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Effects of Modeling on the Behavior of Prestressed Concrete System

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Abstract

This study deals with the modeling of prestressed concrete components and its effects on the behavior of the structure. Two cases are presented, i.e., simple vs continuous beams, and crossing of prestressed and reinforced concrete beams. Based on the findings in this study, the modeling has significant effects in prestressed concrete behavior. The effects might create serious problems on structural safety if not addressed properly in the analysis and design of prestressed concrete systems. As much as possible, it is best to design prestressed components as free-standing statically determinate systems, thereby avoiding the possibility of additional secondary stresses that may reduce the capacity of the designed member. To achieve the above goals, it is best to use a precast concrete system to build a prestressed concrete system.

Keywords: Prestressed concrete, bridge girder, modeling of components, effects of modeling

1. Introduction

It is known that concrete material has weaknesses in tensile strength due to the nature of concrete which often cracks under certain loading conditions. To overcome this condition, three types of concrete systems can be applied, namely reinforced concrete systems, composite concrete systems, and prestressed concrete systems [1-3]. In the first system, reinforcing steel bars are used to compensate for cracked areas in the tensile concrete section. In a system called a reinforced system (R/C), the crack area remains even though it has been replaced with steel bars. The amount of steel reinforcement is limited, usually up to about 2% for beams and up to 6% for columns. For a higher percentage of steel requirements, a concrete composite system (C/C) can be applied, where steel profiles can be embedded into the concrete. The amount of steel is almost the same as the amount of concrete. In this system, the crack area still exists.

The third sub-system is called prestressing concrete system (P/C) [4]. Prestressed concrete system can be defined as concrete that is given a compressive stress with a certain distribution and magnitude of stress so that it can neutralize an amount of tensile stresses caused by external loads [1]. There are two sub-systems in this system, i.e., pre-tensioning and post tensioning sub-systems. In the first sub-system, a high tensile strength wire or cable is stressed, and then the concrete is poured. After the concrete is hardened enough and connected with the cable along the periphery of the cable, then the cable is cut at its two ends. The cable then tends to return to its original shape, and this creates the compression in the concrete through bond between the cable and the concrete [5-7].

The second mechanical behavior of prestressed concrete system is to undergo upward displacement due to the negative bending moment exerted by prestressing force, called camber [8-9]. For example, the negative moment due to parabolic shape of a prestressing force in a simple supported beam is

$$M(x) = \frac{4\,x(L-x)}{L^2} F_e e_0 \tag{1}$$

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in which $M(x)$ is the negative bending moment at location measure from the left end, L is the beam span, F_e the efective prestressing force, and e_0 is the eccentricity of the cable at mid span. The upward uniformly distributed force corresponding to the above negative bending moment is

$$q_F = \frac{d^2M(x)}{dx^2} = -8\ \frac{F_e e_0}{L^2} \tag{2}$$

The third mechanical behavior of prestressing component is the tendency of the cable to return to its original shape, i.e., to perform shortening movement. This movement has to be allowed to happen, so as to let the cable to exert compression in the concrete. Based on the mechanical behavior of the prestressed components above, this study will discuss the effects of modeling on the behavior of the prestressed concrete system. From this study, it is hoped that it can provide recommendations for the design of prestressed concrete system components.

2. Prestressing of Concrete Component

The prestressing of a concrete component is carried out in stages. The process may be divided into four stages as follows [1], Stage 1: The prestressing force is carried out. Stage 2: The upward displacement due to the prestressing force occurs, and the own weight of the girder is active, Stage 3: The dead loads, i.e., own weight of the girder and the weight of superimpose components are active, and Stage 4: Service stage, all of external forces active. Generally, Stage 1 and 2 occur in relatively short of time: so, in design, only Stage 3 and Stage 4 are considered.

2.1 The beam is prestressed ahead of slab placement.

For the case where the beam is prestressed ahead of slab placement, in prestressing process, only the girder is in the process. In Stage 3, the stresses f_{3t} on top fiber and f_{3b} on bottom fiber of the beam at mid span are given by

$$f_{3t} = \frac{F_0}{A_g} + \frac{F_0 e_0}{A_g} y_t + \frac{M_d}{I_{gg}} y_t \geq 0;\ f_{3b} = \frac{F_0}{A_g} + \frac{F_0 e_0}{A_g} y_b + \frac{M_d}{I_{gg}} y_b \leq \bar{f_c} \tag{3}$$

in which F_0 is the initial prestressing force before losses, A_g is the area of girder concrete, e_0 is the eccentricity of prestressing cable at mid span, y_t and y_b respectively are the distance of top and bottom fibers from center of gravity of section, M_d is the dead load moment, and $\bar{f_c}$ is the alowable compression stress. Equation (3) implies that no tensile stress is allowed at top fiber of concrete at Stage 3.

In Stage 4, the stresses f_{4t} on top fiber and f_{4b} on bottom fiber of the beam at mid span are given by

$$f_{4t} = \frac{F_e}{A_t} + \frac{F_e e_0}{A_g} y_t + \frac{M_t}{I_{tt}} y_t \leq \bar{f_c}\ ;\ f_{4b} = \frac{F_e}{A_t} + \frac{F_e e_0}{A_g} y_b + \frac{M_t}{I_{tt}} y_b \geq 0 \tag{4}$$

in which F_e is the effective prestressing force after all losses, M_t is the total moment due to own weight of girder, superimposed dead load and live load, A_t and I_{tt} respectively are the area and moment of inertia of total section, i.e., girder and slab. Equation (4) implies that no tension is allowed at bottom fiber at Stage 4.

2.2 The beam and slab prestressed as one system.

For this case, in prestressing process, the girder and the slab are involved in the process. In Stage 3, the stresses f_{3t} on top fiber and f_{3b} on bottom fiber of the beam at mid span are given by

$$f_{3t} = \frac{F_0}{A_t} + \frac{F_0 e_0}{A_t} y_t + \frac{M_d}{I_{tt}} y_t \geq 0;\ f_{3b} = \frac{F_0}{A_t} + \frac{F_0 e_0}{A_t} y_b + \frac{M_d}{I_{tt}} y_b \leq \bar{f_c} \tag{5}$$

Equation (5) implies that no tensile stress is allowed at top fiber of concrete at Stage 3. In Stage 4, the stresses f_{4t} on top fiber and f_{4b} on bottom fiber of the beam at mid span are given by

$$f_{4t} = \frac{F_e}{A_t} + \frac{F_e e_0}{A_g} y_t + \frac{M_t}{I_{tt}} y_t \leq \bar{f}_c; \;\; f_{4b} = \frac{F_e}{A_t} + \frac{F_e e_0}{A_g} y_b + \frac{M_t}{I_{tt}} y_b \geq 0 \tag{6}$$

The two methods mentioned above have the same applicability in the design process. However, the two methods have some differences, among others, are as follows. The first method requires smaller prestressing force compared to the second method. In the second method, the presence of the slab moves the center of gravity of cross section slightly upward, making the top fiber understressed in Stage 4. In the first method, only the girder web is prestressed, while in the second method, all of girder and the slab are prestressed.

Prestressed concrete systems often to be constructed as precast components due to some beneficial reasons. First is the stressing of the cable, that may be carried easier if the component is stressed while the component still being as separated element. The precast practice also ensures better quality of obtained concrete that poured and hardened in fully strict supervision in a plant. But the most fruitful is the fact that stressing separate component ensures the fulfilment of the mechanical properties of the prestressed concrete system mentioned above.

Since a prestressed concrete system is a system that sensitive to the movement, then the exact conditions of supports need to be investigated and determined properly. There happened some cases in which crossing points of prestressed beam with several reinforced concrete beams were considered as fixed supports for the prestressed concrete beam and also for the crossing reinforced concrete beams. In fact, those points moved upward due to the nature of the prestressed concrete beam. The upward movement created secondary tensile stresses in crossing R/C beams which eventually exhibited cracks.

On the other hand, a prestressed concrete system with the two ends connected to a relatively fixed conditions, such as connected to sturdy columns, experienced relatively large prestressing stress due to the constraints of the two ends created by that sturdy column. The prestressed concrete component received less stress and the component exhibited cracks.

As already discussed previously, the process of stressing may be applied on the beam alone, or on the girder and the slab as a total cross section. The choice in the method applied will significantly affect the stresses occurring in Stage 3 and Stage 4 of the prestressing process.

3. Modeling of Prestressed Concrete Components

Two cases of modeling system [10] and their effects on the mechanical properties of the prestressed concrete system are pesented as follows. First, problem of modeling of the statical indeterminacy prestressed concrete system. Secondly, case of prestressed concrete component crossing with reinforced concrete beam is described.

3.1 Continuous prestressed concrete beam

As opposed to simple supported beam, a continuous beam has some advantages, as well as disadvantages. The advantage is that the overall beam has longer total span. Another advantage is that the bending moment is smaller [2], i.e.,

$$M^{+}_{max} = \frac{1}{8} q L^2 \tag{7}$$

in simple supported beam, and

$$M^{-}_{max} = \frac{1}{8} q \left(\frac{L}{2}\right)^2 = \frac{1}{32} q L^2 \tag{8}$$

if the beam is given hinge support at mid span. Smaller bending moment reads smaller reinforcing bars and smaller prestressing force needed to overcome the bending moment. Unfortunately, the continuous beam case has some disadvantages in the case of prestressing system. The bending moment diagram has reentrant point (sharp change of direction) occuring at top of the middle support as seen in Fig. 1.

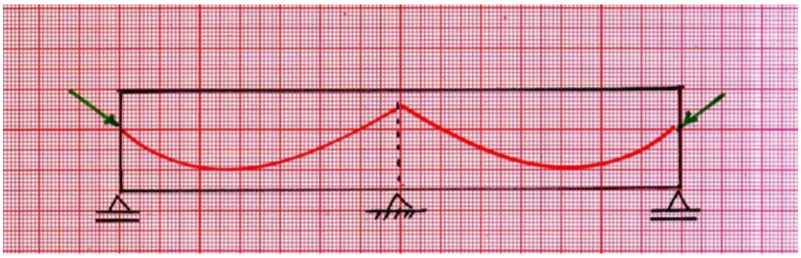

Fig. 1 Continuous prestressed concrete system

If the designer decides to use a continuous cable with an end clamped at one end and stretched only from another end, then the prestressing loss would be significantly large. In this case, the designer may choose a better design model by using two cables, with one end embedded on the setion of middle support, and the other end is stretched from the other end of the beam. In this model, the prestressing loss may be minimized.

3.2 Prestressed concrete beam crossing with reinforced concrete beam.

This kind of case oftenly happen when the designer concentrates more on the prestressed concrete beam itself, and pays less attention to the crossing reinforced concrete beam. The designer assumes that the crossing reinforced concrete beam is simply supported at the prestressing concrete beam. In fact, the prestressd concrete beam exhibits upward displacement, called camber, as mentioned already previously. This upward displacement certainly will create extra negative bending moment as secondary internal force, that are not considered in the design calculation of the crossing reinforced concrete beam.

Suppose that a prestressed concrete beam with span L_p and bending stiffnes EI_p crosses a reinforced concrete beam having span L_r and bending stiffness EI_r. The two beams crosses at their mid spans as shown in Fig. 2. The prestressing force F_e creates upward uniformly distributed force q_F in the prestressed concrete beam,

$$q_F = -\frac{8F_e e_o}{L_p^2} \quad (9)$$

The reaction force R between the beams and uniformly distributed force q_F then create displacement in the prestressed concrete beam as

$$\Delta_p = \frac{5F_e e_0 L_p^2}{48\, EI_p} - \frac{RL_p^3}{48\, EI_p} \quad (10)$$

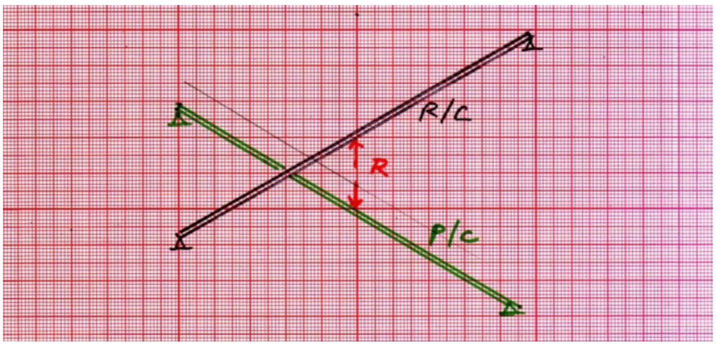

Fig. 2 Crossing of prestressed concrete and reinforced concrete beams

On the other hand, the displacement on the reinforced concrete beam is

$$\Delta_r = + \frac{RL_r^3}{48\,EI_r} \tag{11}$$

Consistency of the displacement states that

$$\Delta_p = \Delta_r \tag{12}$$

so that

$$\frac{5F_e e_0 L_p^2}{48\,EI_p} - \frac{RL_p^3}{48\,EI_p} = + \frac{RL_r^3}{48\,EI_r} \tag{13}$$

which eventually gives

$$R = \frac{5}{1+\frac{L_r^3}{L_p^3}} \frac{F_e e_0}{L_p} \tag{14}$$

The secondary negative moment in reinforced concrete beam mid span is

$$\Delta M_r = \frac{5}{4\left(1+\frac{L_r^3}{L_p^3}\right)} \frac{F_e e_0}{L_p} L_r \tag{15}$$

and secondary positive bending moment in prestressed concrete beam is

$$\Delta M_p = \frac{5}{4\left(1+\frac{L_r^3}{L_p^3}\right)} F_e e_0 \tag{16}$$

In the design process, the designer must not consider the crossing point of the two beams as fixed support for the respectively two beams. Suppose for example, $L_p = 20$ meters, $L_r = 8$ meters, $F_e = 10{,}000$ kN, and $e_0 = 0.5$ meter, then $\Delta M_r = 0.470\ F_e e_0 = 2350.0\ kN - m$: $\Delta M_p = 1.175\ F_e e_0 = 5875.0\ kN - m$, which are relatively large amounts that have to be considered in the design of both prestressed and reinfoced concrete beams.

4. Examples of Application

Some examples that numerically quantify the problematic cases are described in this section. This includes simple beam, continuous prestressed concrete beam and case of prestressed concrete beam crossing with reinforced concrete beam. The material of beams as follows. For concrete material, the material properties [11-12] are the characteristic compression strength, $f_c' = 60\ MPa$ (at service), the allowable compression, $\bar{f}_{cs} = 0.45\ f_c'$ (at service), $\bar{f}_{ct} = 0.60\ f_c'$ (at transfer), the allowable tension, $\bar{f}_{ts} = 0$, and the modulus of elasticity, E_s = 200,000 MPa. For steel, the following data and limitations are adopted. The allowable stresses are 0,94 f_{py} due to anchorage but not greater than 0.80 f_{ou} or that recommended by fabric; 0,82 f_{py} immediately after transfer of prestresses, but not greater than 0,74 f_{pu}; and $0.70 f_y$ for tendon in post tension system. The sign convention throughout the discussion, it is better to make a sign convention in describing the quantities involved as follows. The force or stress is given positive sign if it compresses the section, and negative if it pulls out the cross section. The moment is given positive sign if it causes compression at top fiber and tension at lower fiber and given negative sign if otherwise. The displacement or eccentricity is given positive sign if its direction is upward, and negative if otherwise.

The structural geometries are as follows. The total span of beam, L = 20 m, the cross section is $b\ x\ d$ = 0.40 m x 1.00 m (single span) and for continuous span is $b\ x\ d$ = 0.40 m x 0.5 m, the concrete cover is s = 0.10 m for single span and s = 0.05 m for continuous span, the girder space, S_g = 2 m, and the thickness of slab, t_s = 0.15 m.

The external forces are as follows [12]. The girder own weight is $q_g = 0.4\ x\ 1.0\ x\ 24 = 9.6\ kN/m$ for simple span and

$q_g = 0.4\,x\,0.5\,x\,24 = 4.8\,kN/m$ for continuous span. The superimposed dead load is $q_s = 0.15\,x\,24\,x\,2 = 7.2\,kN/m$, the live uniform load is $q_\ell = 9\,kPa\,x\,2 = 18$ kN/m, and the live point load is $P = 49\,x\,2 = 98\,kN$. The internal forces, the moments at mid span: the girder dead load moment is $M_g = \frac{1}{8} q_g L^2$, the dead load superimpose moment is $M_s = \frac{1}{8} q_s L^2$, the live uniform load moment is $M_\ell = \frac{1}{8} q_\ell L^2$, the live point load moment is $M_p = \frac{1}{4} P\,L$. The shear forces at support: the girder dead load shear force is $V_g = \frac{1}{2} q_g L$, the dead load superimpose shear force is $V_s = \frac{1}{2} q_s L$, the live uniform load shear force is $V_\ell = \frac{1}{2} q_\ell L$, and the live point load shear force is $V_p = \frac{1}{2} P$.

4.1 Analysis of post tension cross section, simple beam

As mentioned previously, the stages that control the design is Stage 3 and 4. At Stage 3, the dead load moment M_d consists only due to the own weight or the beam if the stressing of the cable is carried out before the placing of the superimposed dead loads. But it consists also superimposed load moment M_s if the stressing is carried out after superimposed loads are already at place. At Stage 3, the concrete stress f_{3t} at the top fiber and f_{3b} at lower fiber are given by,

$$f_{3t} = \frac{F_0}{A_c} + \frac{F_0 e}{I_{zz}} y_t + \frac{M_d}{I_{zz}} y_t \geq 0 \tag{17}$$

$$f_{3b} = \frac{F_0}{A_c} + \frac{F_0 e}{I_{zz}} y_b + \frac{M_d}{I_{zz}} y_b \leq \bar{f}_c \tag{18}$$

in which F_0 is the initial prestressing force, e is the eccentricity of the cable, M_d is the dead load moment, A_c is the area of concrete cross section, I_{zz} is the moment of inertia of section with respect to z –axis that passes through center of gravity of the section, y_t is the distance of the top fiber from center of gravity and y_b is the distance of lower fiber from center of gravity. For Stage 4, the controlling inequalities,

$$f_{4t} = \frac{F_e}{A_c} + \frac{F_e\, e}{I_{zz}} y_t + \frac{M_d}{I_{zz}} y_t + \frac{M_\ell}{I_{zz}} y_t \leq \bar{f}_c \tag{19}$$

$$f_{4b} = \frac{F_e}{A_c} + \frac{F_e e}{I_{zz}} y_b + \frac{M_d}{I_{zz}} y_b + \frac{M_\ell}{I_{zz}} y_b \geq 0 \tag{20}$$

in which F_e is the effective prestressing force after all prestressed losses have taken place, and M_ℓ is the moment due to the live load, and the total moment is $M_d + M_\ell = M_t$. The moment are

$$M_g = \frac{1}{8} x 9.6 x (20)^2 = 480.00\,kN - m;\;\; M_s = \frac{1}{8} x 7.2 (20)^2 = 360.00\,kN - m$$
$$M_\ell = \frac{1}{8} x 18 x (20)^2 = 900.00\,kN - m;\;\; M_p = \frac{1}{4} x 98 x (20) \quad = 490.00\,kN - m$$

so that

$$M_t = 2230\text{ kN} - \text{m}$$

Before the magnitude and the eccentricity of the cable are determined, the upper and lower limits of the layout of the cable are first determined. If for the time being, the tensile stress is not allowed to occur, then the lower limit is given as

$$e \geq -k_b - \frac{M_d}{F_0} \tag{21}$$

in which k_b is the lower bound of Kern region, and the upper limit is given as

$$e \geq -k_t - \frac{M_t}{F_0} \tag{22}$$

in which k_t is the upper bound of Kern region.

To compute for the prestressing force F and eccentricity e, rearrange equations (17) to (20) in the form of that used by Magnel diagram. Setting

$$\alpha_b = \frac{y_t}{I/A} = -\frac{1}{k_b} = +6.00\ m;\ \ \alpha_t = \frac{y_b}{\frac{I}{A}} = -\frac{1}{k_t} = -6.00\ m \tag{23}$$

get

$$\frac{1}{F_0} \le \frac{1+\alpha_b e_0}{A\bar{f}_t - \alpha_b M_g} \tag{24}$$

$$\frac{1}{F_0} \le \frac{1+\alpha_t t e_0}{A\bar{f}_c - \alpha_t M_g} \tag{25}$$

$$\frac{1}{F_e} \ge \frac{1+\alpha_b e_0}{A\bar{f}_c - \alpha_b M_t} \tag{26}$$

$$\frac{1}{F_e} \ge \frac{1+\alpha_t e_0}{A\bar{f}_t - \alpha_t M_t} \tag{27}$$

The Magnel diagram is shown in Fig. 3. In order to give smallest prestressing force and largest eccentricity, Equations (25) and (26) control. The intersection of the two lines gives,

$$F_0 = 5116\ kN, \qquad F_e = 0.85x\ \ 5116 = 4349\ kN;\ \ e_0 = -0.279\ m$$

The conditions of stress at Stage 3 are

$$f_{ct} = \frac{5116}{0.40} + \frac{(5116)\ (-0.279)(0.50)}{0.033} + \frac{(480)(0.50)}{0.033} = -1.57 \approx 0(ok)$$

$$f_{cb} = \frac{5116}{0.40} + \frac{(5116)(-0.279)(-0.50)}{0.033} + \frac{(480)(-0.50)}{0.033} = 27.15 \cong 27.00\ (ok)$$

The conditions of stress at Stage 4 are

$$f_{ct} = \frac{4349}{0.40} + \frac{(4349)\ (-0.279)(0.50)}{0.033} + \frac{(2230)(0.50)}{0.033} = 26.28 \le 27.00\ (ok)$$

$$f_{cb} = \frac{4349}{0.40} + \frac{(4349)(-0.279)(-0.50)}{0.033} + \frac{(2230)(-0.50)}{0.033} = -4.53\ \cong 0\ (ok)$$

Check the location of the prestressing cable as follows. Upper limit is

$$e \le +k_t - \frac{M_t}{F_e} = +0.167 - \frac{2230}{4349} = \ -0.346\ m$$

while the lower limit is

$$e \ge\ k_b - \frac{M_g}{F_0} = -0.167 - \frac{840}{5116} = -0.331\ m$$

so that

$$-0.346\ m\ \ge (e_0 = -0.279\ m) \ge -0.331\ m\ \ (ok)$$

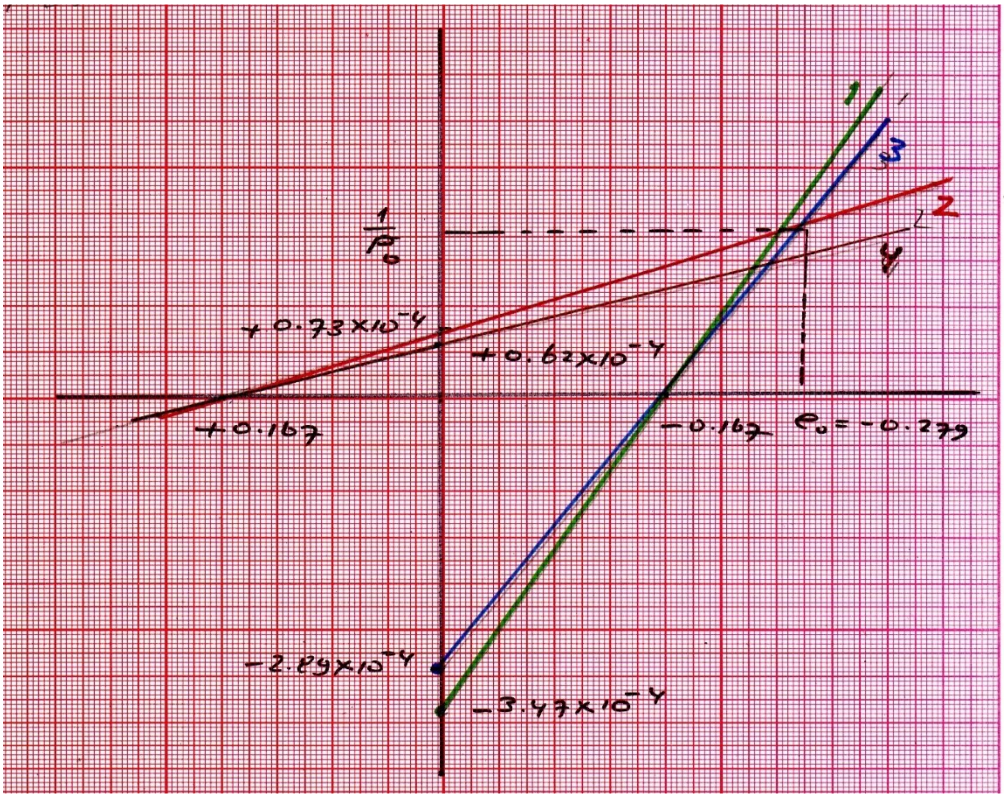

Fig. 3 Magnel diagram of the simple beam

4.2 Analysis of post tension cross section, continuous beam

For the continuous beam analysis (see Fig. 1 as explanation), the moments are

$$M_g = \tfrac{1}{8} x 9.6 x (10)^2 = 120.00\ kN - m;\ \ M_s = \tfrac{1}{8} x 7.2 (10)^2 = \ \ 90.00\ kN - m$$

$$M_\ell = \frac{1}{8} x 18 x (10)^2 = 225.00\ kN - m;\ M_g = \frac{3}{16} x 98 x (10) \ \ = 183.75\ kN - m$$

so that

$$M_t = 618.75 \text{ kN} - \text{m}$$

Setting

$$\alpha_b = \frac{y_t}{I/A} = -\frac{1}{k_b} = +12.00\ m;\ \ \alpha_t = \frac{y_b}{\frac{I}{A}} = -\frac{1}{k_t} = -12.00\ m$$

The Magnel diagram is shown in Fig. 4 and the intersection of the two lines gives,

$$F_0 = 2230\ kN, \qquad F_e = 0.85x\ 2230 = 1895\ kN;\ \ e_0 = -0.172\ m$$

The conditions of stress at Stage 3 are

$$f_{ct} = \frac{2230}{0.200} + \frac{(2230)\ (-0.172)(0.25)}{0.00417} + \frac{(120)(0.25)}{0.00417} = -4.62 \cong 0\ (ok)$$

$$f_{cb} = \frac{2230}{0.200} + \frac{(2230)(-0.172)(-0.25)}{0.00417} + \frac{(120)(-0.25)}{0.00417} = 26.92 \leq 27.00\ (ok)$$

The conditions of stress at Stage 4 are

$$f_{ct} = \frac{1895}{0.200} + \frac{(1895)\ (-0.172)(0.25)}{0.00417} + \frac{(618.75)(0.25)}{0.00417} = 27.04 \cong 27\ (ok)$$

$$f_{cb} = \frac{1895}{0.200} + \frac{(1895)\ (-0.172)(-0.25)}{0.00417} + \frac{(618.75)(-0.25)}{0.00417} = -8.08\ \cong 0\ (ok)$$

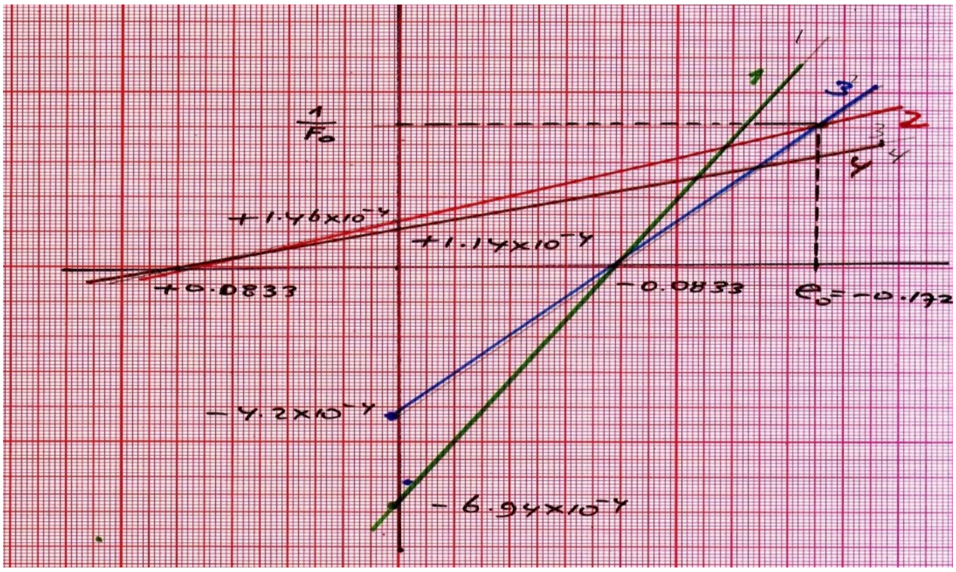

Fig. 4 Magnel diagram for the continuous beam

4.3 Analysis of prestressed concrete beam crossing with reinforced concrete beam.

Suppose that a prestressed concrete beam with span $L_p = 20\ m$ and the cross section dimension is b x d = 0.40 m x 1.0 m, crosses a reinforced concrete beam having span $L_r = 8\ m$ and the dimension b x d = 0.25 x 0.40 m. The two beams crosses at their mid spans. See Fig. 2 as explanation. In the design process, the designer must not consider the crossing point of the two beams as fixed support for the respectively two beams. The prestressing force and eccentricity are obtained previously as $F_e = 4349\ kN$, and $e_0 = -0.279$ meter, then

$$\Delta M_r = 0.470\ F_e e_0 = 0.470x4349x0.279 = \ 570.28\ kN - m;$$

$$\Delta M_p = 1.175\ F_e e_0 = 1.175x4349x0.279 = 1425.71\ kN - m$$

The total moment in prestressed concrete beam is 2230 kN-m; so, the additional moment in prestressed concrete beam is 1425.71x100%/2230 = 63.93 %, which is relatively large amount of additional moment that has to be considered in the design of the prestressed concrete beam. Crack would also happen in the reinforced concrete beam.

5. Conclusions

Based on the findings in this study, there are several conclusions that can be drawn as follows. When modeling a prestressed concrete system during designing work, the mechanical properties of the prestressed concrete system must be carefully considered so that problems do not occur in the field. Whenever possible, it is best to design prestressed components as free-standing statically determinate systems, thereby avoiding the possibility that additional secondary stresses could reduce the capacity of the designed structural component. To achieve the above intention, it is best to use a precast concrete system to build a prestressed concrete system.

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