Long-Term Behaviour of Segmental Bridges

Md Azim Equbal Farooqui
Master of Technology (Completed)
Department of Civil Engineering
Indian Institute of Technology, Roorkee, India

Abstract— This paper presents the long-term behaviour of bridges constructed by segmental cantilever construction due to the time-dependent effects of creep and shrinkage of concrete and relaxation of prestressing steel. Time-dependent effects of creep and shrinkage of concrete and relaxation of prestressing steel affect the deformation of post-tensioned segmental bridges at each stage of construction and service life. These effects have to be considered at every stage to ensure effective control of the girder profile. The analysis of typical segmental bridge has been done for evaluating the long-term deformation due to time-dependent effects. Numerical studies have been performed to show the effect of various parameters on the long-term deformation. The effect of construction schedule on the bridge profile is also presented. The variation of bending moment diagram with time after the completion of construction of the bridge has also been presented. External prestressing as a solution for controlling long-term deformations and stresses has been discussed.

Keywords: Segmental, Cantilever, Creep, Shrinkage, Relaxation, Long-Term

I. INTRODUCTION

In segmental bridges, construction is done by assembling the bridge segments in appropriate position and post-tensioning them together. One of the common methods of construction of bridges is the cantilever construction which involves addition of segments form both sides of the pier and post-tensioning them together. Using segmental cantilever construction, the economy of continuous construction is enhanced. This method is particularly economical where construction of superstructure using staging from the river bed is not feasible. Segments can be precast or cast-in-place. This type of bridge is suitable in the span range of 50 to 200 m, though a few bridges have been built beyond 200 m span.

The segmental cantilever method of construction of prestressed concrete bridges has several advantages. Centering and falsework are avoided, enabling construction of structures with tall piers and over deep valleys. The speed of construction is also increased. Quality and workmanship are enhanced due to the mechanization of repetitive tasks. By using precast segments, shrinkage effects can be avoided due to age of concrete at the time of erection and creep of concrete is less due to age at the time of initial loading. Further, precast segments lead to saving in construction time and protection from weather during concreting as precasting is done in a factory.

II. LONG-TERM DEFORMATION IN SEGMENTAL BRIDGES

During the erection of segments in case of segmental cantilever construction, the segments continue to deflect with time due to the time-dependent effects. When the two ends of the cantilever meet, there may be considerable difference in the ends to be joined. This difference can be reduced or eliminated by jacking or providing a predetermined camber. Therefore the estimation of time-dependent deformation is important to control the bridge profile. When structural form changes from determinate to indeterminate, the analysis becomes more involved. Time-dependent forces and stresses develop due to the restraint imposed on the deformation by indeterminacy.

III. REVIEW OF LITERATURE

Tadros, Ghali and Dilger (1979) presented a step-by-step computer method for predicting the deflection and stress distribution due to creep and shrinkage of concrete and relaxation of prestressing steel. The computer program accounted for the presence of the non-prestressed steel, the difference in ages of concrete segments, the multiple stages in which the external loads and prestressing are applied, and the changes in geometry and support conditions as the construction progresses. The authors applied the proposed method to a three span continuous bridge and presented the results to indicate the significance of time-dependent effects.

Shushkewich K W (1986) presented a computer program for the time-dependent analysis of segmental bridges. Loadings considered at each stage of construction includes self-weight, time-dependent effects, temperature and construction loads. The program was intended to be used for routine day-to-day design. The author used the direct stiffness method for the analysis of stresses and deformations of segmental bridges. The usefulness of the program was illustrated through five numerical examples.

Herbert J T (1990) presented a methodology and computer program for the analysis of stage constructed bridges and two dimensional prestressed concrete structures. The method uses step-by-step superposition of strains and accounts for time-dependent effects including creep, shrinkage and relaxation. Structural elements comprise supports, hinges and temporaty links as well as the concrete segments, and can be erected in any logical order. The computer program is used to illustrate the method with an example problem involving a simple three-span bridge. An important feature of the method is that it can be applied independently of a particular code of practice and computer program demonstrates this by incorporating the provisions of six different codes. The author based the computer approach on the step-by-step superposition of strains as described by Tadros, Ghali and Dilger.

Guo-Jing HE, Yuan-yuan LI, Zhong-quan Zou and Ling-liang Duan (2008) investigated the effects of concrete creep on the pre-camber of a long span prestressed concrete continuous rigid-frame bridge constructed by cantilever casting method. The difference of creep coefficients calculated with two Chinese codes, CC-1985 and CC-2004 was discussed. Based on the calculations, the pre-camber of a prestressed concrete continuous rigid-frame box bridge was computed for construction control purpose.

Malm R and Sundquist H (2010) presented the time-dependent analyss of segmentally constructed balanced cantilever bridges. The analysis presented in the paper was performed with finite element (FE) software Abaqus/Standard 6.7. The modeling approach used was using three-dimensional shell elements. Three-dimensional element is chosen to capture the effect of shear lag in box section. The shell elements were used in the main and two adjacent spans. The remaining spans and pier were modeled with beam elements.

From the literature review, it can be concluded that time-dependent effects of creep, shrinkage and relaxation affects the long-term behaviour of post-tensioned segmental bridges. In case of indeterminate bridge structures like continuous and rigid frame bridges constructed by segmental cantilever construction, the restraint on the time-dependent deformations imposed by the indeterminacy gives rise to additional stresses which should be accounted for in the design. During the construction stages, the addition of segments and post-tensioning coupled with the time-dependent effects gives rise to increase in the deflection. The accurate estimation of the time-dependent deformations are essential to prevent the misalignment of the joining ends of the cantilever.

IV. ANALYSIS METHODOLOGY

The analysis of the long-term deformation has been performed using the LUSAS 14 software. a three-span segmental bridge constructed by cantilever construction is modeled and analysed. The time-dependent deformations of a particular joint are studied. Further the effect of construction sequence on the difference between deflections of two meeting ends of the cantilever is evaluated. In this case, dead load and multi-stage post-tensioning are considered. Numerical studies are performed to show the effect of various parameters on the long-term deformation. The variation of bending moment diagram with time has also been presented.

V. ANALYSIS OF SEGMENTAL BRIDGE

A three-span segmental bridge has been analyzed using LUSAS 14 software. The analysis includes different stages of bridge construction and service life. The cross-section of the bridge is box-section of constant depth which has been taken for simplicity. Each span consists of four segments in the cantilever. There are three closure segments in the side span and one closure segment in the middle span. Therefore, there are seven segments in each side-span and nine segments in the middle span. Deformations due to dead load of the bridge structure and prestress have been considered. The development of deformations with time due to time-dependent effects has been presented. The significance of construction schedule is presented. Numerical studies have been performed to show the effect of environmental parameters like relative humidity on long-term deformation. The details of the bridge are as follows:

- Bridge type: Continuous rigid frame bridge constructed by segmental cantilever construction.
- Spans: Three spans with the side-spans of length of 53.5 m and middle span of length 65 m.
- Length of segments: 7.5 m for cantilever segments, 5 m for closure segment in the middle span. In the side-spans, the three closure segments are of length 7.5 m, 7.5 m and 8.5 m respectively towards the end support.

A schematic of the bridge is shown in Fig. 1.

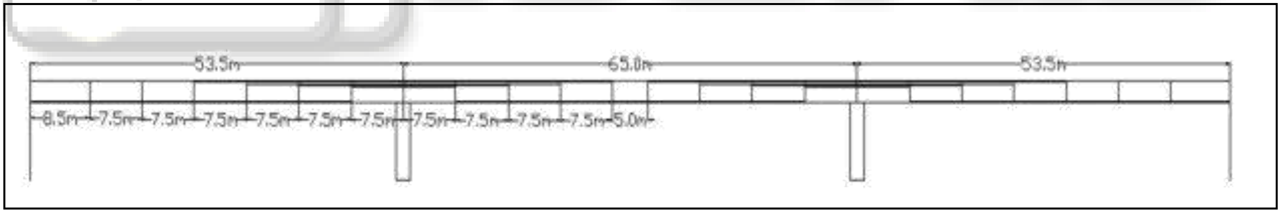


Fig. 1: Schematic of Three Span Bridge

Area of cross-section: 9.0854 m^2
Second moment of area: 10.561 m^4
Concrete grade: M45
Concrete density: 24 kN/m^3
Cement type: Normal or rapid hardening
Relative humidity: 40 %

Nominal size: 0.7
Age of precast segment: 28 days
Creep and shrinkage model: CEB-FIP90
Cable profile: Straight

The cable profile at various stages is shown in Figs. 2 to 4.

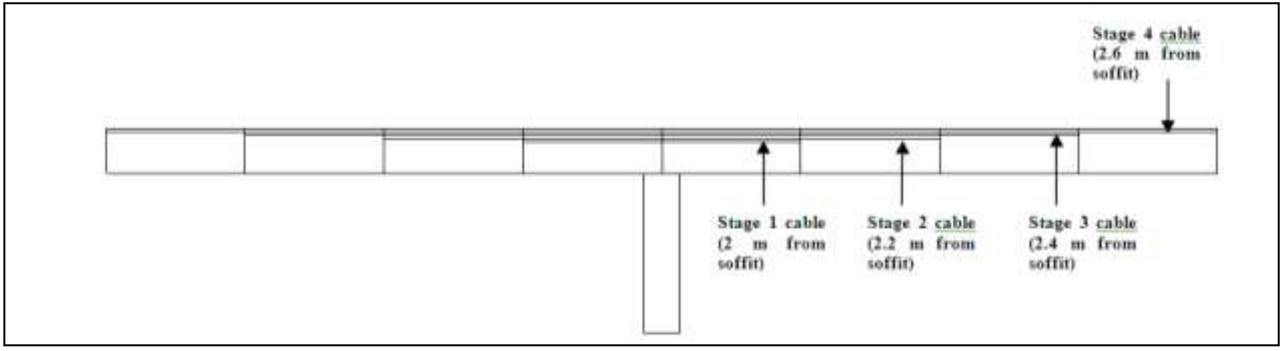


Fig. 2: Cable Profile in the Cantilever Stages

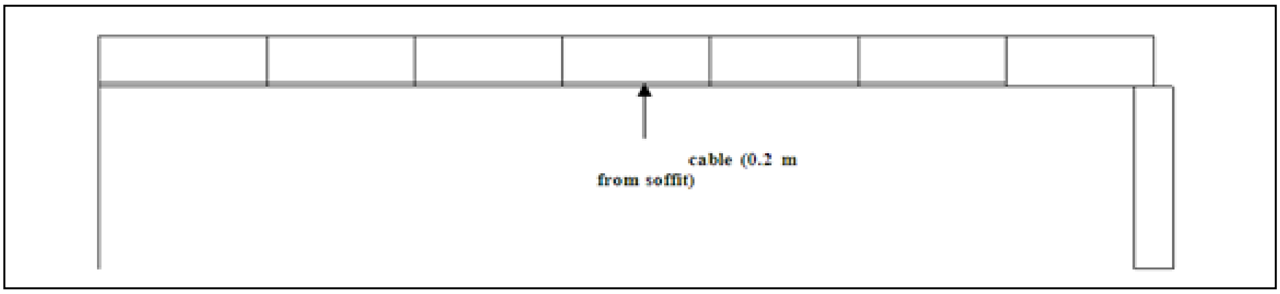


Fig. 3: Cable Profile in the Side Span

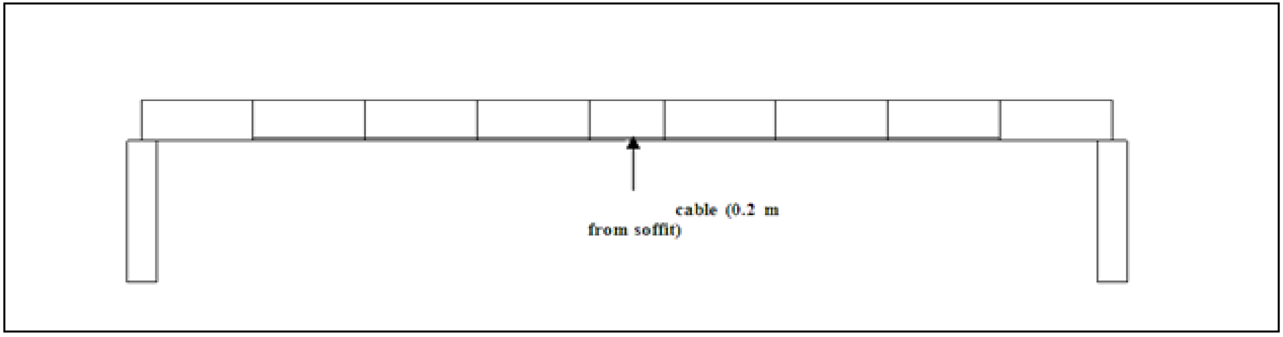


Fig. 4: Cable Profile in the Middle Span

The model of the bridge is meshed using three-dimensional thick non-linear beam elements. The age of the precast segment at the time of erection is taken as 28 days. There are seven construction stages. The time duration of each stage is 60 days. Therefore, the time of completion of bridge is 420 days.

VI. DEFLECTED SHAPE OF BRIDGE AT VARIOUS STAGES OF CONSTRUCTION

Deflected shapes of bridge at various at different stages of construction are shown from Fig. 5 to Fig. 11.

Scale: 1: 912.467

Zoom: 105.0

Eye: (0.0, 0.0, 1.0)

Nonlinear analysis

Loadcase: 16:Time Step 15 Time = 60.0000

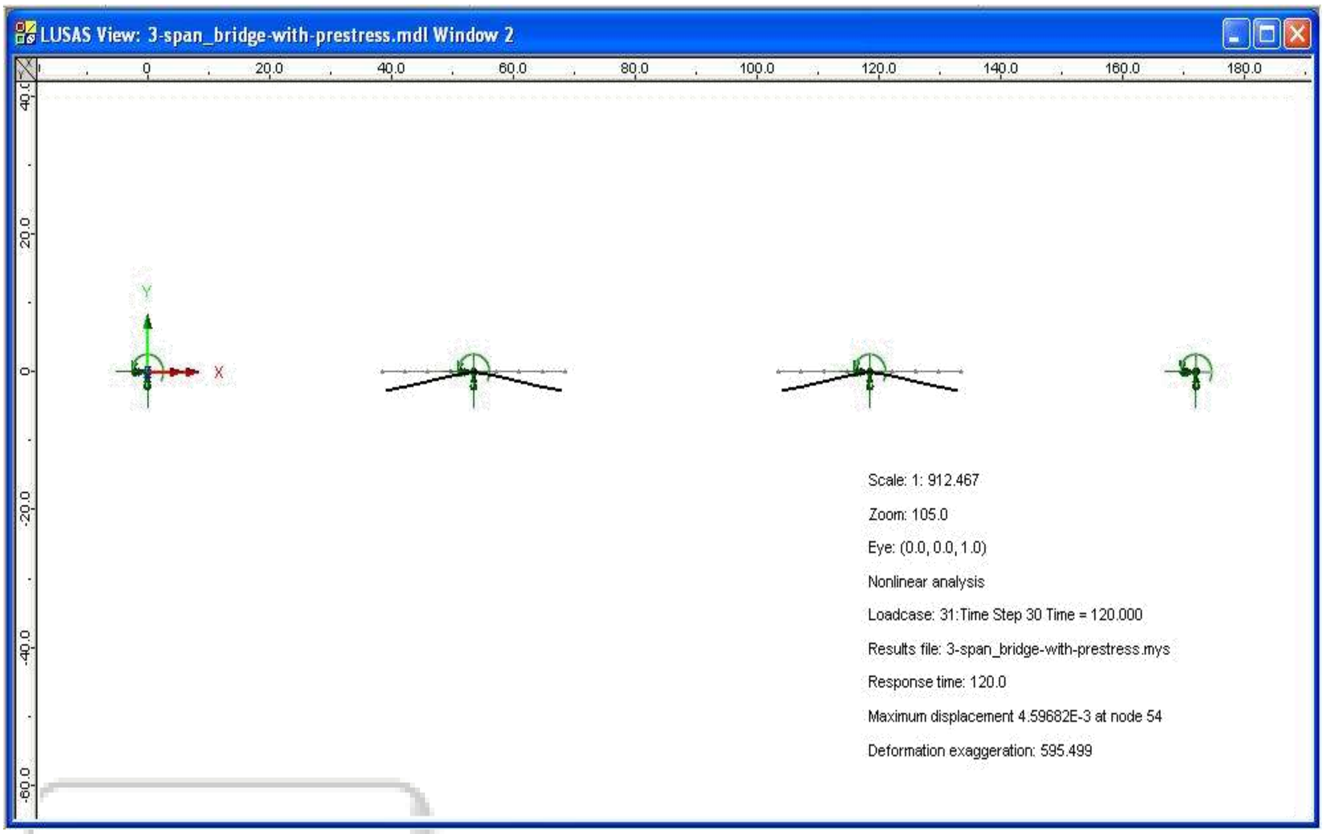
Results file: 3-span_bridge-with-prestress.mys

Response time: 60.0

Maximum displacement 0.45979E-3 at node 30

Deformation exaggeration: 5.95359E3

Fig. 5: Deflected Shape of Bridge at the End of Stage 1 (60 Days)



Scale: 1: 912.467

Zoom: 105.0

Eye: (0.0, 0.0, 1.0)

Nonlinear analysis

Loadcase: 31:Time Step 30 Time = 120.000

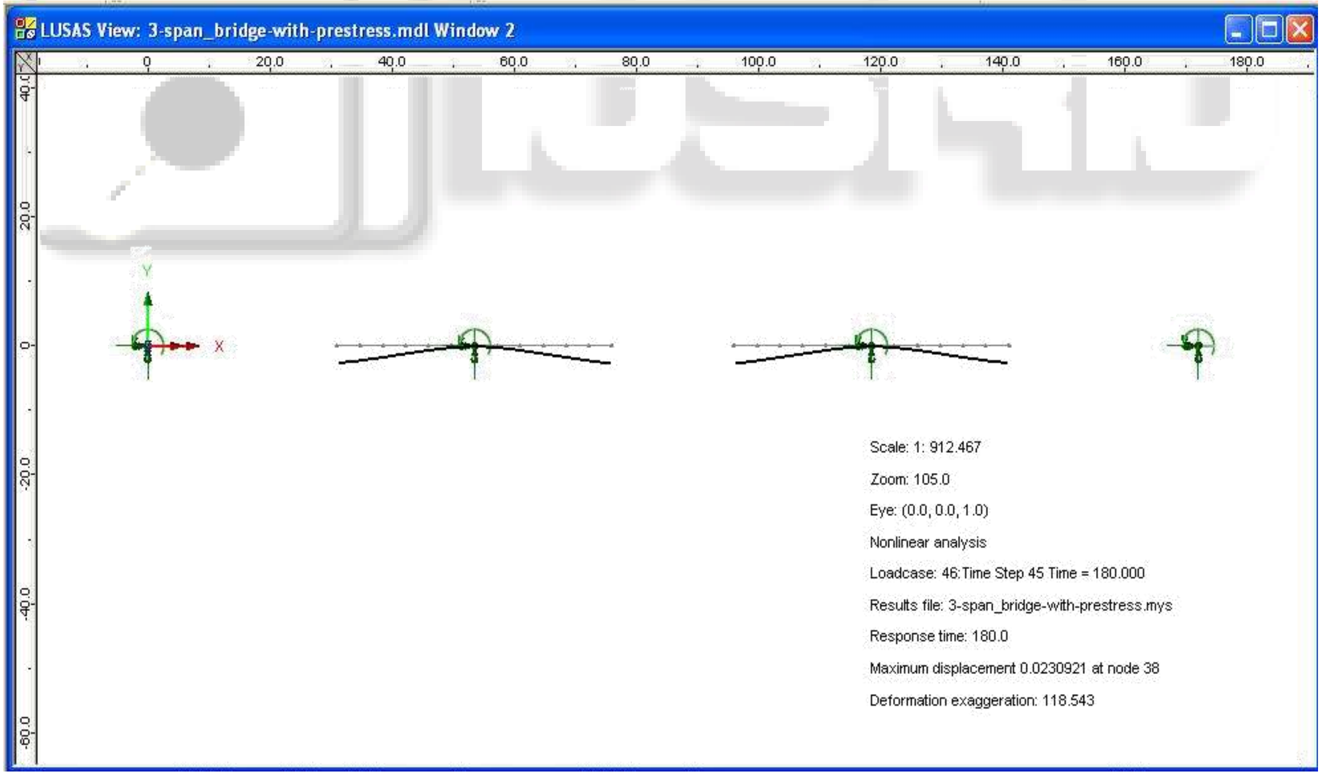
Results file: 3-span_bridge-with-prestress.mys

Response time: 120.0

Maximum displacement 4.59682E-3 at node 54

Deformation exaggeration: 595.499

Fig. 6: Deflected Shape of Bridge at the End of Stage 2 (120 Days)



Scale: 1: 912.467

Zoom: 105.0

Eye: (0.0, 0.0, 1.0)

Nonlinear analysis

Loadcase: 46:Time Step 45 Time = 180.000

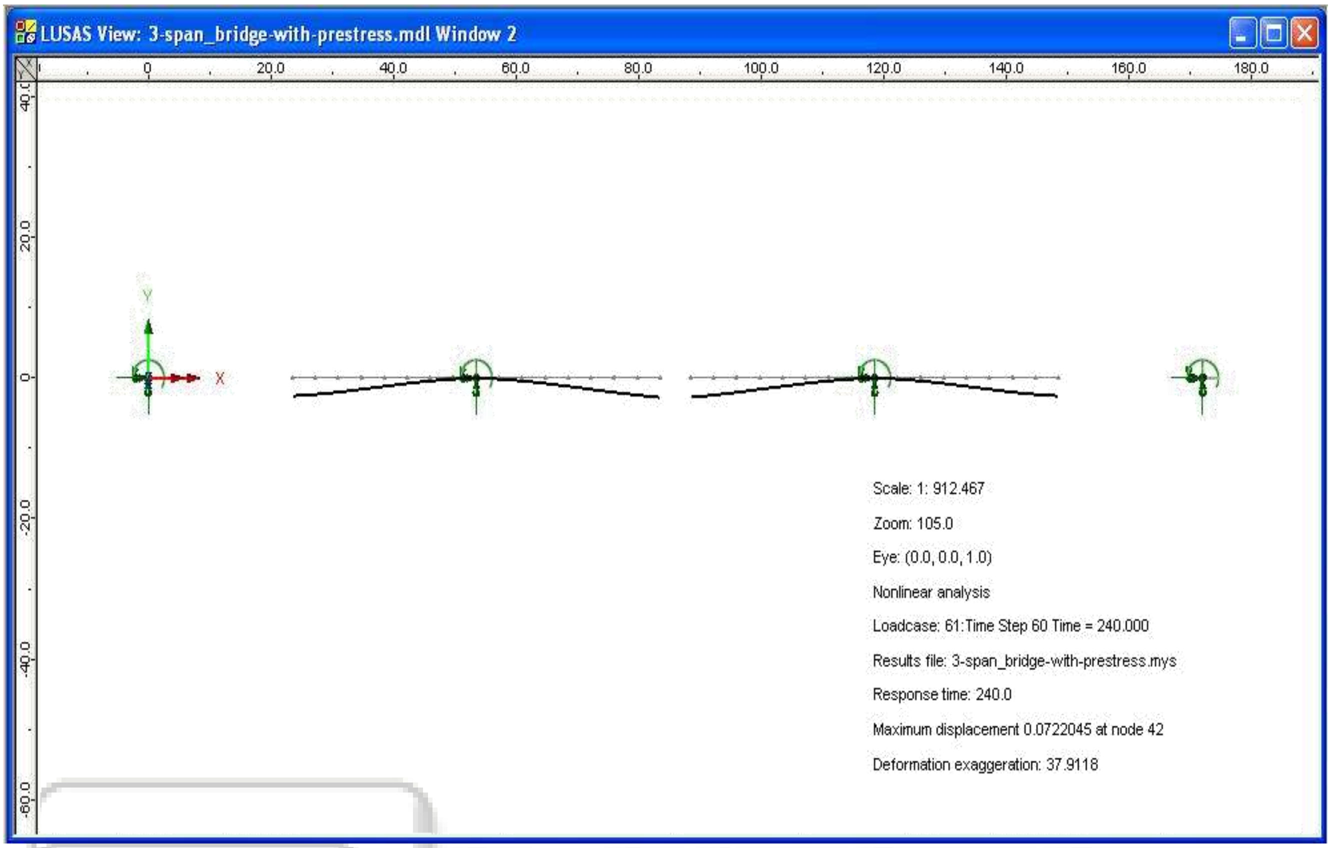
Results file: 3-span_bridge-with-prestress.mys

Response time: 180.0

Maximum displacement 0.0230921 at node 38

Deformation exaggeration: 118.543

Fig. 7: Deflected Shape of Bridge at the End of Stage 3 (180 Days)



Scale: 1: 912.467

Zoom: 105.0

Eye: (0.0, 0.0, 1.0)

Nonlinear analysis

Loadcase: 61:Time Step 60 Time = 240.000

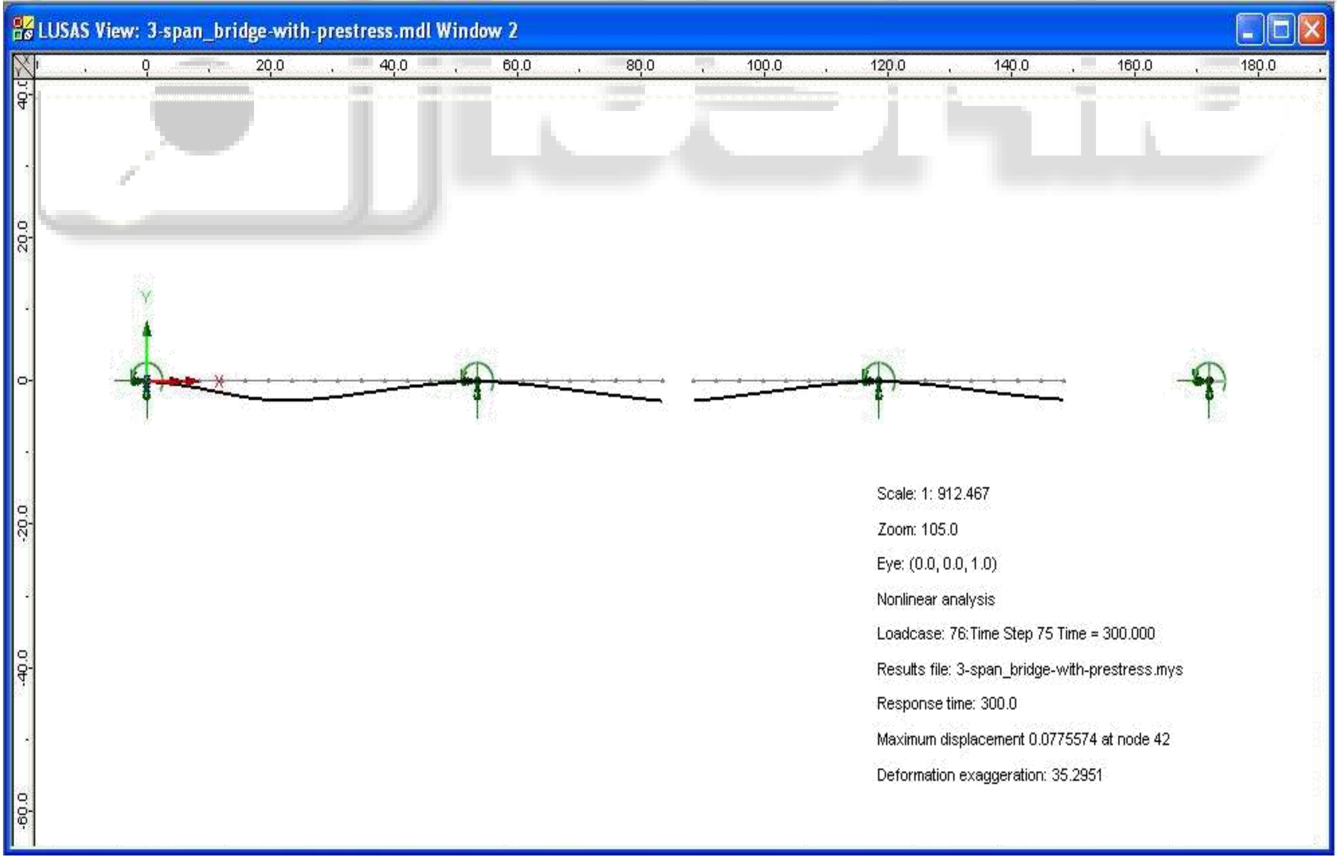
Results file: 3-span_bridge-with-prestress.mys

Response time: 240.0

Maximum displacement 0.0722045 at node 42

Deformation exaggeration: 37.9118

Fig. 8: Deflected Shape of Bridge at the End of Stage 4 (240 Days)



Scale: 1: 912.467

Zoom: 105.0

Eye: (0.0, 0.0, 1.0)

Nonlinear analysis

Loadcase: 76:Time Step 75 Time = 300.000

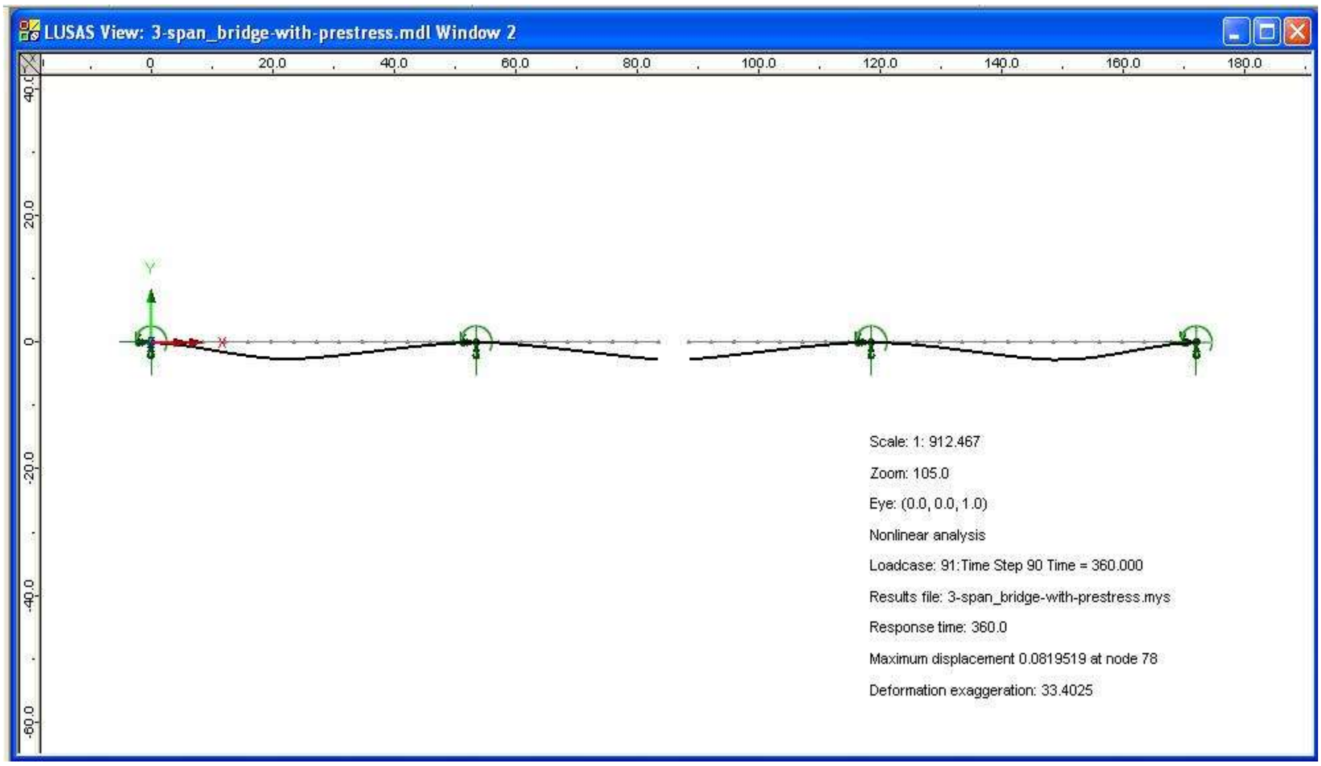
Results file: 3-span_bridge-with-prestress.mys

Response time: 300.0

Maximum displacement 0.0775574 at node 42

Deformation exaggeration: 35.2951

Fig. 9: Deflected Shape of Bridge at the End of Stage 5 (300 Days)



Scale: 1: 912.467

Zoom: 105.0

Eye: (0.0, 0.0, 1.0)

Nonlinear analysis

Loadcase: 91:Time Step 90 Time = 360.000

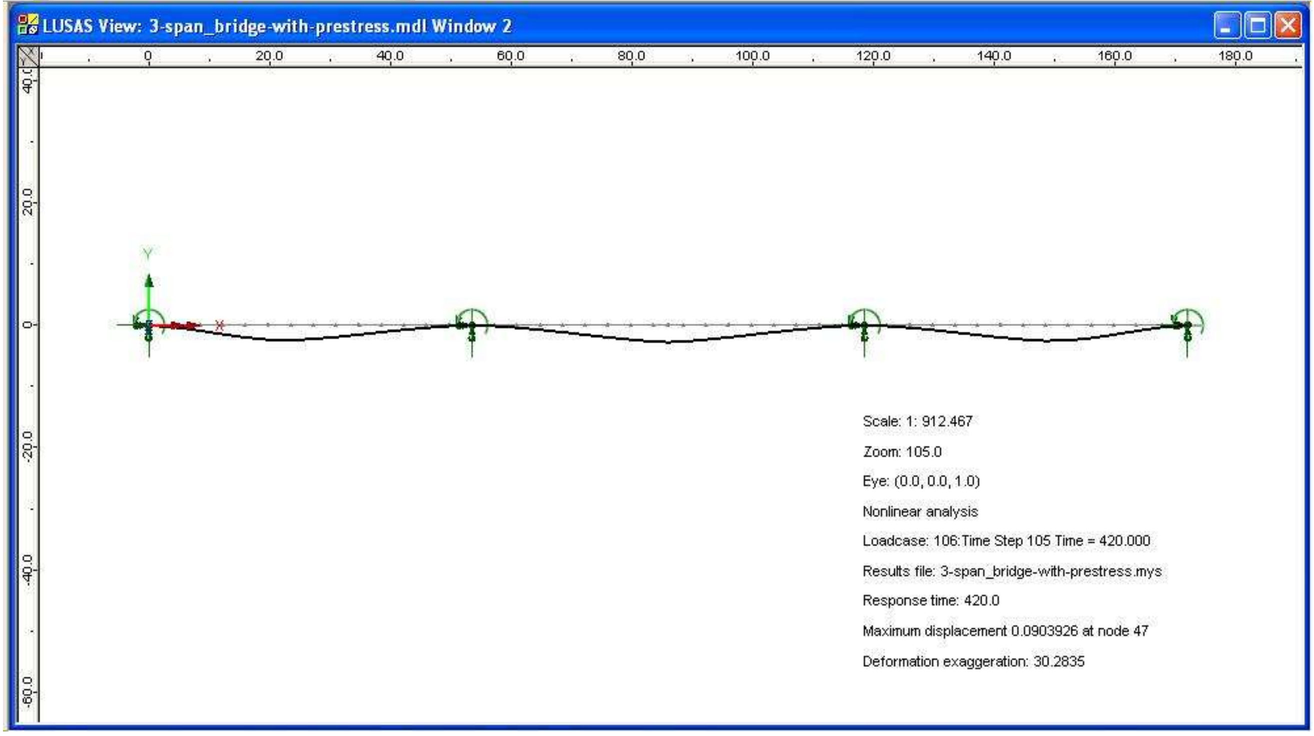
Results file: 3-span_bridge-with-prestress.mys

Response time: 360.0

Maximum displacement 0.0819519 at node 78

Deformation exaggeration: 33.4025

Fig. 10: Deflected Shape of Bridge at the End of Stage 6 (360 Days)



Scale: 1: 912.467

Zoom: 105.0

Eye: (0.0, 0.0, 1.0)

Nonlinear analysis

Loadcase: 106:Time Step 105 Time = 420.000

Results file: 3-span_bridge-with-prestress.mys

Response time: 420.0

Maximum displacement 0.0903926 at node 47

Deformation exaggeration: 30.2835

Fig. 11: Deflected Shape of Bridge at the End of Stage 7 (420 Days)

Table 1 gives the deflection at the end of cantilever segments at different stages of construction and at 10000 days.

Deflection (mm) at end of	Completion of erection of					Long-term deflection (10000 days)
	segment 1 (60 days)	segment 2 (120 days)	segment 3 (180 days)	segment 4 (240 days)	bridge (420 days)	
segment 1	0.3	2.2	5.4	10.2	12	14.6
segment 2	-	4.5	14.6	30.3	36.2	43.5

segment 3	-	-	23.1	53.1	64	75.7
segment 4	-	-	-	72.2	87.2	101.4

Table 1: Deflection at the End of Cantilever Segments at Different Stages

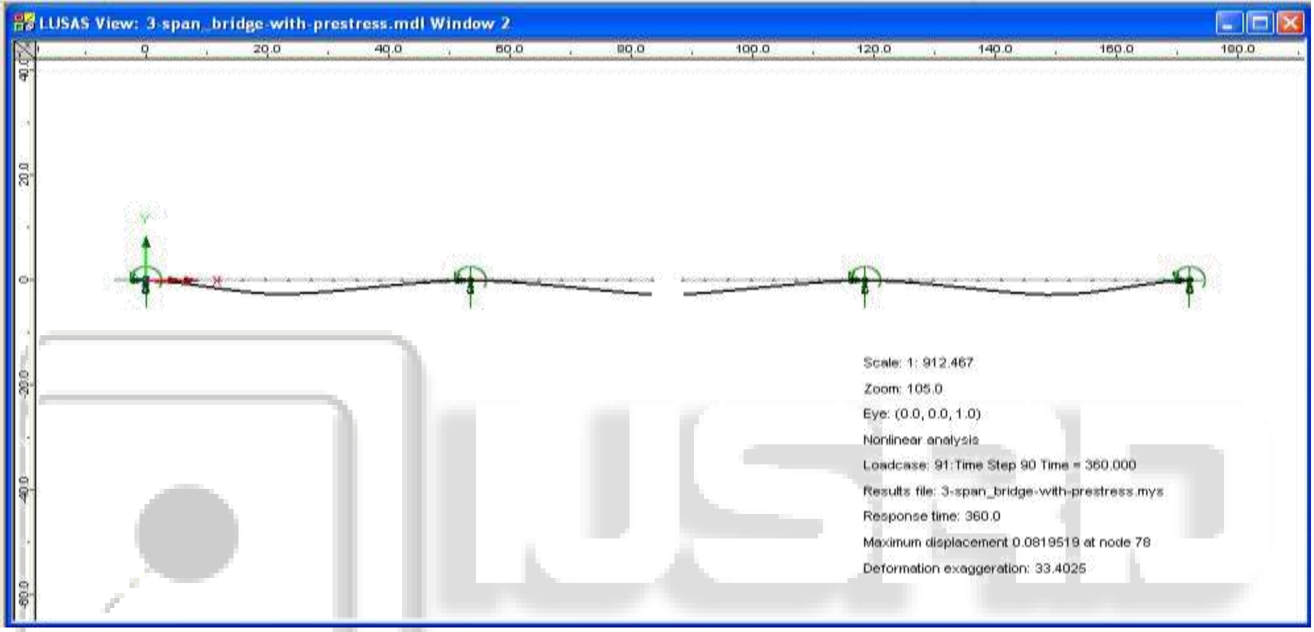
Table 1 gives the deflection at the end of cantilever segments at the time of completion of erection of different segments. From table 1, it can be observed that large portion of long-term deflection occurs during the construction stages than that after the completion of the bridge.

VII. EFFECT OF CONSTRUCTION SCHEDULE

The effect of construction schedule on the deflected shape of the bridge is presented here. In the first case addition of segments from the two pier is done simultaneously while in the second case, after the completion of construction of cantilever from first pier and completion of first span only the construction from second pier is started. This can be better illustrated with the help of deformed shape of the bridge for the two cases. The two cases are presented here.

A. Case I: Addition of segments from two piers simultaneously

Fig. 12 shows the deflected shapes for this case at each construction stage before the addition of middle closure segment.

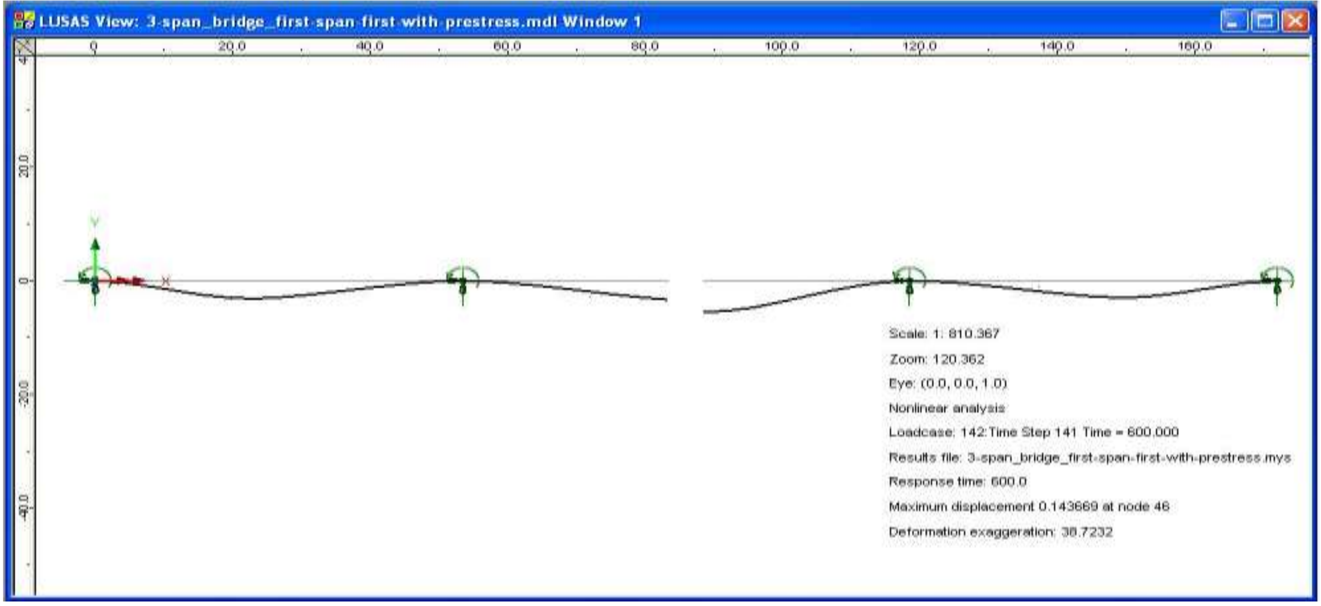


Scale: 1: 912.467
Zoom: 105.0
Eye: (0.0, 0.0, 1.0)
Nonlinear analysis
Loadcase: 91:Time Step 90 Time = 360.000
Results file: 3-span_bridge-with-prestress.mys
Response time: 360.0
Maximum displacement 0.0819519 at node 78
Deformation exaggeration: 33.4025

Fig. 12: Deflected Shape before the Addition of Closure Segment (Case I)

B. Case II: Addition of segments from first span and completion of first span first

Fig. 13 shows the deflected shapes for this case before the addition of middle closure segment.



Scale: 1: 810.367
Zoom: 120.362
Eye: (0.0, 0.0, 1.0)
Nonlinear analysis
Loadcase: 142:Time Step 141 Time = 600.000
Results file: 3-span_bridge_first-span-first-with-prestress.mys
Response time: 600.0
Maximum displacement 0.143669 at node 46
Deformation exaggeration: 38.7232

Fig. 13: Deflected Shape before the Addition of Closure Segment (Case II)

From Fig. 12 and Fig. 13, it is found that the difference in vertical deflection of the meeting ends of cantilever in the middle span is more in case II while it is zero in case I. From the analysis, the difference in vertical deflection of the two meeting ends is found to be 57.6 mm in case II.

VIII. NUMERICAL STUDIES

Numerical studies are performed to show the variation of deflection with time and effect of relative humidity and age of precast segment at the time of erection on long-term deformation. The long-term deformation taken is the vertical deflection at the end of cantilever segments at 10000 days. Results are presented in the form of plots.

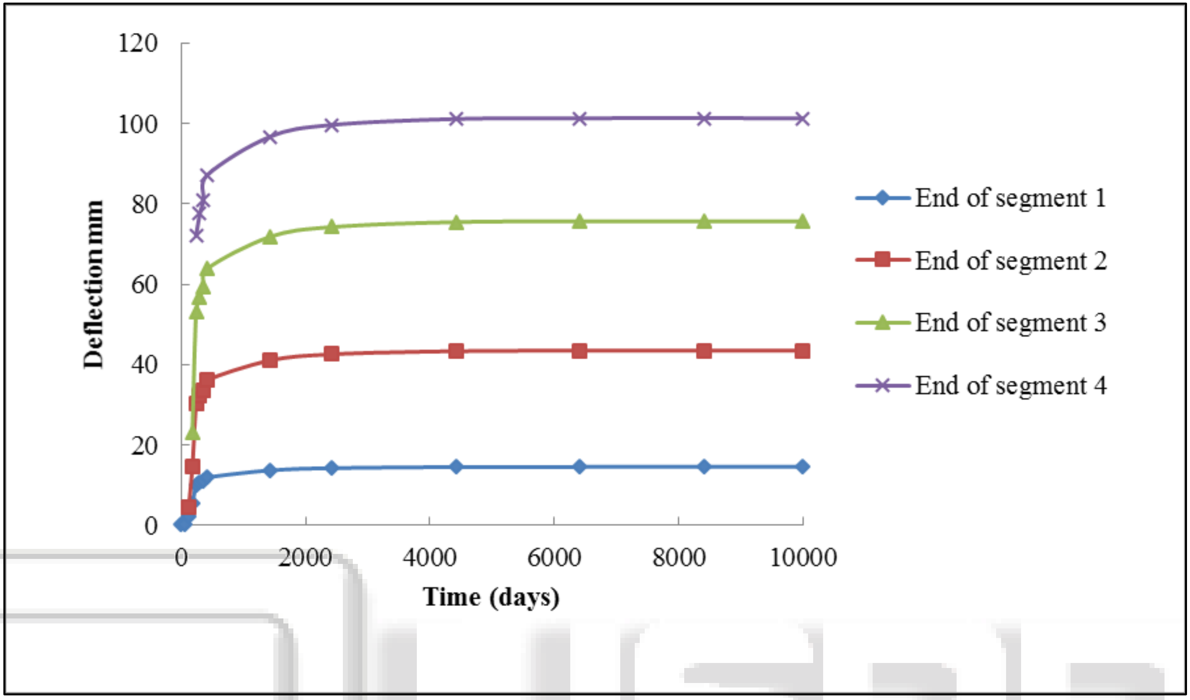


Fig. 14:Deflection at the End of Cantilever Segments Vs Time

Fig. 6.20 shows the variation of vertical deflection at the end of cantilever segments with time. It is observed that deflection increases with time. The rate of increase is more in the beginning while the deflection stabilizes in the end. For the end of segment 1, long-term deflection at 10000 days is found to be about 73 times of the instantaneous deflection at the start (t=0) and 1.22 times the deflection at the time of completion of bridge (t=420 days).

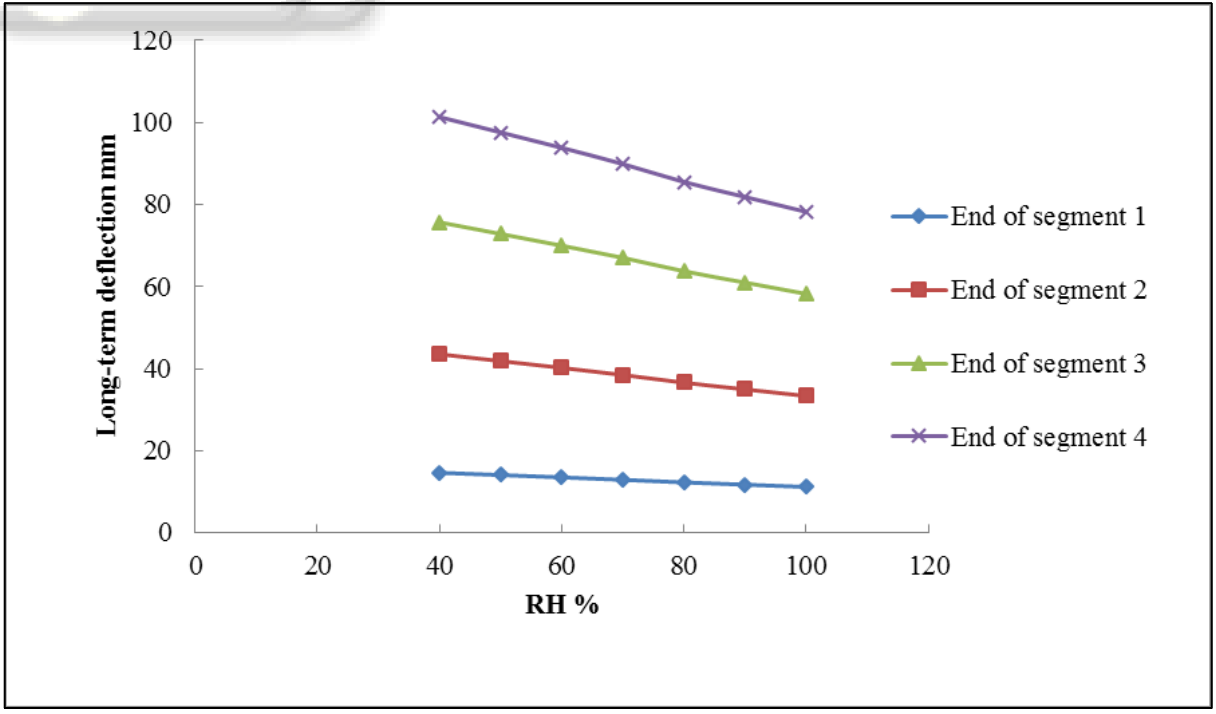


Fig. 15: Long-Term Deflection Vs Relative Humidity

From Fig. 15, it is observed that long-term deflection decreases as relative humidity increases from 40 % to 100 %. The percentage decrease in long-term deflection at the end of cantilever segments is given in Table 2.

End of segment	Percentage decrease in long-term deflection at 10000 days as relative humidity increases from 40 % to 100 %
1	23.7
2	23.4
3	23.1
4	22.8

Table 2: Effect of Relative Humidity on Long-Term Deflection

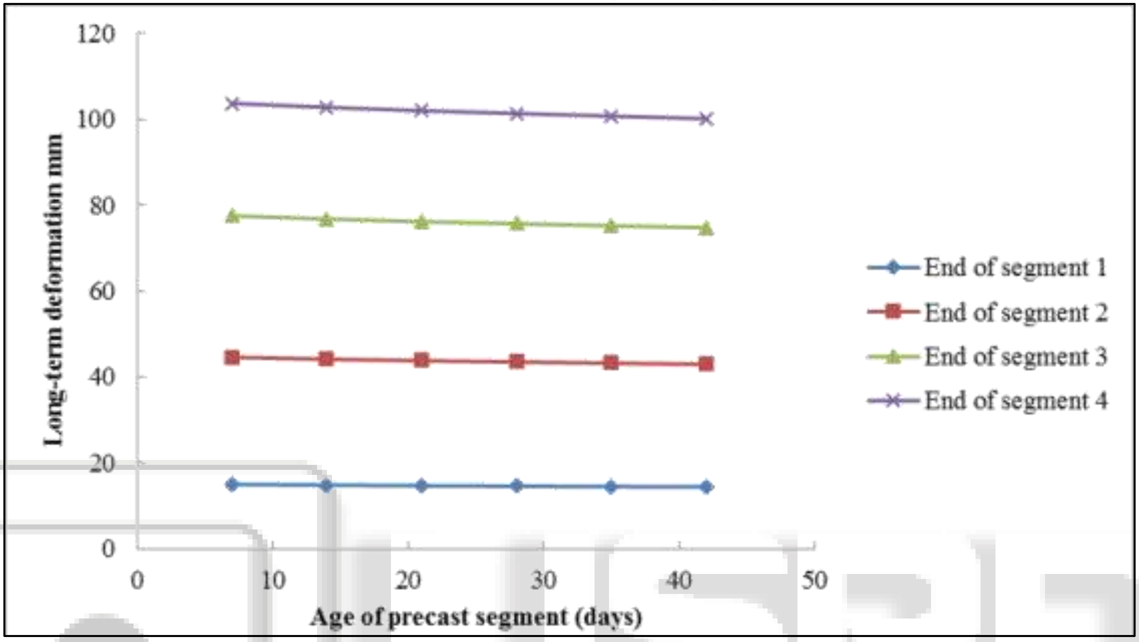


Fig. 16: Long-Term Deflection Vs Age of Precast Segment

From Fig. 16, it is observed that long-term deflection decreases as the age of precast segment at the time of erection increases from 7 days to 42 days. The percentage decrease in long-term deflection at 10000 days at the end of different segments is given in Table 3.

End of segment	Percentage decrease in long-term deflection at 10000 days as the age of precast segment increases from 7 days to 42 days
1	4
2	3.7
3	3.6
4	3.4

Table 3: Effect of Age of Precast Segment at the Time of Erection on Long-Term Deflection

Variation of Bending Moment in the Completed Bridge with Time

Fig. 17 shows the bending moment diagram of the bridge at two times, i.e., at 420 days (time of completion of bridge) and at 10000 days.

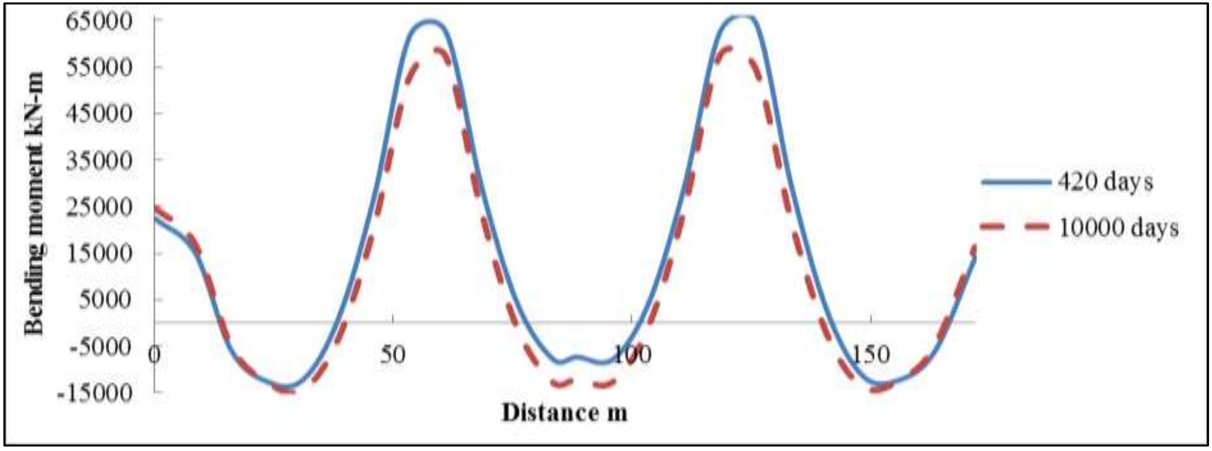


Fig. 17: Bending Moment Diagram of Completed Bridge

From Fig. 17, it can be observed that bending moment at the intermediate supports decreases with time while at the mid-span, it increases with time after the completion of construction of bridge.

IX. RESULTS AND DISCUSSION

The results of the analysis of a three-span segmental bridge using LUSAS 14 software are presented here. For modeling the behaviour of creep and shrinkage of concrete, only CEB-FIP90 model has been used. Deflections due to dead load and prestress have been considered.

1) *Variation of Deflection with Time*

- Long-term deflection at the end of first segment at 10000 days is found to be about 73 times of the instantaneous deflection at the start (t=0) and 1.22 times the deflection at the time of completion of bridge (t=420 days).

2) *Effect of Construction Schedule*

- Two cases of construction sequence have been considered. In case I, the addition of precast segments from both the piers is done simultaneously while in the in case II, cantilever from first pier and first span are completed first. It is found that the difference in vertical deflection of the meeting ends of cantilever in the middle span is more in case II while it is zero in case I.
- From the analysis, the difference in vertical deflection of the two meeting ends is found to be 57.6 mm in case II.

3) *Effect of Relative Humidity*

- As the relative humidity increases from 40 % to 100 %, long-term deflection at 10000 days decreases. The quantitative information is given in table 6.2 in chapter 6.

4) *Effect of Age of Precast Segment at the Time of Erection*

- As the age of precast segment at the time of erection increases from increases from 7 days to 42 days, long-term deflection at 10000 days decreases. The quantitative information is given in table 6.3 in chapter 6.

5) *Variation of Bending Moment in the Completed Bridge with Time*

- Bending moment at the intermediate supports decreases with time while at the mid-span, it increases with time after the completion of construction of bridge.

6) *Discussion of Results*

- Long-term deflection at the end of first segment at 10000 days is about 73 times the initial deflection while it is only 1.22 times the deflection at the time of completion of bridge. This is because during the construction stages, increase in load due to the addition of segments and post-tensioning coupled with the time-dependent effects results in a large increase in deflection. But, after the completion of bridge, structural form changes to indeterminate which results in restraint in the time-dependent deflection. Therefore, the deflection does not increase to the same extent as in case of simply-supported bridge structures which are determinate.
- With an increase in relative humidity, long-term deflection decreases due to reduction in the creep of concrete.
- Long-term deflection at 10000 days decreases with an increase in the age of precast segment at the time of erection because creep and shrinkage of concrete reduces as the age of concrete at the time of application of loading increases.
- The construction sequence is very important in the case of segmental cantilever construction of bridge to prevent misalignment of the segments. There should be provision for external post-tensioning so that the profile of the bridge girder can be adjusted by stressing the external tendons.
- Due to restraint imposed on the deformation due to creep and shrinkage of concrete due to indeterminacy, bending moment changes with time even after the completion of construction of bridge.

X. CONCLUSIONS

- The accurate prediction of time-dependent deformation is of extreme importance in case of indeterminate bridge structures like continuous and rigid frame bridges which are constructed by segmental cantilever construction. The excessive long-term deflection during the construction stages can result in misalignment of the meeting ends of the cantilever.
- In case of bridges constructed by segmental cantilever construction, time-dependent deformations during the construction stages can result in misalignment of the joining ends. In such situation where structural form changes from determinate during construction to indeterminate during service, both the problems of deformations and stresses become significant.
- In case of indeterminate bridge structures, restraint imposed on the time-dependent deformations due to indeterminacy results in additional stresses which should be accounted for in the design.

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