Journal of Civil Engineering
The Institution of Engineers, Bangladesh
Vol. CE 28, No. 1, 2000

ANALYSIS OF SEGMENTALLY ERECTED CONCRETE BRIDGES AT CONSTRUCTION STAGES

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ABSTRACT : A computer method for the analysis of segmentally erected concrete bridges at various stages of their construction is presented. The program developed can analyze bridges with varieties of cross-section including box section. Stiffness method of analysis has been used. Program has been developed to perform necessary calculation for dead load, temperature gradient, creep and shrinkage of concrete, prestressing and other construction forces. The structure at its various of construction can be analyzed for operations used in segmental construction such as addition of segments, changing of support boundary conditions, application or removal of construction loads and prescribed displacements. At each construction stage, the current structure is analyzed and the displacements are obtained. Numerical results obtained have been compared with experimental and analytical results obtained by other researchers.

KEYWORDS : Segmental erection, construction stage, box girder bridge, stiffness method, Prestressed concrete, creep.

INTRODUCTION

In the progressive cantilever method of construction for segmentally erected concrete bridges, unlike that in the conventional method of construction where loading on the completed bridge governs the design, the dead load stresses and the stresses due to gantry and other construction equipment during construction may be critical. This makes the analysis and design works for such bridges much more complicated as compared to that for conventional method of construction. Here designers must consider, with all the details, the phases and the special techniques the contractor would employ at each stage of construction as the work progresses. The effects of dead weight, gantry, construction equipment, creep, shrinkage and post-

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tensioning, as the construction progresses, on each element as well as their effects on the part of the bridge already constructed must also be incorporated in the design. A designer has to ensure proper deformation at all stages of construction for keeping the correct profile of the completed bridge in addition to controlling the built-in-stresses in it.

A complete analysis of a large segmentally erected concrete bridge, which is done by computer, requires a considerable amount of input data. Libby (1976) described the erection sequence as well as the analysis and expressed the need for a sophisticated computer analysis involving all the time-dependent and construction phase phenomena. The computer program developed by Danon and Gamble (1977) for straght segmental bridges was used to do a parameter study of the variables influencing the time-dependent behaviour and can handle a simple cantilever up to the stage prior to closure. Although the input is simple, this program has a limited field of application. another major program that has been published is the one developed by Brown at el. (1974). This program does not perform a time-dependent analysis. Another major program has been developed by Van Zyl and Scordelis (1978). The program is generalized also for curved bridges. But input data is fairly complex and relatively more computational effort is required.

In order to make the analysis relatively simpler, a computer program in FORTRAN 77 has been developed. The stiffness method of analysis is used assuming the bridge longitudinally as a frame. The results reported by Van Zyl and Scordelis (1978) for Corpus Christi Intercoastal Canal Bridge, constructed in Texas in USA (1972-73), have used for comparative study of the results obtained by the program developed in this study. The Corpus Christi Intercoastal Canal Bridge is a box girder bridge that includes three spans erected by segmental erection procedure. The prototype consists of a main span of 60.96 m (200 ft) with two side spans of 30.48 m (100 ft) each. The elevation, erection sequence and cross-section of the bridge are shown in Fig. 1, Fig. 2 and Fig. 3 respectively. Prestressing tendon layout and segment and element numbering are shown in Fig. 4.

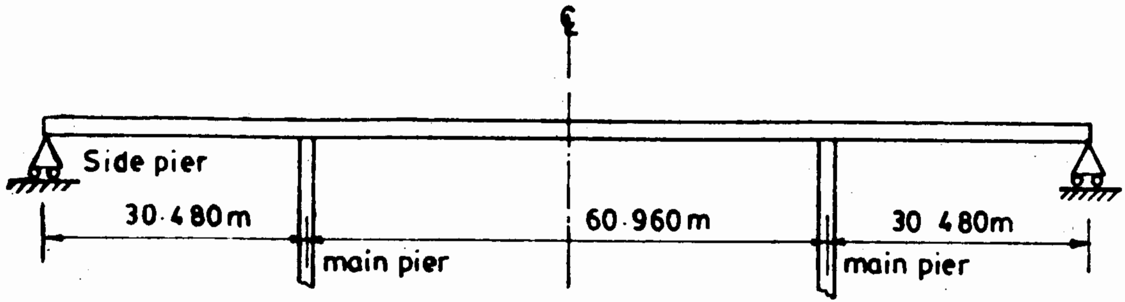

Fig 1. Elevation of Corpus Christi Intercoastal Canal Bridge

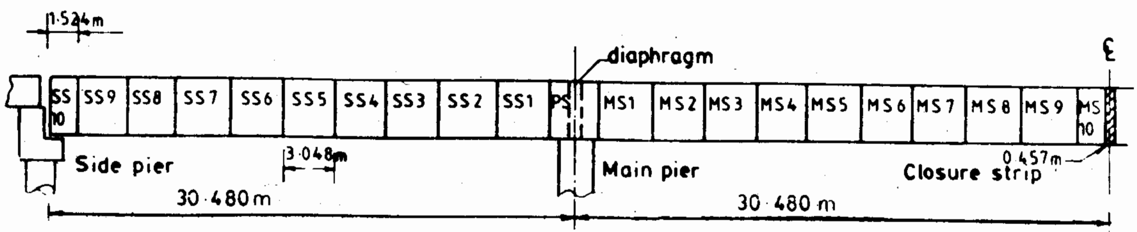

Fig 2. Erection Sequence

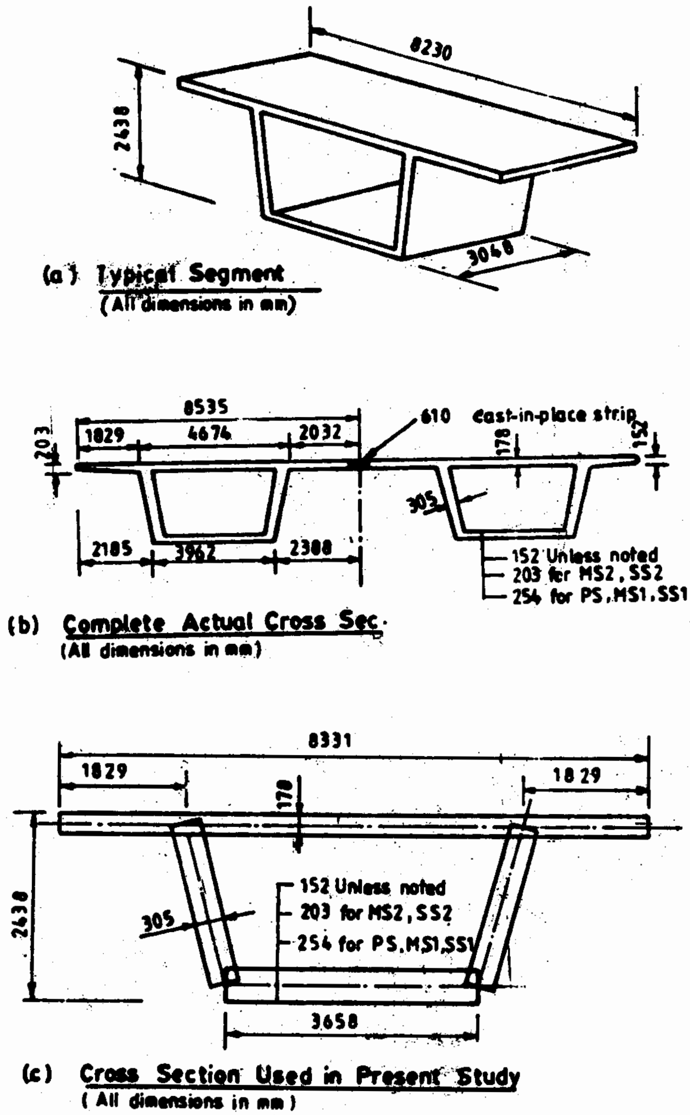

Fig 3. Cross-section of Corpus Christi Intercoastal Canal Bridge

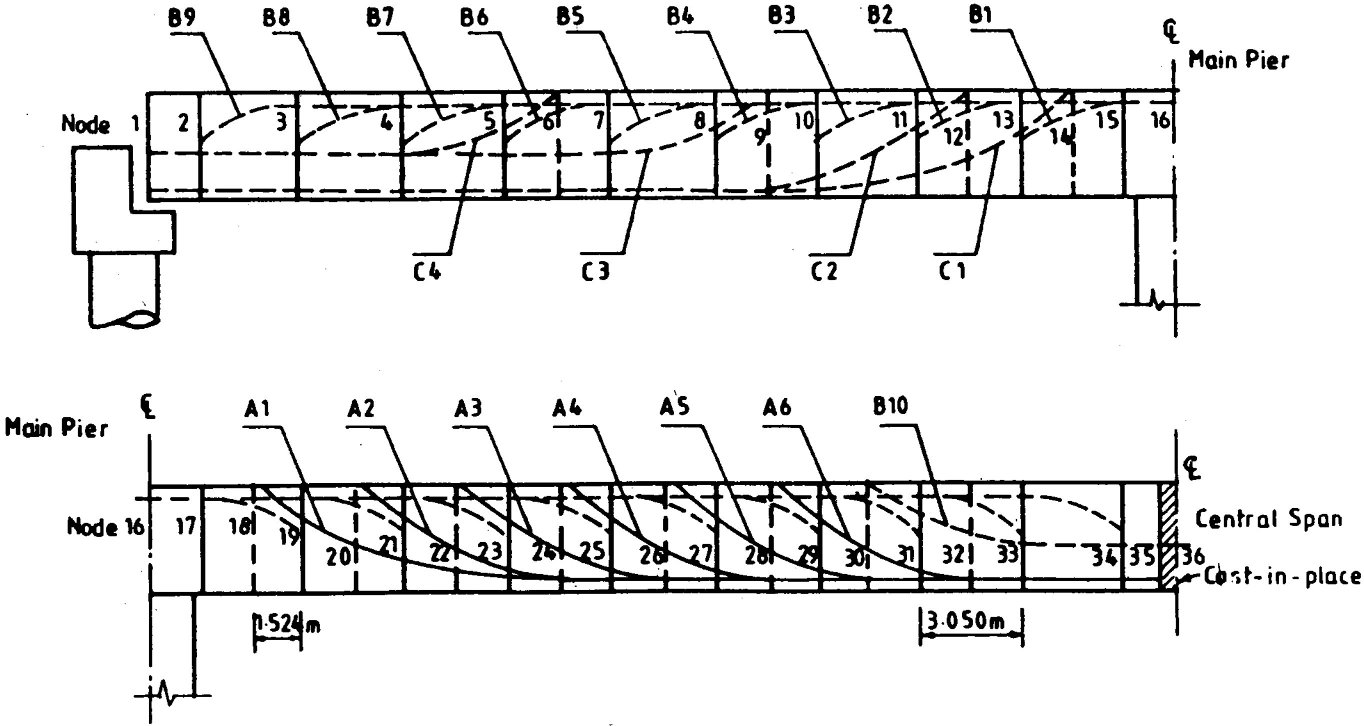

Fig 4. Tendon Layout, Segment and Element Numbering for Intercoastal Canal Bridge

GENERAL STIFFNESS EQUATIONS INCLUDING INITIAL STRAINS

Harrison (1079) has given the details of the stiffness formulation. Initial strains in the member AB of a rigidly connected plane frame are axial extension e^H and end slopes $\phi_{AB}{}^H$ and $\phi_{BA}{}^H$ as shown in Fig. 5. Effects of these upon member flexibility equations are as follows:

$$\begin{bmatrix} e \\ \phi_{AB} \\ \phi_{BA} \end{bmatrix} = \begin{bmatrix} \frac{L}{EA} & 0 & 0 \\ 0 & \frac{L}{3EI} & \frac{-L}{6EI} \\ 0 & \frac{-L}{6EI} & \frac{L}{3EI} \end{bmatrix} \begin{bmatrix} T \\ M_{AB} \\ M_{AB} \end{bmatrix} + \begin{bmatrix} e^H \\ \phi_{AB}{}^H \\ \phi_{AB}{}^H \end{bmatrix}$$

Where, e is the axial deformation of member; ϕ_{AB} is the rotation at end A of member AB; I is the moment of inertia; ϕ_{BA} is the rotation at end B of member AB; L is the length of member; E is the modulus of elasticity; A is the cross-sectional area of member; T is the axial force; M_{AB} is the moment at end A of member AB and M_{BA} is the moment at end B of member AB

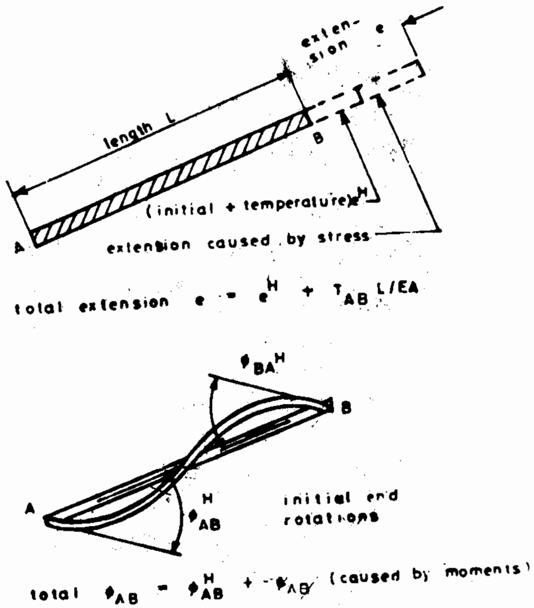

Fig 5. Member with Initial Strains

In matrix notation,

$$\{X\} = [F].\{SR\} + \{X^H\} \qquad (1)$$

where, {X} is the member deformation vector; [F] is the member flexibility matrix; {SR} is the member stress resultants and $\{X^H\}$ is the initial vector of member.

Member stiffness relationships with initial strains are:

$$\begin{bmatrix} T \\ M_{AB} \\ M_{BA} \end{bmatrix} = \begin{bmatrix} \frac{EA}{L} & 0 & 0 \\ 0 & \frac{4EI}{L} & \frac{2EI}{L} \\ 0 & \frac{2EI}{L} & \frac{4EI}{L} \end{bmatrix} \begin{bmatrix} e \\ \phi_{AB} \\ \phi_{AB} \end{bmatrix} - \begin{bmatrix} \frac{EA}{L} & 0 & 0 \\ 0 & \frac{4EI}{L} & \frac{2EI}{L} \\ 0 & \frac{2EI}{L} & \frac{4EI}{L} \end{bmatrix} \begin{bmatrix} e^H \\ \phi_{AB}{}^H \\ \phi_{BA}{}^H \end{bmatrix}$$

In matrix notation,

$$\{SR\} = [S]\{x\} - [S]\{X^H\} \qquad (2)$$

where, [S] is the member stiffness matrix

For equilibrium, $\{W\} = [A].\{SR\}$ (3)

where, {W} is the vector representing loads at joints and [A] is the member statics matrix.

For compatibility, $\{X\} = [A]^T.\{X\}$ (4)

where, $[A]^T$ is the transpose of statics matrix and {X} is the joint displacement vector.

Consequently, $\{W\} = [A].[S].[A]^T.\{X\} - [A].[S].\{X^H\}$

or, $\{W\} + [A].[S].\{X^H\} = [K].\{X\}$ (5)

where, [K] is the contribution of one member to the structure stiffness matrix. The elements of member stiffness matrix are assembled in proper sequence to form the frame stiffness matrix for the analytical model. The joint load vector and joint displacement vector are arranged in sequence. The equilibrium equations, thus formed, are solved by using Triple Matrix Decomposition Method (Harrison, 1979). Having solved for joint movements {X}, stress resultants are calculated as follows:

$$\{SR\} = [S].[A]^T.\{X\} - [S].\{X^H\}$$

GENERATION OF LOAD VECTOR {W}

Dead Load

Dead load is computed directly to form the basic components of the load vector.

Live Load

Influence line ordinates are generated and stored. The largest positive and negative ordinates and the area under the influence line diagram are calculated. The contribution of live load to the load vector is then obtained.

Load due to creep and Shrinkage of Concrete

Shrinkage strains and creep coefficients are calculated according to ACI Committee 209 (1970) recommendations. The shrinkage strains are used to generate a pseudo-load vector. For creep analysis, stresses at different levels due to dead and prestressing loads are estimated first. Using these stresses and creep coefficents, creep strains are obtained. A pseudo-load vector due to creep strain, thus generated, is added to the load vector.

Load due to Temperature Gradient

Fixed-end effects caused by linear temperature gradient, which are added to the load vector, have been given by Weaver and Gere (1986) as

Moment, $M_A = -M_B = \alpha EI(T_1 - T_2)/d$ (6)

And Axial Force, $F = \alpha T_{cg} AE$ (7)

where, α is the coefficent of thermal expansion; T_1 is the temperature at bottom of girder; T_2 is the temperature at top of girder; d is the depth of girder and T_{cg} is the temperature at centroid of girder section.

Load due to Prestressing

Prestressing forces are calculated from the data of prestressing steel (Islam, 1997). These forces, in general inclined to the axis of a member, are resolved into their horizontal components, vertical components and moments to obtain the load vector due to prestressing.

ANALYSIS AT CONSTRUCTION STAGES

A construction stage can include any or all of the following:

(a) A change in the structure as a result of the addition of a new segment.

(b) A change in the boundary conditions. Temporary supports may be removed or new supports may be removed or new supports may be added.

(c) A change in the construction loads. Some loads may be removed and new ones may be added.

(d) Given displacements can be imposed at any of the supported joints.

(e) Tendons, which have just been installed, can be stressed for the frist time while previously installed tendons can be restressed or removed.

In the present study, all of these changes can be dealt with proper input of relevant data.

COMPARATIVE STUDY

Prior to the construction of the Corpus Christi Intercoastal Canal Bridge, a comprehensive study was done at the Center for Highway Research at the University of Texas at Austin. The study included the development of an analysis computer program, SIMPLA2, and the construction as well as testing of a model of the bridge.

Brown et al. (1974) used the program SIMPLA2, developed by them, to do an analysis of the bridge. Only one of the two identical boxes was analyzed and the symmetry about the centreline of the main span was used to limit the analysis to one quarter of the total bridge. The elastic modulus for concrete was taken as 30.36 MPa (4403 ksi) and for steel as 200 MPa (29028 ksi). The wobble coefficient for prestressing steel was taken as 0.0002 and the friction factor as o.25. Their analysis does not include time-dependent effects.

As part of the same research program a one sixth scale model was built by Kashima and Breen (1975). The division into segments and the construction sequence were the same as that for the prototype (Fig.2). The modulus of elasticity of the concrete was found to be between 30.8 MPa (4458 ksi)·and 31.5 MPa (4563 ksi) and the average Poisson's ratio was o.184.

Van Zyl and Scordelis (1978) used the program SEGAN, developed by them, to perform an analysis of the same bridge. The analysis was done on one quarter of the total structure by taking advantage of symmetry. The assumed cross-section is shown in Fig. 3c. Division into segments was the same as used in the prototype (Fig.4) with the exception that all tendons were considered to be located in the webs. In the analysis, 35 elements were used. Nodal points were as marked in Fig. 4. Segments were considered to be 30 days old at the time of erection and were erected in pairs with a five-day interval between erection of two pairs. Time-dependent material data was based on the ACI recommendations ACI Committee 209, 1970) using a 28-day compressive strength of 55 MPa (8Ksi), ambient relative humidity of 4% and a constant temperature of 20° C (68° F). Tendons were stressed to the three-fourth of their ultimate strength.

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As part of the present study an analysis was done on one quarter of the same bridge by taking data similar to those of Van Zyl and Scordelis (1978). A comparison of deflection obtained in the present study was made with those obtained by experiment (Kashima and Breen, 1975), softwares SIMPLA2 (Brown et al., 1974) and SEGAN (Van Zyl and Scordelis, 1978) in Fig. 6. As reported by Van Zyl and Scordelis (1978), no results were available for the prototype, but the experimental results were considered by them to be a fair representation.

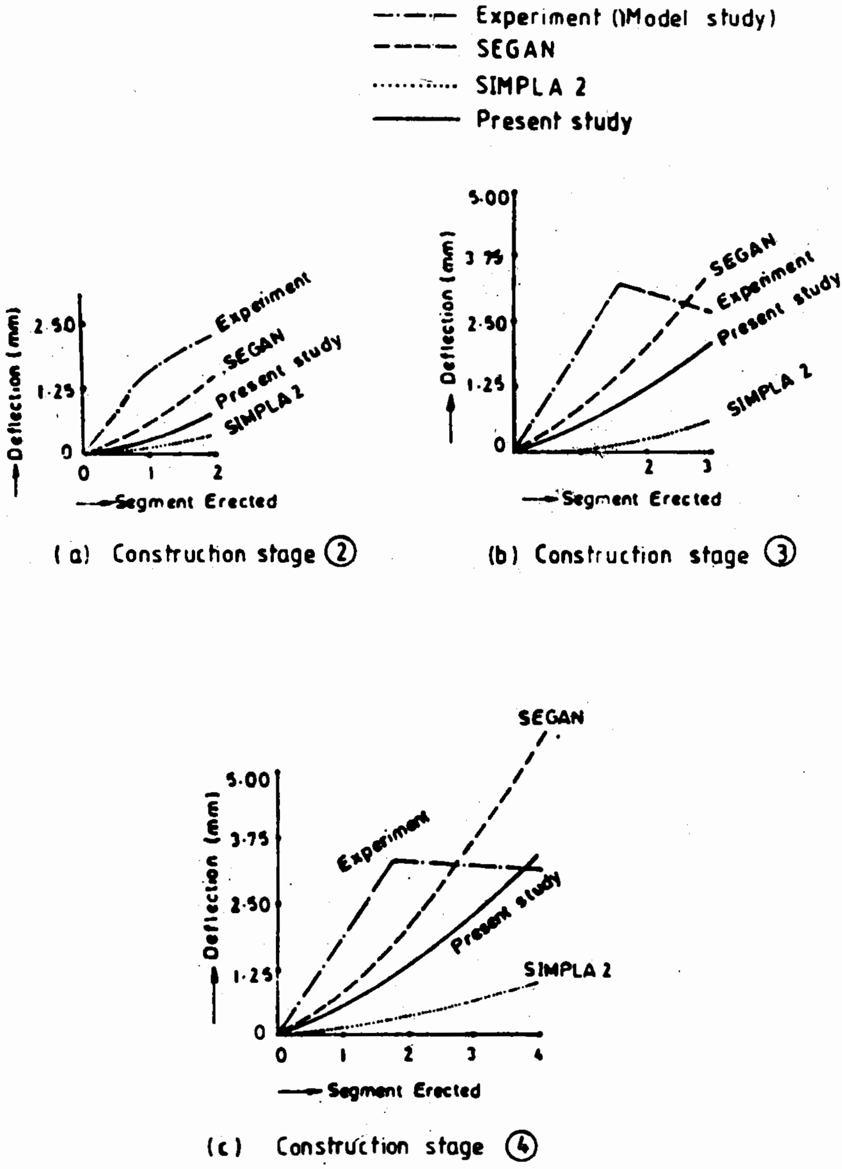
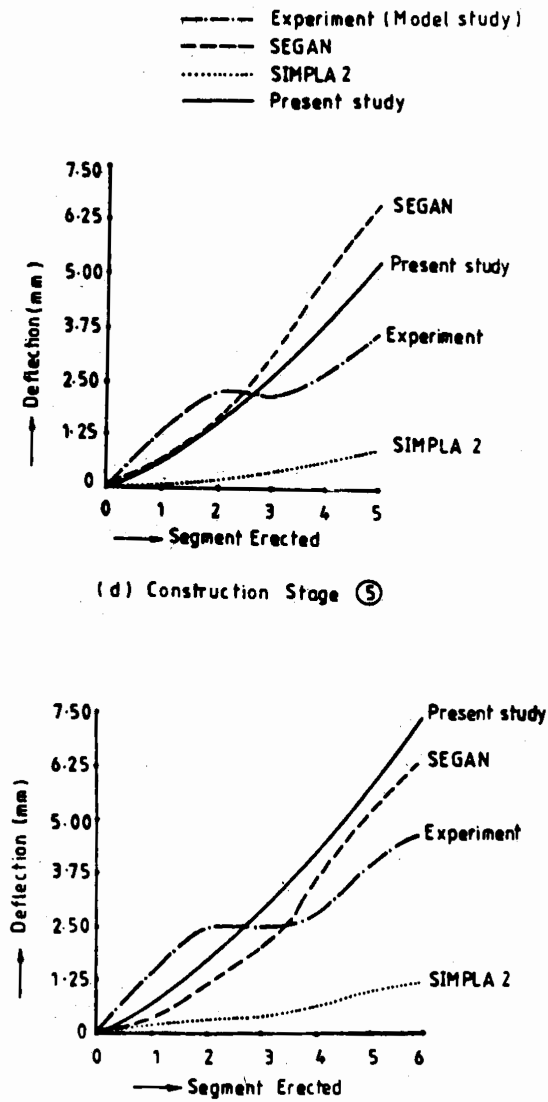


Fig 6. Deflection of Corpus Christi Intercoastal Canal Bridge at Various Stages of Construction



(e) Construction Stage ⑥

Fig 6. Deflection of Corpus Christi Intercoastal Canal Bridge at Various Stages of Construction (contd.)

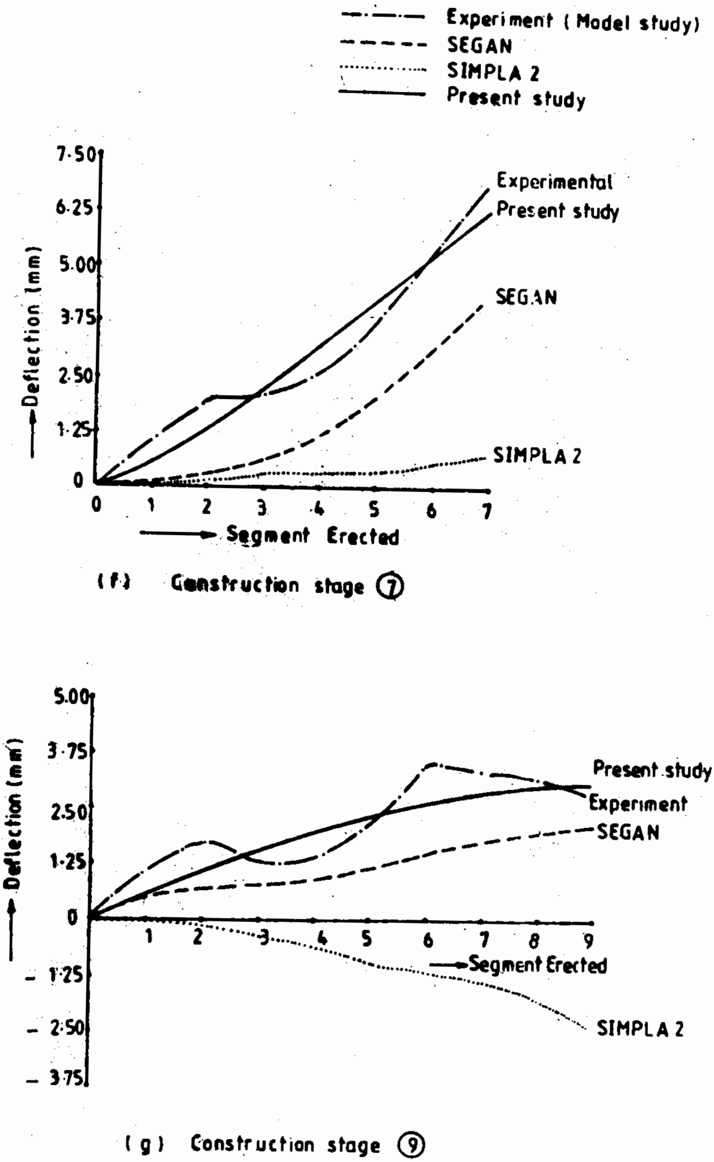


Fig 6. Deflection of Corpus Christi Intercoastal Canal Bridge at Various Stages of Construction (contd.)

From Fig. 6a it can be seen that present study gives results similar to those obtained by using SEGAN and SIMPLA2. Present study gives lower values than those of SEGAN and experiment but higher values than that of SIMPLA2 do. Similar pattern continues up to construction stage 4 (Fig. 6b and Fig. 6c).

In construction stages 5 (Fig, 6d) and 6 (Fig.6e), closer agreement was observed among the results obtained by using SEGAN, experiment and present study. At these stages of construction, present study and SEGAN give similar results. But experimental results are higher up to segment number two and after that they are lower than those obtained by SEGAN and present study. SIMPLA2 gives values, which are the lowest among the values obtained by four methods,. This may be due to the fact that SIMPLA2 does not include time-dependent effects in the analysis.

In construction stages 7 (Fig, 6f) and 9 (Fig. 6g), the results of the present study best fit with those of the experiment. Though the results of the present study are slightly higher than those obtained by using SEGAN, the two curves show similar pattern. Experimental results do not show any regular pattern. This may be due to the variation of prestressing jacking force, material properties, quality control and such other factors related to human error, In construction stage 9 (Fig. 6g), SIMPLA2 gives negative values of deflection. It may be attributed to the prestressing force application without considering the time-dependent creep and shrinkage effects. So it can be concluded that cxclusion of time-dependent effect cannot give accurate profile of the bridge during construction.

From the figures, it can be observed that the correlation among the deflection values of SEGAN, experiment and present study is fairly good. The maximum difference at any stage is only about 3.81 mm (0.15 inches) on an 18.3 m (60ft) cantilever which is an extremely small quantity, considering the magnitude of loads applied. It may be noted that the closer agreement among the results is obtained as the construction progresses towards completion.

CONCLUSIONS

The real problems encountered in the construction stages of segmentally erected concrere box girder bridges may conveniently be analyzed with acceptable accuracy by using the relatively simple analytical model presented in this paper. The program developed for the analysis of construction stages of segmentally erected concrete box girder bridges is fairly reliable, efficient and relatively faster as compared to the methods available in literature. The techniques used in this paper for prestressing and time dependent creep and shrinkage analyses give realistic represntations of these effects on displacements. The computer method presented in this paper would be useful to a designer for visualizing a reliable overall picture of the bridge at different stages of construction of segmentally erected concrete bridges. Inclusion of time-dependent effect in the analysis is essential for the design and construction of segmentally erected prestressed concrete bridges to maintain the correct profile of the bridge.

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NOTATION

A = cross-sectional area of member

[A] = member statics matrix

$[A]^T$ = transpose of statics matrix

d = depth of girder

e = axial deformation of member

e^H = initial axial deformation of member

E = modulus of elastictiy

F = axia force of a member due to temperature gradient

[F] = member flexibility matrix

I = moment of inertia

[K] = contribution of one member to the structure stiffness matrix

L = length of member

M_{AB} = moment at end A of member AB

M_{AB} = moment at end B of member AB

[S] = member stiffness matrix

{SR} = member stress resultants

T = axial force of member

T_1 = temperature at bottom of girder

T_2 = temperature at top of girder

T_{cg} = temperature at centroid of girder section

{W} = vector representing load at joints

{x} = member deformation vector

$\{X^H\}$ = initial strain vector of member

{X} = joint displacement vector

α = coefficient of thermal expansion

ϕ_{AB} =rotation at end A of member AB

ϕ_{AB}^H = initial slope at end A of member AB

ϕ_{AB} = rotation at end B of member AB

ϕ_{AB}^H = initial slope at end B of member AB