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Construction stage analysis of Kömürhan Highway Bridge using time dependent material properties

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Abstract. The aim of this study concerns with the construction stage analysis of highway bridges constructed with balanced cantilever method using time dependent material properties. Kömürhan Highway Bridge constructed with balanced cantilever method and located on the 51st km of Elazığ-Malatya, Turkey, highway over Fırat River is selected as an application. Finite element models of the bridge are modelled using SAP2000 program. Geometric nonlinearity is taken into consideration in the analysis using P-Delta plus large displacement criterion. The time dependent material strength variations and geometric variations are included in the analysis. Elasticity modulus, creep and shrinkage are computed for different stages of the construction process. The structural behaviour of the bridge at different construction stages has been examined. Two different finite element analyses with and without construction stages are carried out and results are compared with each other. As analyses result, variation of internal forces such as bending moment, axial forces and shear forces for bridge deck and column are given with detail. It is seen that construction stage analysis has remarkable effect on the structural behaviour of the bridge.

Keywords: balanced cantilever method; construction stage analysis; highway bridges; time dependent material properties.

1. Introduction

Bridges are one of the most important engineering structures which are commonly used for interplant and intercity transportation. To obtain the structural behaviour of these structures under variable loads, finite element analysis is carried out. But, in the analytical solutions based on finite element models, it is assumed that the structure is built and loaded in a second. However, this type of analysis does not always give the reliable solutions. Because, construction period of the important engineering structures such as highway, cable-stayed and suspension bridges continue along time and loads may be change during this period. So, construction stages and time dependent

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material properties must be considered in the analysis for these types of structures.

For the passing of large and long valley with reinforced concrete highway bridges using maximum span and minimum piers, the best and optimum method is the balanced cantilever method. The use of the balanced cantilever construction method, for medium and long span concrete highway bridges, is recommended especially where a scaffolding is difficult or impossible to erect as over deep valleys, wide rivers, traffic yards or in case of expensive foundation conditions for scaffolds. In this method, the superstructure of bridges is usually built from one or more piers by means of formwork carriers. Normally the structure advances from a short stub on top of a pier symmetrically in segments of about 3 m to 5 m length to the mid span or to an abutment, respectively. Each cantilevered part of the superstructure is tied to a previous one by concreting a key segment and post-tensioning tendons. The prestressing tendons are arranged according to the moment diagram of a cantilever, with a high concentration above the pier. Towards the mid span or the abutment the number of tendons gradually decreases.

Balanced cantilever method can be applied to all type bridge superstructures which have constant or variable section height. But, superstructures with variable section heights are preferred against to the static deformations in the construction stages and after construction. In this type of the construction system, box girder section forms are generally used. According to the bridge wide, single or double box girder combinations can be made. The superstructure of the bridge combines with piers as monolithic. Also, some isolators (friction or rubber) may be established in the connections. Besides, rapid work plan is arranged and moving cast is used along the segments at different times.

In the literature, some papers exist about the construction stage analysis of the bridges considering time dependent material properties. Cho and Kim (2008) carried out probabilistic risk assessment for the construction stages of the Hanbit suspension bridge. The bridge is under construction and will be one of the longest suspension bridges in Korea in 2010. The main span is designed to be 850 m with two side spans of 255 and 220 m each. Tensile forces for main cables and deflections for stiffening girders are controlled for each construction stages. Somja and Goyet (2008) studied about nonlinear finite element analysis of segmentally constructed cable stayed bridge. Time dependent effects including load history, creep, shrinkage and aging of the concrete are considered in the analyses. Modification of the bridge topology has been carried out using an efficient procedure for creating/removing elements. Karakaplan *et al.* (2007) performed the construction stage analysis of a cable supported pedestrian bridge considering time dependent material strength variations. Analysis results are compared with the conventional finite element analysis and the differences are determined. Pindado *et al*. (2005) investigated the influence of the section shape of box girder decks on the moments during construction stages experimentally. Wang *et al*. (2004) analyzed a cable stayed bridge during construction using the cantilever method. Two computational processes, one is a forward process analysis and the other is a backward process analysis are established. Cheng *et al*. (2003) carried out the wind induced load capacity of a long span steel arch bridge during two construction stages. The Lupu Bridge which has 550 m central span length and 100 m side spans is selected as a case study. Kwak and Seo (2002) determine the time dependent behaviour of precast prestressed concrete girder bridge. To analyze the long-term behaviour of bridges, the effects of creep, the shrinkage of concrete, and the cracking of concrete slabs in the moment regions is considered. Ko *et al*. (1998) calculated the dynamic characteristics such as natural frequencies and mode shapes of suspension deck in construction stages. The Tsing Ma suspension bridge with a main span of 1377 m and an overall length of 2160 m is performed.

Beside these studies, there are no enough publications related to construction stage analysis using time dependent material properties of Highway Bridges constructed with balanced cantilever method. So, in this paper, construction stage analysis of Kömürhan Highway Bridge constructed with balanced cantilever method using time dependent material properties is performed.

2. Description of Kömürhan Highway Bridge

The Kömürhan Highway Bridge is a reinforced concrete box girder bridge located on the 51st km of Elazığ-Malatya, Turkey, highway. Construction of the bridge started in 1983 and completed in 1986. The bridge deck consists of a main span of 135 m and two side spans of 76 m each. The total bridge length is 287 m and width of bridge is 11.50 m. The structural system of Kömürhan Highway Bridge (Fig. 1) consists of deck, columns, side support and expansion joint. Schematic representation of Kömürhan Bridge including plan and elevation is given in Fig. 2.

Fig. 1 Kömürhan Highway Bridge constructed with balanced cantilever method

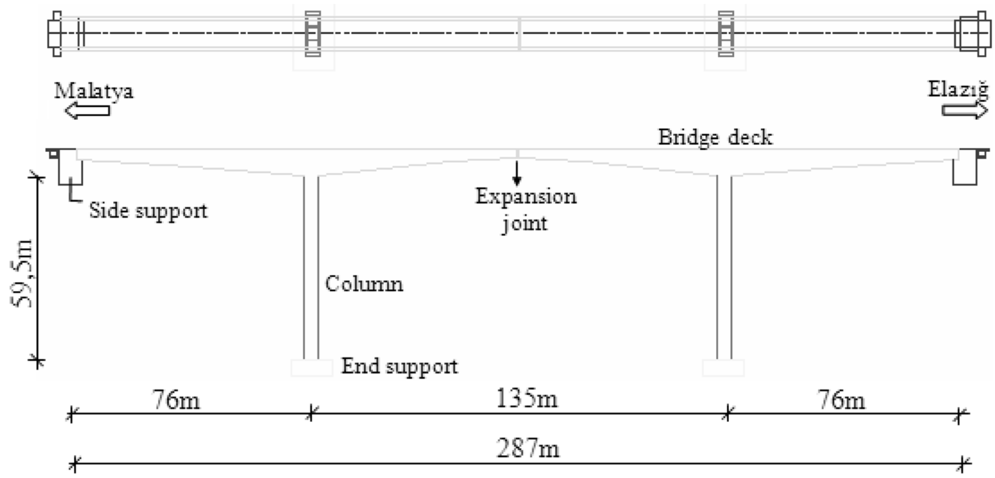


Fig. 2 Schematic representation including plan and elevation

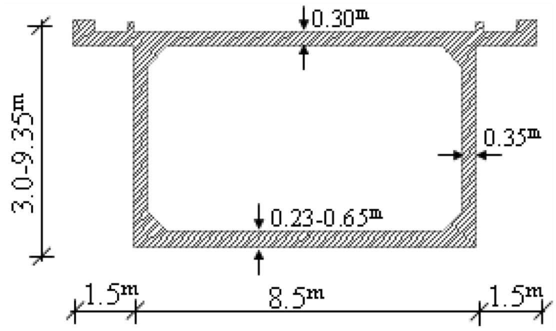


Fig. 3 Dimensions of box girder

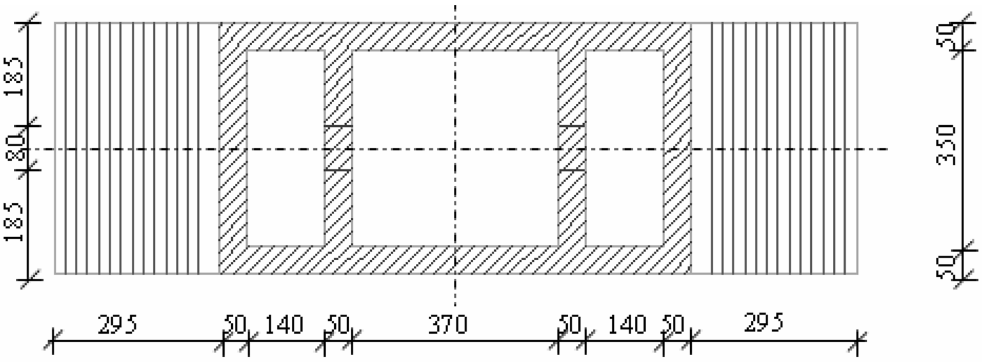


Fig. 4 Variable section of the main columns (dimensions as cm)

The deck of the bridge constructed with balanced cantilever and prestress box beam method consists of 56 segments. All of the segments are nearly 5 m length. The height of the box girder is 9.35 m on the main columns, but it decreases parabolically to 3.5 m at the side supports and 3.0 m at the expansion joint as shown in Fig. 3.

There are two main columns of 59.50 m length each. They consist of a variable section with three divisions. The width of the section decreases linearly from 14.40 m at the foundation to 8.50 m at the top of the column (Fig. 4). To combine deck cantilevers, an expansion joint is built in the main span of bridge. It consists of two IPB 600 steel beams. In this way, the edge of the cantilever at the main span is free and expansion due to thermal effect is allowed.

3. Finite element analysis

Finite element models are commonly considered in the design and project phase of important engineering structures such as bridges using some special software. In this study, SAP2000 finite element program (SAP2000 2008) which is used for linear and non-linear, static and dynamic analyses of 3D models of structures is considered in the analysis.

3.1 Modelling of the construction stages

Bridges constructed with balanced cantilever method consist of main structural elements such as deck, piers and side abutments. In this method, precast segmental construction and cast-in-place construction techniques can be implemented. There are some advantages and disadvantages of these techniques (Kumar 2003);

- Cast in-place construction may permit a rate of one pair of segments three to six meters long to be constructed and stressed every four to seven days. On the average, a pair of travelers permits the completion of approximately 50 meters of bridge deck within a month, excluding the transfer from pier to pier and fabrication of the pier table.
- Cast-in-place cantilever construction is basically a slow process, while precast segmental construction with matching joints is among the fastest.
- Precast segmental construction for long, repetitive structures may be more economical than a cast-in-place solution.
- Precast segmental solutions are limited by the capacity of transportation and placing equipment. Segments exceeding 250 tonnes are seldom economical. Cast-in place construction does not have the same limitation, although the weight and cost of the travelers are directly proportional to the weight of the heaviest segment.
- In the segmental construction, some limitations arise in the form of the curvature of the bridge and the size and weight of the segment.
- Both precast and cast-in-place segmental construction permits all work to be performed at the top.

In the construction stage analysis, some special points given in below should be considered;

- All construction stages and their details should be determined from design to opening the traffic of the bridge,
- Working plan including construction durations of main structural elements (piers, deck and abutments) of the bridge should be prepared,
- Added and removed loads for each construction stages should be determined,
- To obtain the reliable solution, each stage results should be added to end of the each stage and next stage analysis is done,
- Non-linear solution parameters should be selected depending on the literature.

Kömürhan Highway Bridge constructed with cast-in-place construction technique is selected as an example. Firstly, piers and small part of bridge deck are constructed over substructure using suitable formwork. Then, segments (3-5 m length) are erected on opposite sides of each pier to balance the loads by using a movable form carrier. After the concreting, prestress tendons are inserted in the segments and stressed with post-tension. Finally, form carrier is moved to the next position and a new cycle starts. This sequence is completed at one week on average and is going on until bridge decks meet at mid span. At the mid span, closure segment is established to complete one span. Because of the fact that maximum displacements are occurred at this point after finite element analysis, construction of this segment is very important. The typical operation sequence is summarized in Table 1. The schematic view of balanced cantilever construction of prestressed concrete highway bridges is given in Fig. 5.

Table 1 The typical operation sequence of balanced cantilever construction (Kumar 2003, Harputoğlu *et al*. 2007)

Time	Working Plan
1st Day	Setting up and adjusting carrier
2nd Day	Setting up and aligning forms
3rd Day	Placing reinforcement and tendon ducts
4th Day	Concreting
5th Day	Inserting prestress tendons in the segment and stressing
6th Day	Removing the form work
7th Day	Moving the form carrier to the next position and starting a new cycle

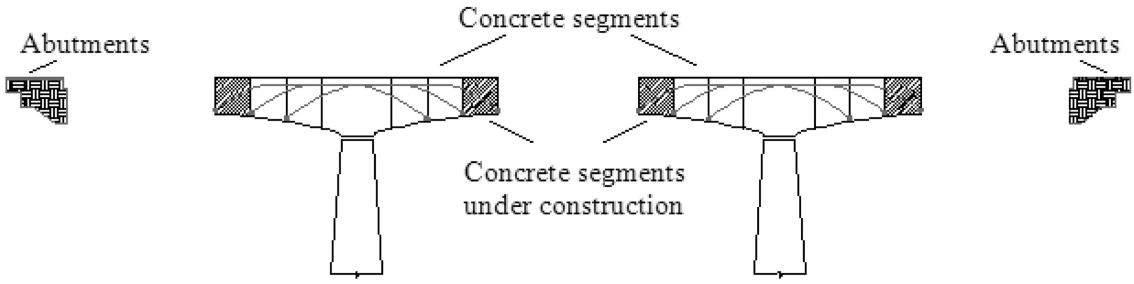


Fig. 5 The schematic view of balanced cantilever construction method

In the construction stage analyses of Kömürhan Bridge, a total of 51 construction stages are considered. Total duration from the beginning of construction to nowadays is considered as 10000 days. Maximum total step and maximum iteration for each step are selected as 200 and 50, respectively. Some construction stages using SAP2000 finite element analysis program is shown in Fig. 6.

To understand finite element model of the bridge more accurately, detailed presentation of Section A, B and C shown in Fig. 6 are given in Fig. 7.

3.2 Time dependent material properties

In the construction stage analysis of highway bridges, time dependent material properties such as elasticity modulus, creep and shrinkage for concrete and relaxation for the prestressed steel should be considered, because they are variable due to the climate during construction. For example, strength of the concrete increase continuously at 7th, 28th and 1000th days of concreting. If these properties are not considered in the analysis, there may be a rise at the construction of middle span.

Time effects and cracking make analysis even more complex for concrete bridges. Creep strains develop at early stages of the construction process and continue to evolve significantly after the structure is built. Depending on the construction method, restrained creep can appear and induce important stress redistribution in the structure (Somja and Goyet 2008). To accurately analyze structures both during their construction and along their entire life, engineers must have at their

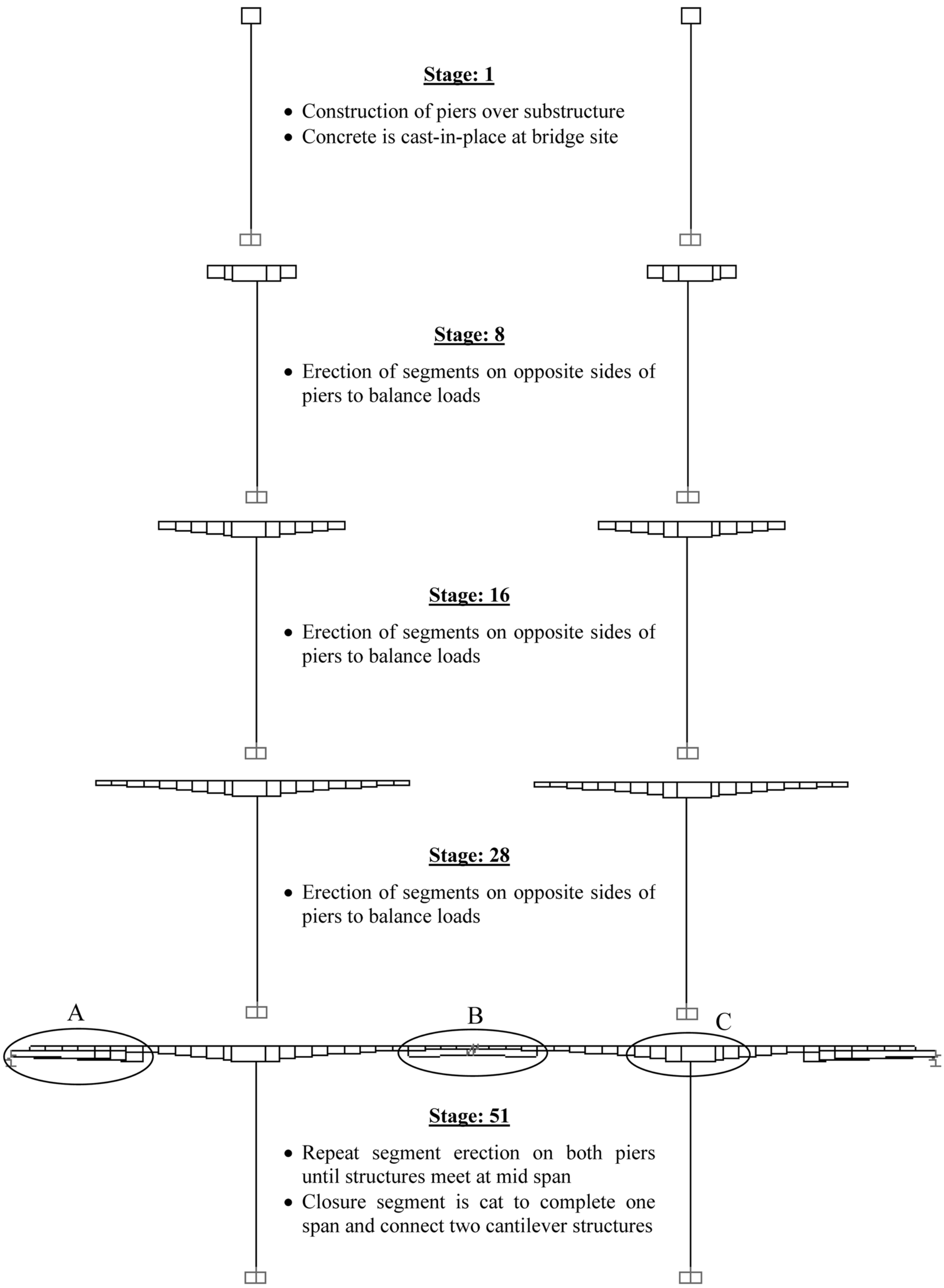


Fig. 6 Some construction stages of Kömürhan Highway Bridge

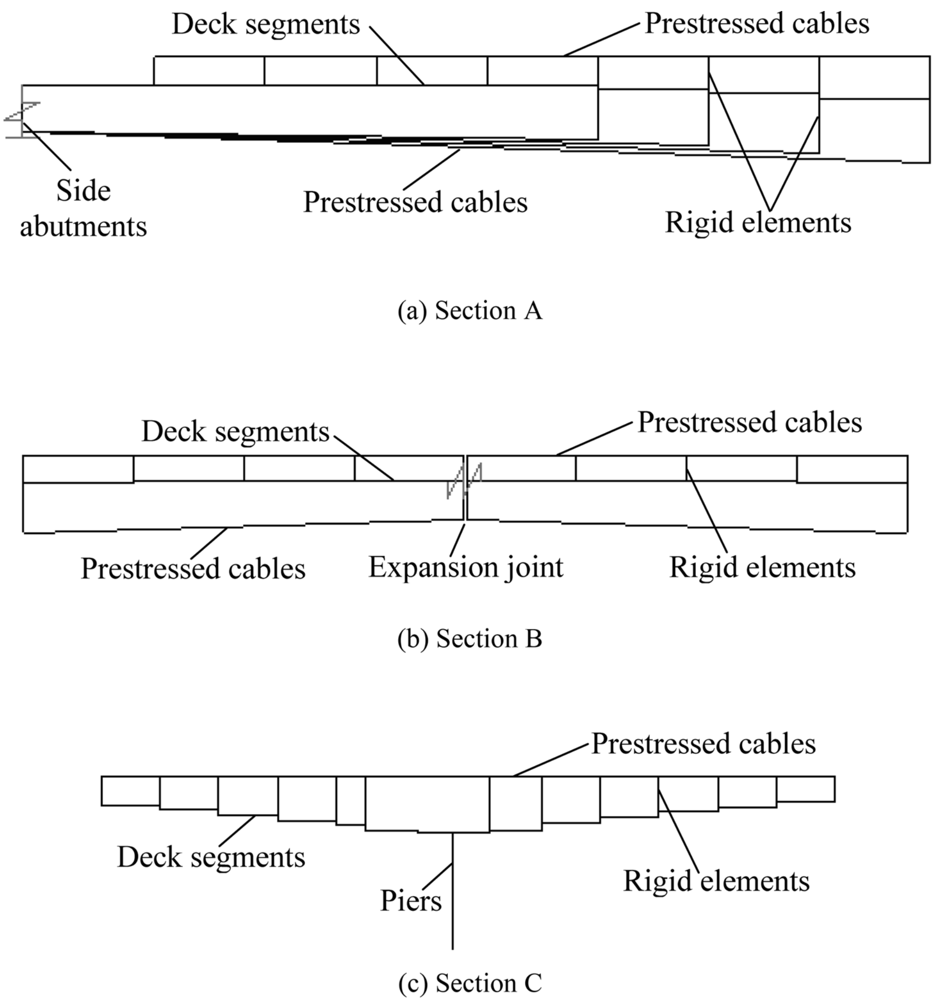


Fig. 7 Detailed presentation of section A, B and C

disposal appropriate design methods. The effects of geometry changes occurring during construction of the structure cannot be taken into account using standard finite element codes since structural elements are added and removed at certain time instants (Somja and Goyet 2008).

3.3 Compressive strength

The compressive strength of concrete at an age *t* depends on the type of cement, temperature and curing conditions. The relative compressive strength of concrete at various ages may be estimated by the following formula (CEB-FIP 1990)

$$f_{cm}(t) = \beta_{cc}(t) f_{cm} \tag{1}$$

in which $\beta_{cc}(t)$ is a coefficient with depends on the age of concrete and is calculated by

$$\beta_{cc}(t) = \exp\left\{s\left[1-\left(\frac{28}{t/t_1}\right)^{1/2}\right]\right\} \tag{2}$$

$f_{cm}(t)$ is the mean concrete compressive strength at an age of t days, f_{cm} is the mean compressive strength after 28 days, t is the age of concrete in days and s is a cement type coefficient.

3.4 Aging of concrete

The modulus of elasticity of concrete changes with time. For this reason, the modulus at an age $t \neq 28$ days may be estimated as below equation

$$E_{ci}(t) = E_{ci}\sqrt{\beta_{cc}(t)} \tag{3}$$

where $E_{ci}(t)$ is the modulus of elasticity at age of t days, E_{ci} is the modulus of elasticity at an age of 28 days, $\beta_{cc}(t)$ is a coefficient which depends on the age of concrete.

3.5 Shrinkage of concrete

The CEB-FIP Model Code gives the following equation of total shrinkage strain of concrete

$$\varepsilon_{cs}(t,t_s) = \varepsilon_{cso}\beta_s(t-t_s) \tag{4}$$

where ε_{cso} is notional shrinkage coefficient, β_s is the coefficient to describe the development of shrinkage with time, t is the age of concrete in days and t_s is the age of concrete in days at the beginning of shrinkage.

3.6 Creep

The effect is calculated using CEB-FIP Model Code (1990) creep model. For a constant stress applied at time t_o, this leads to

$$\varepsilon_{cc}(t,t_o) = \frac{\sigma_c(t_o)}{E_{ci}}\phi(t,t_o) \tag{5}$$

in which $\sigma_c(t_o)$ is the stress at an age of loading t_o, $\phi(t,t_o)$ is the creep coefficient and is calculated from

$$\phi(t,t_o) = \beta_c(t-t_o)\phi_o \tag{6}$$

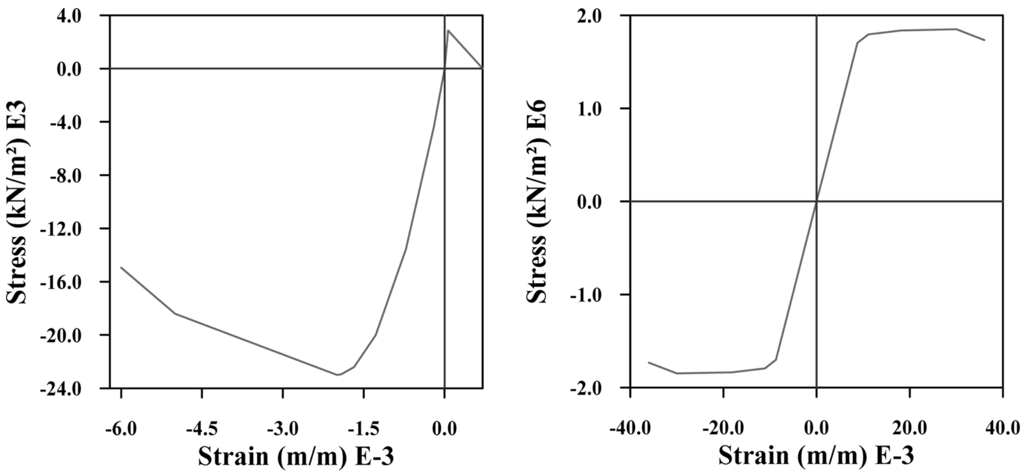
where β_c is the coefficient to describe the development of creep with time after loading, t is the age of concrete in days at the moment considered, to is the age of concrete at loading in days.

Selected analysis parameters to consider time dependent material properties are given in Table 2.

Variation of time dependent material properties used for concrete and prestressed steel is given in Figs. 8-10. These parameters are selected from CEB-FIB design code (CEB-FIB 1990) in SAP2000.

Table 2 Selection of analysis parameters to consider time dependent material properties in SAP2000 (SAP2000 2008)

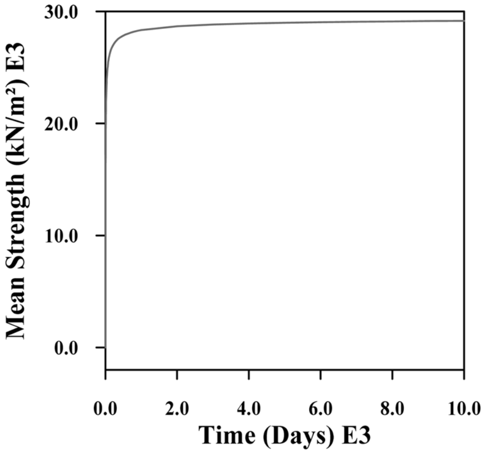
Parameters		Main Structural Elements		
		Deck	Pier	Prestress Steel
Material Properties		Concrete Isotropic	Concrete Isotropic	Tendon Uni-Axial
Nonlinear Material Data	*Hysteresis type*	Kinematic	Kinematic	Kinematic
	Stress-Strain diagram	User defined	User defined	User defined
Time Dependent Properties	*Elasticity modulus*	√	√	√
	Creep	√	√	-
	Shrinkage	√	√	-
	Creep analysis type	*Full*	*Full*	-
	Cement type coefficient	*0.25*	*0.25*	-
	Relative humidity %	*60*	*60*	-
	Notional size	*0.619*	*1.306*	-
	Shrinkage coefficient	*5*	*5*	-
	Shrinkage start age	*0*	*0*	-
	Steel relaxation	-	-	√
	Relaxation analysis type	-	-	*Full integration*
	CEB-FIB class	-	-	*1*



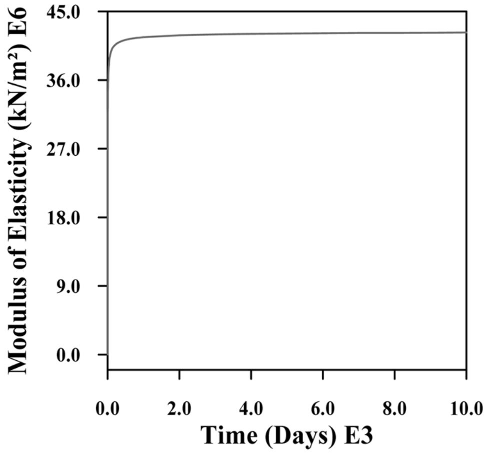
(a) (b)

Fig. 8 Stress-strain diagrams used for (a) concrete and (b) prestressed steel

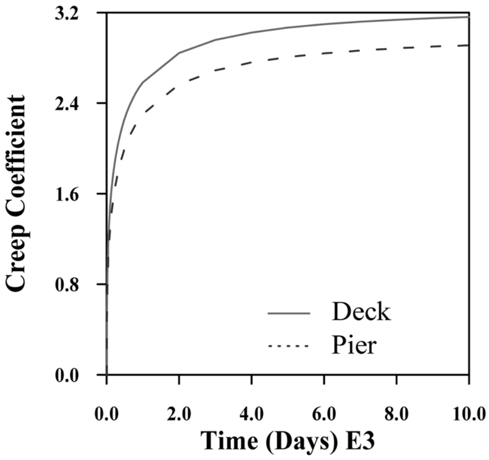
According to the parameters given in Table 2, these graphics may be changed automatically. Total duration of the analysis from beginning the construction of the bridge to nowadays is considered as 10000 days.



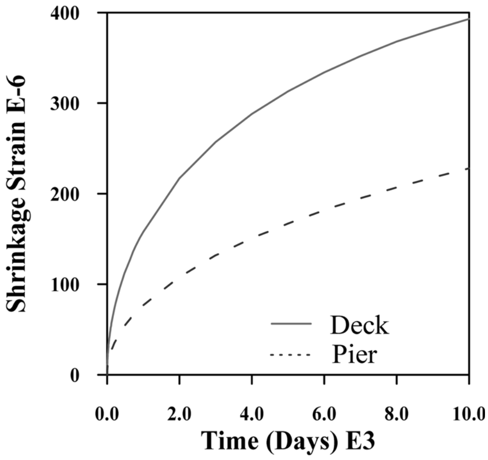
(a) Time dependent mean strength



(b) Time dependent modulus of elasticity



(c) Time dependent creep coefficient



(d) Time dependent shrinkage strain

Fig. 9 Variation of time dependent material properties for concrete

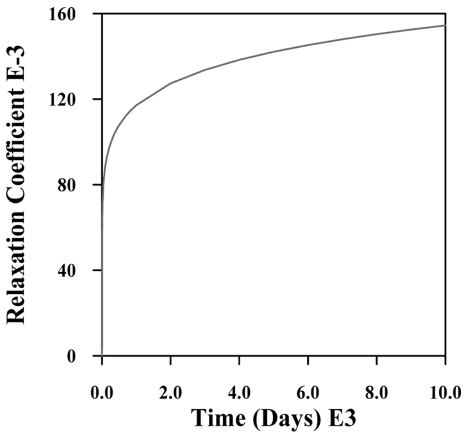


Fig. 10 Variation of time dependent material properties for prestressed steel

3.7 Construction stage analysis

For the construction stage analysis of highway bridges considering time-dependent material properties, a three-span continuous highway bridge is selected as an example. This bridge has a total length of 287 m with 76 m side spans and 135 m main span, and maintains a variable box-girder section along the span length. Analysis is performed using SAP2000 program. Nonlinear staged construction and P-Delta plus large displacements options are selected as analysis type and geometric nonlinearity parameters, respectively.

3.8 Load cases of analyses

In the analyses of the bridge, the following load cases are considered;

- Dead Load: Weight of all elements. They are calculated from the finite element software directly.
- Additional Mass: Weight of the asphalt, cobble, pipeline and its supports, scarecrow. 41.15 kN/m distributed load is added to each segment considering 10 cm asphalt.
- Gantry: Load of the form carrier. This load is implemented to previous one before the construction one segment and slide next one after construction of the segment. According to the final project control report, this load is calculated as 600 kN. After the construction of the bridge, this load is removed wholly.
- Diaphragm: Weight of the reinforced concrete walls at the abutments and both sides of expansion joint are calculated as 1117 kN and 261 kN, respectively and added to the relevant points.
- Prestress: Post-tension cables are modelled using frame elements with constrained rotations and fixed to the end of each segment. Post-tension loads are considered as strain.
- Jack: Load of the jack applied to the side segments before fixed to the side abutments. According to the final project control report, this load is calculated as 500 kN.
- Temperature: This load is applied to consider temperature variation due to the climate. +35°C and −35°C temperatures (according to the bridge region) are considered separately in the analysis.

3.9 Deformation shapes

The deformations of the bridge structure at some construction stages are plotted and the maximum vertical displacements of the bridge deck and maximum horizontal displacements of the bridge column are also given in Fig. 11.

3.10 Deck response

Distributions of vertical displacements and bending moments along the bridge deck are given in Fig. 12. It is seen that displacements have an increasing trend towards to the middle of the bridge deck. But, bending moments have a decreasing trend. Because of the fact that the bridge system is statically indeterminate and the cantilever length is much long, the minimum and maximum bending moments are obtained in the middle of the bridge deck and on the bridge column, respectively. Both displacements and bending moments are obtained symmetrically according to the middle point of

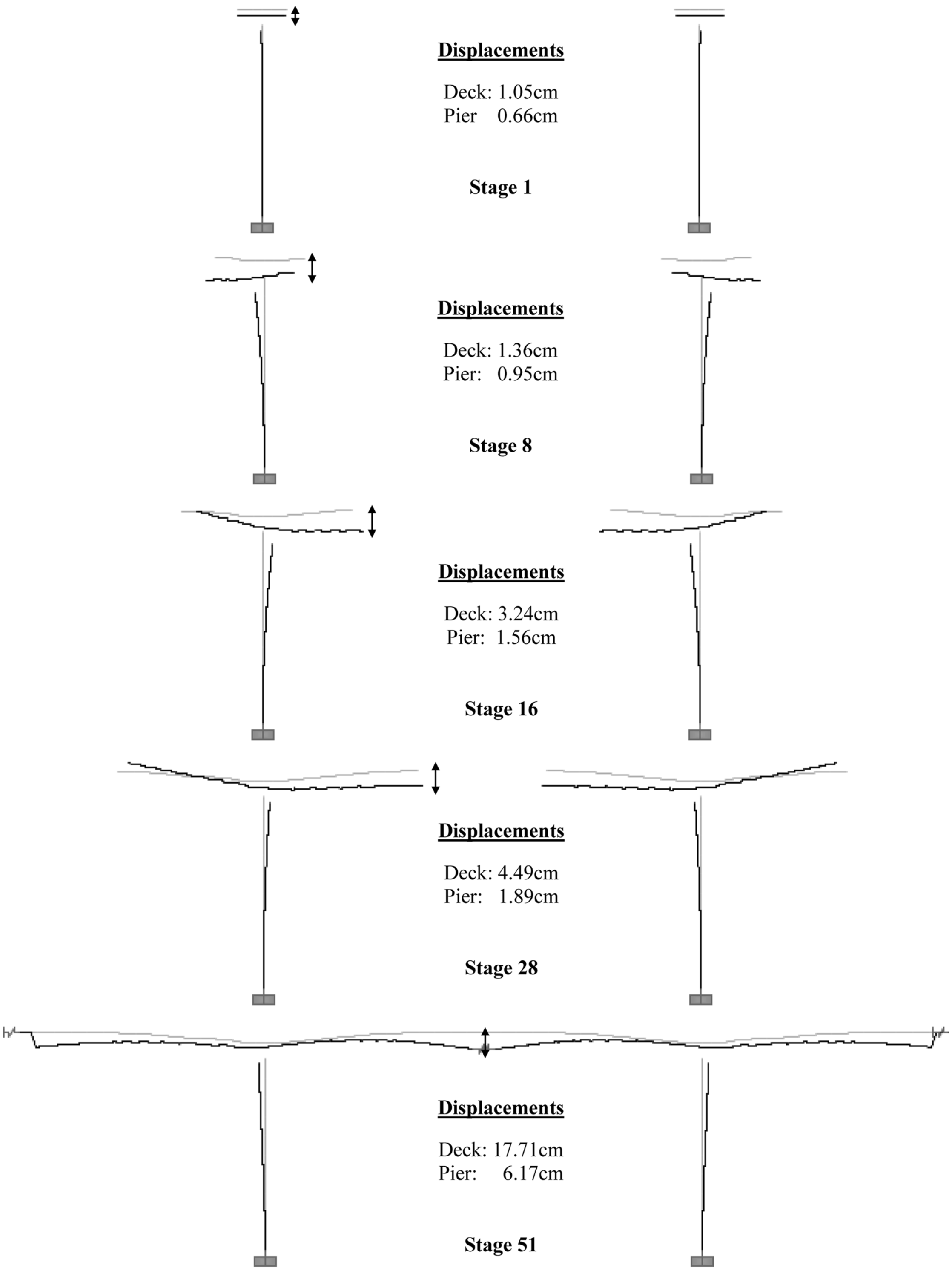
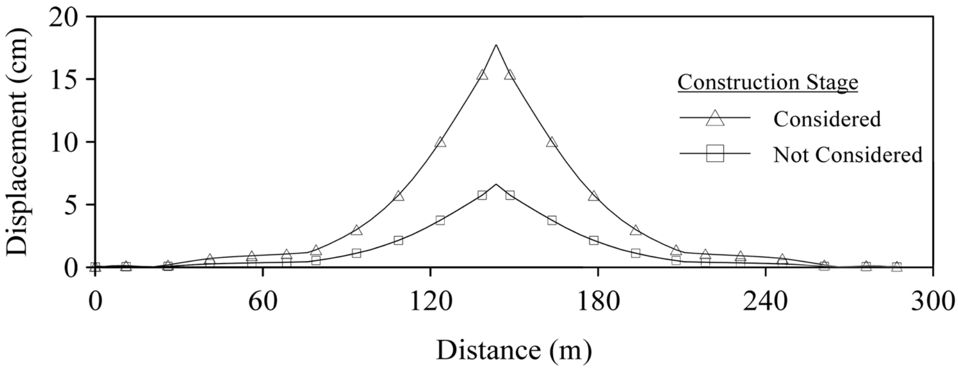
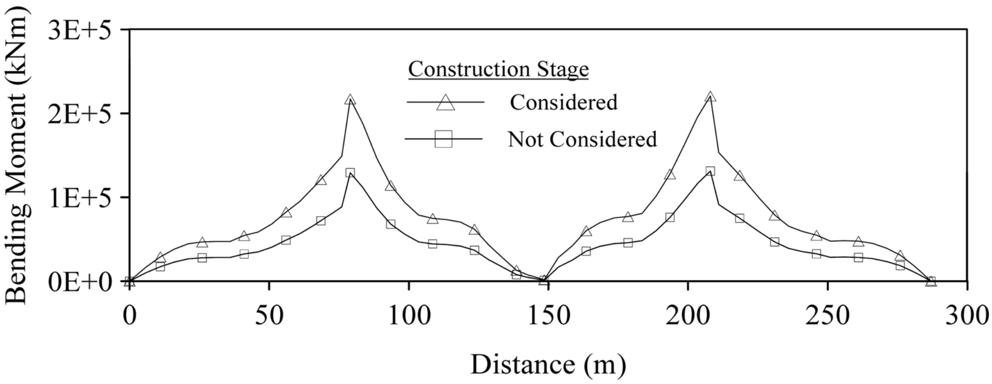


Fig. 11 Deformation of the highway bridge during some construction stages



(a) Displacements



(b) Bending moments

Fig. 12 Changing of maximum (a) displacements and (b) bending moments along the bridge deck

the bridge deck. It is seen from Fig. 12 that the displacements and bending moments obtained from the analyses including construction stages are significantly bigger than those of without the construction stages.

3.11 Column response

Variation of maximum displacements along the height of the column is shown in Fig. 13. It can easily be seen that the horizontal displacements increase with the height of bridge column and reach a maximum of 6.17 cm at the top for the analysis including the construction stage.

Fig. 14 points out the internal forces such as shear and axial forces of the bridge column corresponding to the two analyses. The values of the shear forces are nearly equal along the height of the bridge column, but the values of the axial forces decrease. It can be easily seen from Figure 14 that construction stage analysis is more effective than the other for both internal forces.

A variation of bending moment with height of the bridge column is shown in Fig. 15. It can be easily seen from Fig. 15 that the maximum bending moments occur at a height of approximately 20 m for both analysis and the values of the construction stage analysis are bigger along the column height.

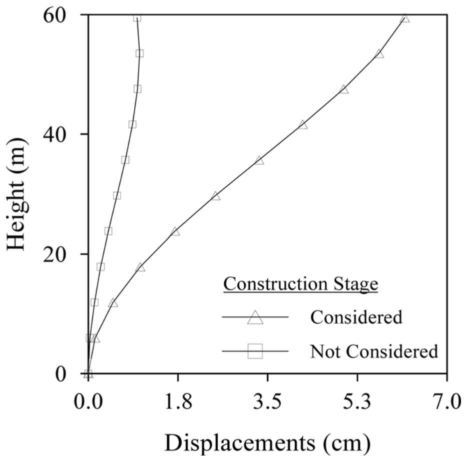


Fig. 13 Changing of displacements along the height of the bridge column

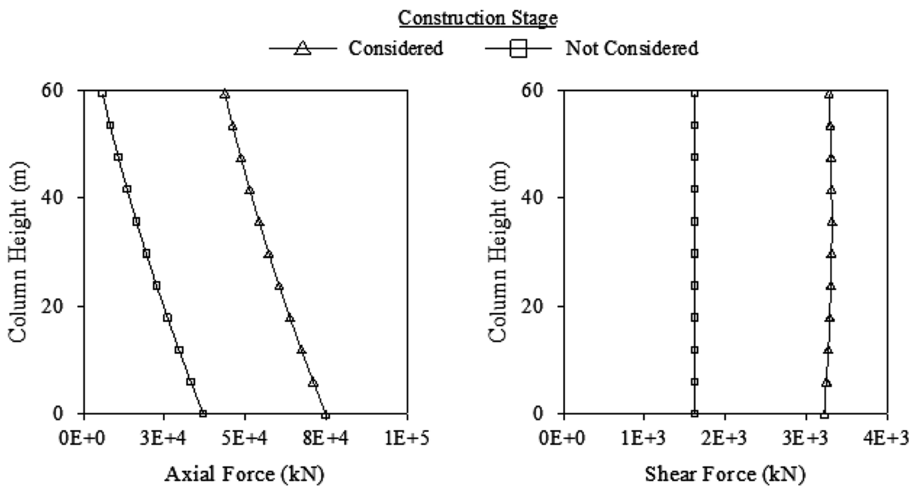


Fig. 14 Changing of internal forces along the height of the bridge column

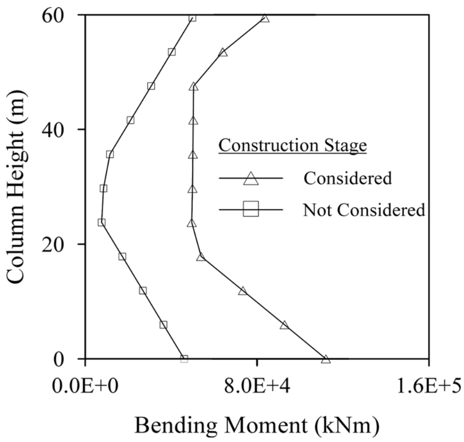


Fig. 15 Changing of bending moment along the height of the bridge column

4. Conclusions

The paper presents an efficient analytical procedure for materially and geometrically nonlinear finite element analysis of segmentally constructed highway bridge including time dependent effects due to creep, shrinkage and aging of the concrete. Kömürhan Highway Bridge constructed with balanced cantilever method is selected as an example. The P-Delta plus large displacement criterion is employed in the geometrical nonlinear analysis. The time dependent material strength variations and geometric variations are included in the analysis. From the results of this study, the following observations can be made:

- The vertical deck displacements towards to the middle of the bridge deck and horizontal displacements along the height of the columns increase for both analysis.
- Maximum bending moments at the deck occur on the bridge column for both analyses. Also, maximum bending moments at the column occur at a height of approximately 20 m for both analyses.
- Shear forces approximately constant and axial forces decrease along the column height for both analyses.
- Large differences observed between the results with and without the construction stages. It can be stated that the analysis without construction stages cannot give the reliable solutions.
- To obtain real behaviour of engineering structures, construction stage analysis using time dependent material strength variations and geometric variations should be done. Especially it is very important for highway bridges, because construction period continue along time and loads may be change during this period.

Acknowledgements

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