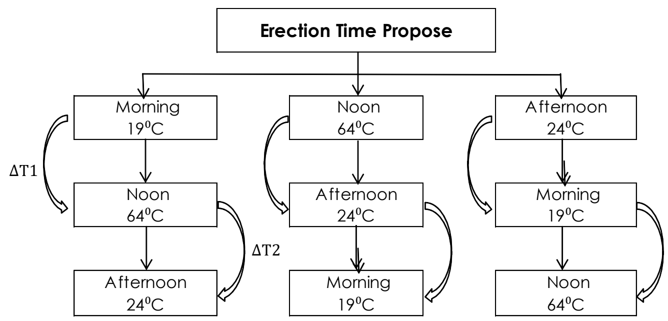

Figure 8. Time variations for erection of bridge elements.

By implementing the analysis using the variations of initial and final temperatures, the average deflections of Nodes 29 and 177 were obtained (Figure 13). From the figure and the assumption that Nodes 29 and 177 had zero deflection in the initial configuration due to its selfweight, resulting the first alternative temperature for closure erection of about 44.6°C. This temperature is similar with the air temperature between 6 AM and 12 noon. Whereas, if the erection of the closure is conducted at an ideal temperature of 41.5°C as described previously, Nodes 29 and 177 (Figure 13) is still deflect downwards of about 16 millimeters from their origins. Furthermore, by evaluating the ratio of the axial force to the axial capacity of steel section, it was found that the erection of closure at temperatures of either 19°C or 64°C yielded the ratio that varied from 3~47 percent greater than those resulted from the erection at the appropriate temperature of 44.6°C, as shown in Table 3.

Table 1. Bridge element sections (not all sections shown).

Element	Location	Positioning	Section		Element	Location	Positioning	Section	
			Type	Dimensions (mm)				Type	Dimensions (mm)
BA11	On support	upper chord	box girder	700x750x11x12	**BA25**	At midspan	upper chord	box girder	800x750x25x38
BB3		lower chord	box girder	1000x750x25x30	**BB17**		lower chord	box girder	550x750x10x10
DG13		diagonal	box girder	600x750x18x25	**DG27**		diagonal	I-girder	450x750x12x20
TG11		vertical	box girder	970x750x20x35	**TG26**		vertical	I-girder	280x750x10x12

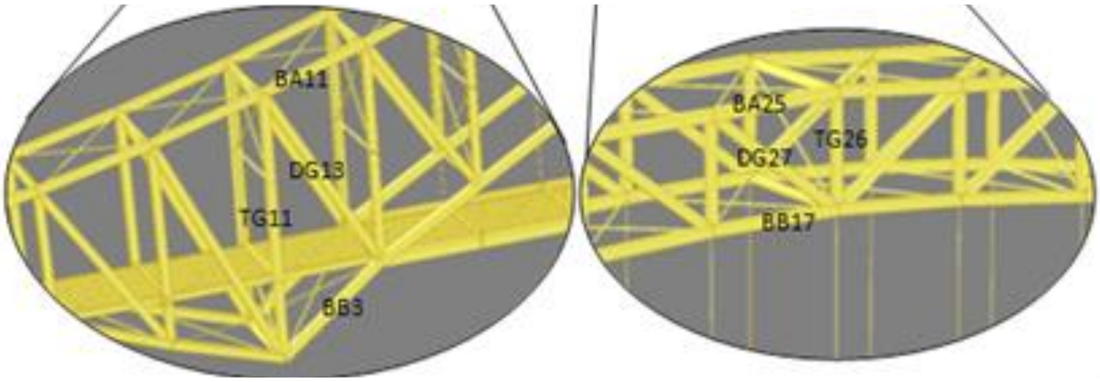

Figure 9. Positionings of element for evaluating the axial forces.

Table 2. Construction stage (not all stages shown).

Stage	Structure Group		Boundary Group		Load Group	
	Activation	Deactivation	Activation	Deactivation	Activation	Deactivation
Stage 7	Stage 7		Temporary Tower		Pretension Load 7	Temperature Load 2
Stage 7a					Temperature Load 1	
Stage 7b					Temperature Load 2	Temperature Load 1
Stage 7c					Mast Crane 7	Temperature Load 2

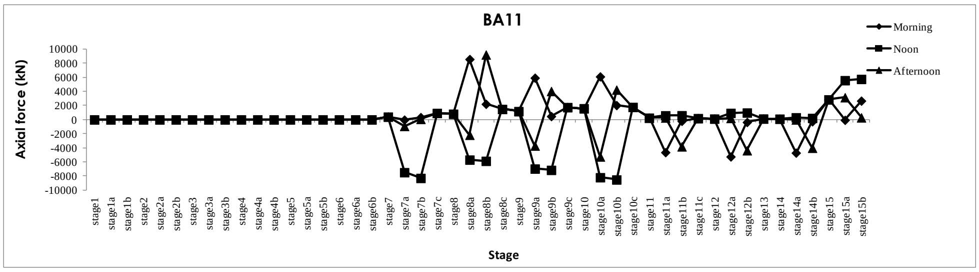

Figure 10. Axial force history of element BA11 during the construction stages.

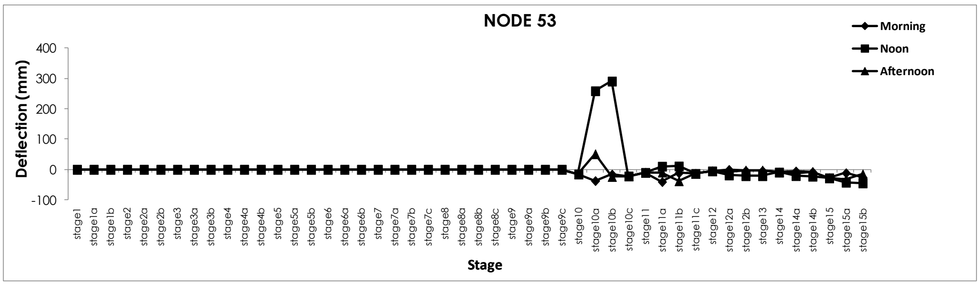

Figure 11. Deflection history of Node 53 during the construction stages.

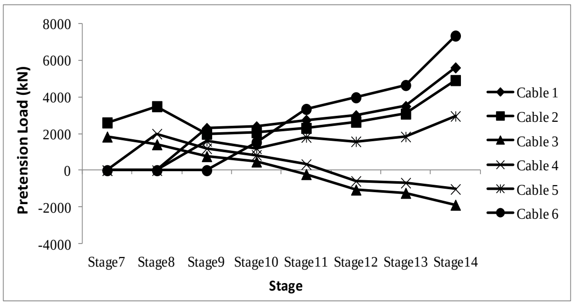

Figure 12. Pretensioning load during the construction stages (+ increase; – reduction).

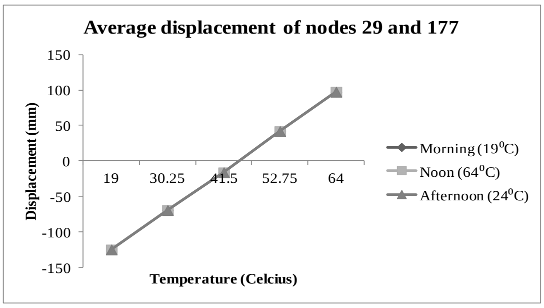

Figure 13. Displacement vs. temperature for defining the appropriate time of closure erection.

5. Conclusions

From the discussion of the current study, the following coclusions can be drawn:

- In general, to define the appropriate temperature for perfect erection time of steel arch bridge closure with the aim to minimize the effect of thermal stress, the actual temperature of bridge elements and the positions of the midspan nodes of the bridge should become the main consideration.
- From the results of the analyses with various temperatures, it can be recommended that appropriate temperature for closure erection is 44.6°C. It means that the closure could be erected during either 6 AM to 12 noon or 12 noon to 6 PM.
- If the closure are erected without considering the appropriate temperature, the axial forces of the bridge elements could increase up to 3 ~ 47 percent higher than those consider the appropriate temperature. The increase of these axial forces should be taken into account accuratelly in the design of a bridge structure.

Table 3. Ratio of thermal axial force to axial section capacity.

Element	Capacity	T-initial=44.6 degree Celcius		T-initial=19 or 64 degree Celcius		Difference
	P (kN)	ΔP (kN)	P/ΔP	ΔP (kN)	P/ΔP	
BA11	9165	2529	28%	9165	75%	47%
BB3	-25306	-5985	24%	-25306	37%	13%
DG13	12173	389	3%	12173	6%	2%
TG11	-14157	-565	4%	-14157	7%	3%
BA25	-26855	-3406	13%	-26855	16%	3%
BB17	7783	1033	13%	-7524	26%	12%
DG27	-4666	-204	4%	-4666	10%	6%
TG26	3506	271	8%	3506	12%	4%

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