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Determination of prestressing forces in statically indeterminate structures

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Determination of Prestressing Forces in Statically Indeterminate Structures

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Abstract

This paper discusses the determination of prestressing force in statically indeterminate structures, where the prestressing force produces a secondary moment in addition to the primary moment. This condition is different from statically determinate ones as there is no secondary moment. In this paper the moment due to prestressing force is assumed to be a direct function of the prestressing force multiplied by a coefficient-β thus the prestressing force is obtained from the stress conditions of the bottom and top fibres under external loading. To show the application of the proposed procedure, a three-storey building is taken as an example.

Keywords: prestressed concrete, statically indeterminate structures, primary moment, secondary moment, moment coefficient, prestressing force.

1 Introduction

Prestressed concrete structures have become an alternative way of design in order to obtain sophisticated and economical structures particularly for long span concrete structures. With the simple principles to give compression to the concrete so that during the service load the tensile stress will be eliminated while limiting the compressive stress within the prescribed value, prestressed concrete has become an attractive approach in concrete structures design. However, some difficulties may arise in designing prestressed concrete members for statically indeterminate structures. This is due to the presence of secondary moment when the prestressing force is applied [1]-[3]. The interaction between the secondary moment and the magnitude of prestressing force produces more challenging tasks, because the magnitude of the secondary moment might be significantly large enough and cannot be neglected.

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Keywords: prestressed concrete, statically indeterminate structures, primary moment, secondary moment, moment coefficient, prestressing force.

Prestressed concrete structures in most cases have become an alternative way of design in order to obtain sophisticated and economical structures. With the simple principles to give compression to the concrete so that during the service load the tensile stress will be eliminated while limiting the compressive stress within the prescribe value, prestressed concrete has become an attractive strategy for the design of concrete structures. However, some difficulties may arise in designing prestressed concrete members for statically indeterminate structures. This is due to the presence of a secondary moment when the prestressing force is applied [1–3]. The interaction between the secondary moment and the magnitude of prestressing force produces more challenging tasks, because the magnitude of the secondary moment might be significantly large enough and cannot be neglected.

When Lin's load balancing method [1] is used some conditions should be satisfied. First, the cable profile is assumed to be a curve or parabolic in each span of the member with no smooth transition. Therefore, the drastic change in the cable profile in continuous support is neglected in the computation so that the prestressing force can balance a part of the external loading in every span of the member. Besides this we cannot have cable eccentricities at the end supports as those eccentricities produce additional moments. This condition results in that when the prestressing force is obtained by using load balancing method, we have to check the stress to account for those two conditions. Another method to handle the secondary moment is by designing the cable profile so that the cable is coincident, i.e., the C-line coincides with the T-line, for the case without external loading. However, obtaining such profiles is not an easy task.

In this paper a simple procedure to obtain the magnitude of prestressing force in statically indeterminate concrete elements is proposed. By assuming that the total moment due to the prestress as a linear function of the magnitude of the prestressing force, as a moment coefficient, and employing the relationships between stress limitation, the magnitude of prestressing force can be obtained. The inequality equations can then be solved by defining the lower and upper bounds of the prestressing force so that when such prestressing force is applied to the members, the stress will be in the prescribed limit with the secondary moment taken into account. With this procedure the determination of the prestressing force will be simple. In addition, this method can be considered as a general procedure that can be used either for statically determinate or indeterminate structures. In statically determinate prestressed concrete structures the value of secondary moment would be zero. The economical design is achieved when the difference between the lower and the upper magnitudes of the prestressing force is small. Thought in a different way the difference between the lower and upper bound magnitudes of prestressing force defines the degree of safety. Numerical examples are then carried out to show the simplicity of the proposed design procedure.

References

[1] T.Y. Lin, "Design of prestressed concrete structure", John Wiley & Sons, N.Y.,1963.
[2] A. Naaman, "Prestressed concrete analysis and design", McGraw-Hill Book Company, N.Y, 1982.
[3] J.R. Libby, "Modern prestressed concrete: design principles and construction methods", Van Nostrand Reinhold, N.Y., 1977.

When Lin's load balancing method [1] is used some conditions should be preserved. First, the cable profile is assumed curved or parabolic in each span of the member with no smooth transition. Therefore, the drastic changes in the cable profile in continuous support are neglected in the computation so that the prestressing force can balance part of the external loading in every span of the member. Besides that we cannot have cable eccentricities at the end supports as those eccentricities produce additional moments. This condition results in that when the prestressing force is obtained by using the load balancing method, we have to check the stress to account for those two conditions.

Another method to handle the secondary moment is by designing the cable profile so that the cable is concordant, i.e., the C-line coincides with the T-line, in the case without external loading [2][3]. However, obtaining such profiles is cumbersome.

In this paper a simple procedure to obtain the magnitude of prestressing force in statically indeterminate concrete elements is proposed. By assuming that the total moment due to prestress as a linear function of the magnitude of prestressing force, and employing the relationships between stress limitation, the magnitude of the prestressing force can be obtained. The inequality equations can then be solved by defining the lower and upper bounds of the prestressing force so that when such a prestressing force is applied to the members, the stress will be in the prescribed limit with the secondary moment has been taken into account. With this procedure the determination of the prestressing force will be simple. In addition, this method can be considered as a general procedure that can be used either for statically determinate or indeterminate structures. In statically determinate prestressed concrete structures, the value of the secondary moment would be zero. It is to be noted that the economical design will be accomplished when the difference between the lower and the upper magnitudes of prestressing force is small. Thought in a different way the difference between the lower and upper bound magnitudes of prestressing force defines the "degree of safety".

2 The Effect of Prestressing Force

The effect of prestressing force on the statically determinate structures can be explained with reference to Figure 1. In Figure 1 the trajectory of tendon is assumed parabolic with no eccentricity at both end. If the curvature of the trajectory is assumed to be small then:

the vertical component of the prestressing force equals to $F \sin \theta = F\theta$,

the horizontal component of the prestressing force equals to $F \cos \theta = F$,

where θ = angle between tendon's trajectory and centre gravity of section at end.

Moment due to the eccentricity of the tendon to the centre of gravity of the section at any point

$$M_1 = F \times e \tag{1}$$

The moment diagram can be seen in Figure 1c. The transverse equivalent load due to prestressing is generated due to the eccentricity along the beam's span. If the tendon's trajectory is curved it produces an equivalent uniform load = q to the beam. The total load should be the same as the vertical component of prestressing at ends of beam. The equilibrium of vertical forces results in $q \times L = 2 \times F\theta$ so that

$$q = \frac{2F\theta}{L} \tag{2}$$

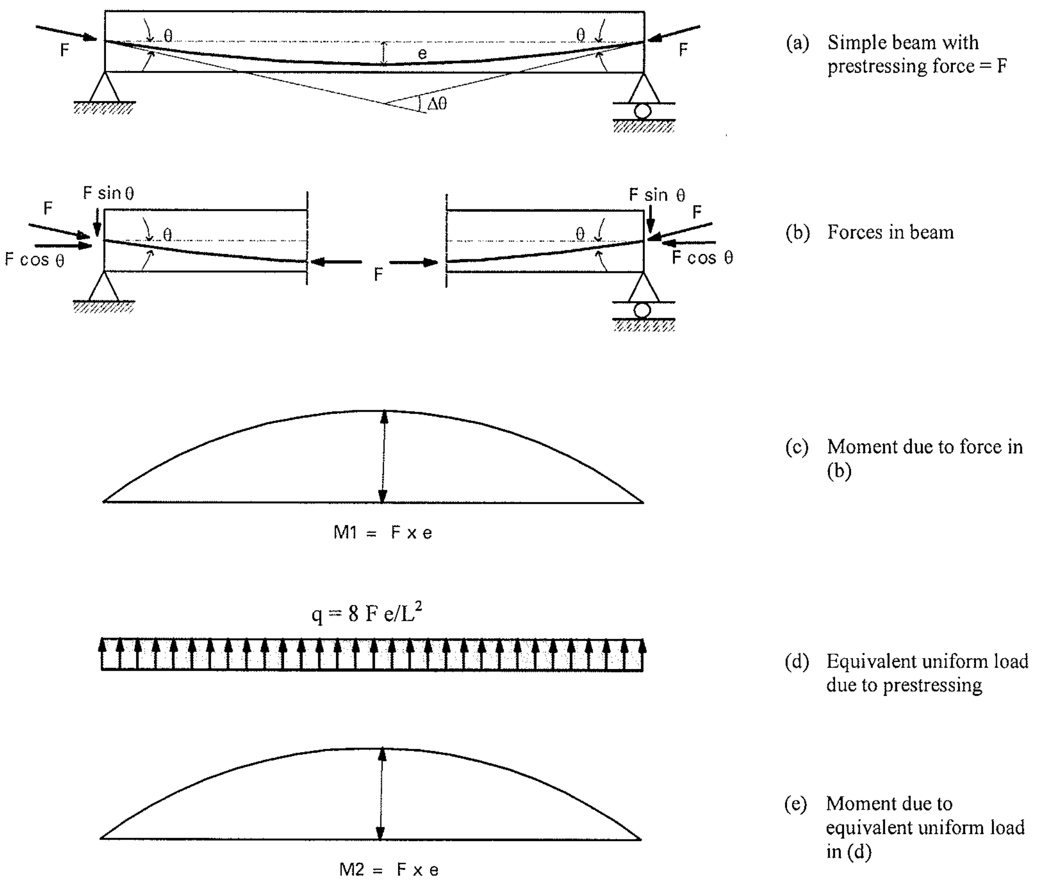


Figure 1: Effect of prestressing force in statically determinate structures

If the tendon trajectory is assumed parabolic, the ordinate of the tendon can be expressed as

$$y = \frac{4ex(L-x)}{L^2} \tag{3}$$

The angle θ becomes

$$\theta = \left(\frac{dy}{dx}\right)_{x=0} = \frac{4e}{L} \tag{4}$$

The uniform load in Equation (2) becomes

$$q = \frac{8Fe}{L^2} \tag{5}$$

Moment due to equivalent uniform load in the middle span is

$$M_2 = \frac{qL^2}{8} = Fe \tag{6}$$

It can be seen that the effect of prestressing force produces the same results as whether it is considered as uniform load or horizontal force. There is no difference between M_2 and M_1.

These results will be different for a statically indeterminate structure. Consider for example a beam with fixity at both ends against rotation, but, allowed to move in the horizontal direction as shown in Figure 2. The tendon trajectory is assumed parabolic as in the case for a simple beam. The moment due to the prestressing and eccentricity are as follows:
At beam end:

$$M_1 = 0 \tag{7a}$$

At midspan

$$M_1 = F \times e \tag{7b}$$

The moment diagram is shown in Figure 2(b). The moment due to an equivalent load is as follows:
At beam ends:

$$M_2 = \frac{qL^2}{12} = \frac{2}{3}Fe \tag{8a}$$

At midspan:

$$M_2 = \frac{qL^2}{24} = \frac{1}{3}Fe \tag{8b}$$

The moment diagram is shown in Figure 2(c). From Figures 2(b) and 2(c) it can be seen that the moment produces by prestressing force multiplied by eccentricity is different from the moment due to the equivalent load. As usually the stresses in beams are computed based on the moment due to the eccentricity, there is an additional moment that should be added to the computation. This moment is called the secondary moment which is obtained by subtracting the moment M_2 from M_1:

$$M_s = \Delta M = M_2 - M_1 \tag{9}$$

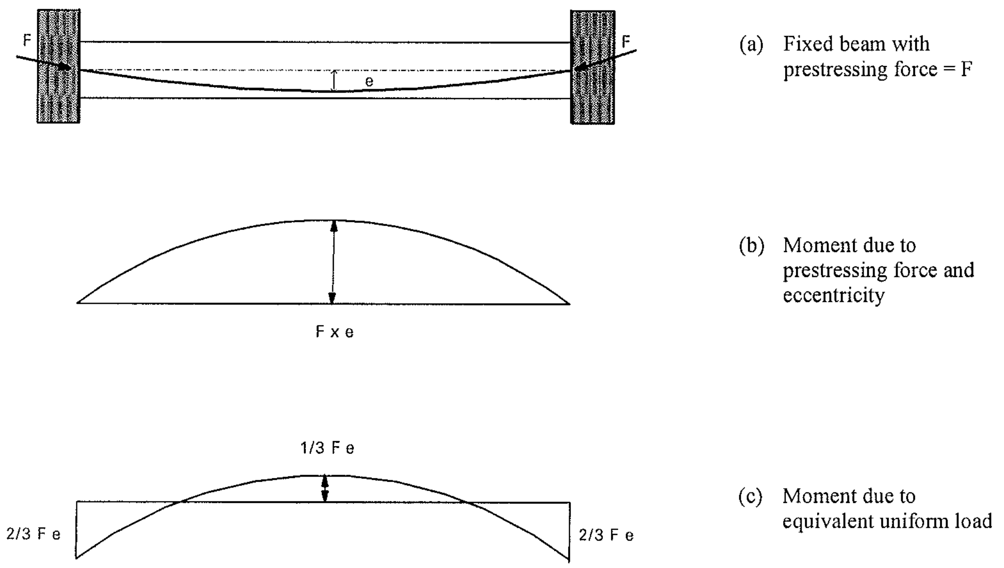


Figure 2: Effect of prestressing force in statically indeterminate structures

By considering the C-line (the line of action of the compression concrete) and T-line (line of action of the tension force in prestressing steel) concepts, it means that in the statically indeterminate structures in general the C-line does not coincidence with the T-line. The shift of C-line and T-line can be calculated by

$$a = \frac{M_s}{F} = \frac{\Delta M}{F} \qquad (10)$$

where M_s = the secondary moment.

Due to the presence of the secondary moment in statically indeterminate structures, the design becomes more complex. One of the methods to avoid this is by using load balancing method [1]. However, there are some limitations on using this method. One limitation is that there is no smooth transition in the support for the case of continuous support. In addition in order to cancel the secondary moment there should be no eccentricity at the beam ends. Therefore, the load balancing method is more appropriate to be used for statically determinate structures. Another method to avoid of calculating the secondary moment is by designing a concordant cable, where the C-line is designed to coincide with the T-line in the case of zero external loading. However, the design process becomes more complex.

3 Coefficient-β Method

In this paper the determination of prestressing force in statically indeterminate structures is obtained through the introduction of the moment coefficient due to prestressing force as β, i.e., the moment due to prestressing force is

$$M_F = \beta F \qquad (11)$$

Assuming that the structure is linear elastic we can obtain

$$M_{Fi} = \beta F_i \qquad (12)$$

where M_{Fi} = moment due to prestresssing force at initial (transfer), F_i = prestressing force at transfer where the effective force.

At the final condition after loss of prestress

$$F = \alpha F_i \qquad (13)$$

α = effective prestress coefficient after loss of prestress.

To obtain the moment due to prestressing some assumptions are taken as follows:

(a) Cable eccentricity is small compared to the beam span;
(b) Loss of prestress due to cable friction is neglected;
(c) The number of cables is the same through the span length.

The determination of the equivalent load due to prestresing can be made with reference to Figure 3.

End A:

Horizontal load = $F\cos\theta_1 \approx F$,
Vertical load = $F\sin\theta_1 \approx F\theta_1$.

Span AB:
Vertical load point load = $F\theta_2$,
Vertical uniform load = $F\theta_3$.

Span BC:
Vertical uniform load 1= $F\theta_3$,
Vertical uniform load 2 = $F\theta_4$.

End C:
Horizontal load = $F\cos\theta_5 \approx F$,
Vertical load = $F\sin\theta_5 \approx F\theta_5$,
Moment = Fe.

With the equivalent load on beam due to prestressing, internal forces in beam can be obtained. The secondary moment can be computed by subtracting the moment due to the equivalent load by the primary moment.

By assuming that:
(a) compression stress in the concrete is negative (-);
(b) positive moment when the bottom fibre is in tension;
(c) prestressing force F and F_i is assigned to be positive in the equation;
the stress in beam shall satisfy the provision provided in the building code as follows. At transfer (initial condition):

At the top fibre:
If the stress results in tension:

$$-\frac{F_i}{A_c} - \frac{M_{Fi}\, y_t}{I_c} - \frac{M_{DL}\, y_t}{I_c} < \sigma_{ti} \tag{14a}$$

If the result is compression:

$$-\frac{F_i}{A_c} - \frac{M_{Fi}\, y_t}{I_c} - \frac{M_{DL}\, y_t}{I_c} > \sigma_{ci} \tag{14b}$$

where A_C= area of section, I_c = second moment area, y_t = neutral axis distance to top fibre, M_{DL} = moment due to dead load, σ_{ti} = allowable tension stress in concrete at transfer, σ_{ci} = allowable compression stress in concrete at transfer,

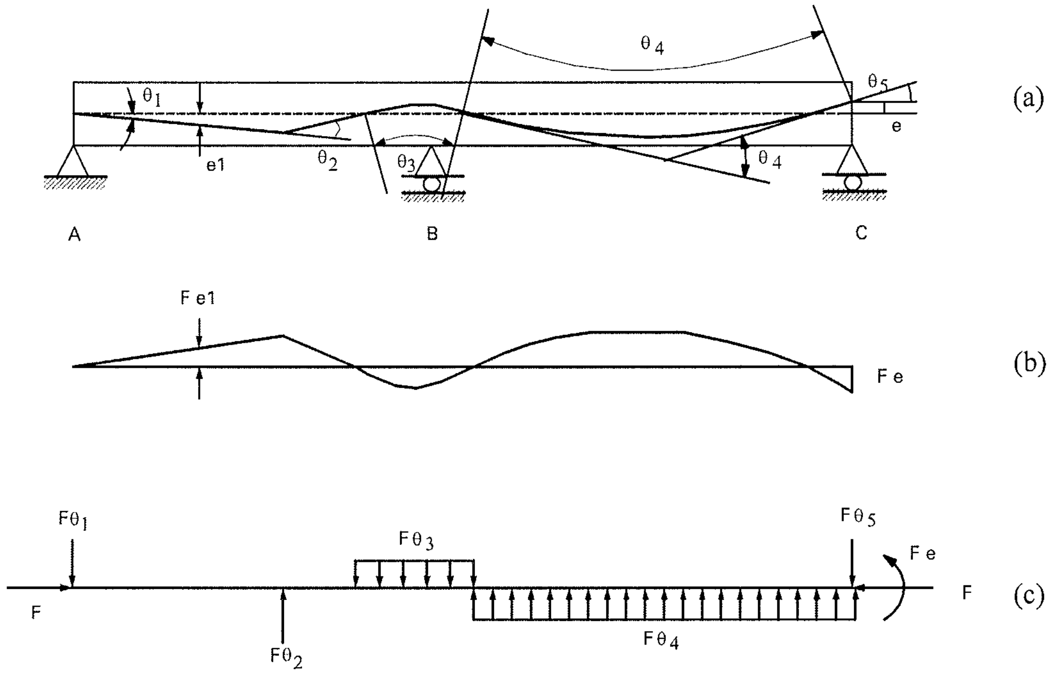


Figure 3: Computation of equivalent load and primary moment in beam: (a) beam with cable profile, (b) primary moment, (c) equivalent load due to prestressing

At bottom fibre:
If the stress results in tension:

$$-\frac{F_i}{A_c}+\frac{M_{Fi}\,y_b}{I_c}+\frac{M_{DL}\,y_b}{I_c}<\sigma_{ti} \qquad (15a)$$

If the result is compression:

$$-\frac{F_i}{A_c}+\frac{M_{Fi}\,y_b}{I_c}+\frac{M_{DL}\,y_b}{I_c}>\sigma_{ci} \qquad (15b)$$

where y_b = neutral axis distance to bottom fibre.

At the final stage (after loss of prestress) the following conditions shall be satisfied.

At top fibre:
If the result is tension:

$$-\frac{F}{A_c}-\frac{M_F\,y_t}{I_c}-\frac{M_{TL}\,y_t}{I_c}<\sigma_t \tag{16a}$$

If the result is compression:

$$-\frac{F}{A_c}-\frac{M_F\,y_t}{I_c}-\frac{M_{TL}\,y_t}{I_c}>\sigma_c \tag{16b}$$

σ_t = allowable tension stress at the final condition, and σ_c = allowable compression test at the final condition.

At bottom fibre:

If the result is tension:

$$-\frac{F}{A_c}+\frac{M_F\,y_b}{I_c}+\frac{M_{TL}\,y_b}{I_c}<\sigma_t \tag{17a}$$

If the result is compression:

$$-\frac{F}{A_c}+\frac{M_F\,y_b}{I_c}+\frac{M_{TL}\,y_b}{I_c}>\sigma_c \tag{17b}$$

In order to obtain the magnitude of prestressing force that satisfies all conditions and by noting that

$$r=\sqrt{\frac{I}{A}} \tag{18}$$

$$Z_t=\frac{I_c}{y_t} \tag{19}$$

$$Z_b=\frac{I_c}{y_b} \tag{20}$$

Equations (14) – (17) are rearranged as follows:

By considering Equations (12), (18) and (19) the stress condition at the top fibre in Equation (14a) may be written as

$$F_i\left(-\beta-\frac{r^2}{y_t}\right)<\sigma_{ci}\,Z_t+M_{DL} \tag{21}$$

so that we have the following conditions:

If $\left(-\beta - \frac{r^2}{y_t}\right) > 0$ the inequality in Equation (21) becomes

$$F_{i\max} = \frac{\sigma_{ti} Z_t + M_{DL}}{\left(-\beta - \frac{r^2}{y_t}\right)} \tag{22a}$$

If $\left(-\beta - \frac{r^2}{y_t}\right) < 0$, the inequality in Equation (21) becomes

$$F_{i\min} = \frac{\sigma_{ti} Z_t + M_{DL}}{\left(-\beta - \frac{r^2}{y_t}\right)} \tag{22b}$$

Similarly from Equation (14b) we can obtain

If $\left(-\beta - \frac{r^2}{y_t}\right) > 0$:

$$F_{i\min} = \frac{\sigma_{ci} Z_t + M_{DL}}{\left(-\beta - \frac{r^2}{y_t}\right)} \tag{23a}$$

If $\left(-\beta - \frac{r^2}{y_t}\right) < 0$:

$$F_{i\max} = \frac{\sigma_{ci} Z_t + M_{DL}}{\left(-\beta - \frac{r^2}{y_t}\right)} \tag{23b}$$

On the other hand, from the condition of stress at the bottom fibre at transfer in Equation (15a) and by using Equations (18) and (20) we can obtain:

If $\left(\beta - \frac{r^2}{y_b}\right) > 0$:

$$F_{i\max} = \frac{\sigma_{ti} Z_b - M_{DL}}{\left(\beta - \frac{r^2}{y_b}\right)} \tag{24a}$$

If $\left(\beta - \frac{r^2}{y_b}\right) < 0$:

$$F_{i\,min} = \frac{\sigma_{ti} Z_b - M_{DL}}{\left(\beta - \frac{r^2}{y_b}\right)} \tag{24b}$$

Similarly, from Equation (15b) we can obtain

If $\left(\beta - \frac{r^2}{y_b}\right) > 0$:

$$F_{i\,min} = \frac{\sigma_{ci} Z_b - M_{DL}}{\left(\beta - \frac{r^2}{y_b}\right)} \tag{25a}$$

If $\left(\beta - \frac{r^2}{y_b}\right) < 0$:

$$F_{i\,max} = \frac{\sigma_{ci} Z_b - M_{DL}}{\left(\beta - \frac{r^2}{y_b}\right)} \tag{25b}$$

Equations (22)-(25) may be used to define the range of prestressing force F_i to satisfy the stress condition at the initial stage (at transfer).

Similar results will be obtained from the stress condition at the final condition (at effective prestressing force) as follows:

From the stress condition at the top fibre at the final stage in Equation (16a) and by considering Equations (11), (13), (18) and (19) we can obtain:

If $\left(-\beta - \frac{r^2}{y_t}\right) > 0$:

$$F_{i\,max} = \frac{\sigma_t Z_t + M_{TL}}{\alpha\left(-\beta - \frac{r^2}{y_t}\right)} \tag{26a}$$

If $\left(-\beta - \frac{r^2}{y_t}\right) < 0$:

$$F_{i\,min} = \frac{\sigma_t Z_t + M_{TL}}{\alpha\left(-\beta - \dfrac{r^2}{y_t}\right)} \tag{26b}$$

Similarly from Equation (16b) we can obtain:

If $\left(-\beta - \dfrac{r^2}{y_t}\right) > 0$:

$$F_{i\,min} = \frac{\sigma_c Z_t + M_{TL}}{\alpha\left(-\beta - \dfrac{r^2}{y_t}\right)} \tag{27a}$$

If $\left(-\beta - \dfrac{r^2}{y_t}\right) < 0$:

$$F_{i\,max} = \frac{\sigma_c Z_t + M_{TL}}{\alpha\left(-\beta - \dfrac{r^2}{y_t}\right)} \tag{27b}$$

On the other hand from the stress condition at the bottom fibre at the final stage in Equation (17a) we can obtain:

If $\left(\beta - \dfrac{r^2}{y_b}\right) > 0$:

$$F_{i\,max} = \frac{\sigma_t Z_b - M_{TL}}{\alpha\left(\beta - \dfrac{r^2}{y_b}\right)} \tag{28a}$$

If $\left(\beta - \dfrac{r^2}{y_b}\right) < 0$:

$$F_{i\,min} = \frac{\sigma_t Z_b - M_{TL}}{\alpha\left(\beta - \dfrac{r^2}{y_b}\right)} \tag{28b}$$

Similarly from Equation (17b) we can obtain:

If $\left(\beta-\frac{r^2}{y_b}\right)>0$:

$$F_{i\,min}=\frac{\sigma_c Z_b - M_{TL}}{\alpha\left(\beta-\frac{r^2}{y_b}\right)} \tag{29a}$$

If $\left(\beta-\frac{r^2}{y_b}\right)<0$

$$F_{i\,max}=\frac{\sigma_c Z_b - M_{TL}}{\alpha\left(\beta-\frac{r^2}{y_b}\right)} \tag{29b}$$

Equations (26)-(29) may be used to define the range of prestressing force F_i to satisfy the stress condition at the final stage (after loss of prestress). Combining Equations (22)-(25) and Equations (26)-(29) the prestressing force F_i can be computed.

It is to be noted that the resulting prestressing force will satisfy the stress conditions in Equations (14)-(17) and alleviate the use of trial and error for designing concordant cable due to the presence of secondary moment in statically indeterminate structures. It is to be noted also that the equations derived in this paper can also be used for statically determinate structures where the coefficient β in Equations (11) and (12) equals to the cable eccentricity since the secondary moment is equal to zero. The coefficient β here can be viewed as 'indeterminate eccentricity' because in statically determinate structures the moment due to prestressing equals the force times eccentricity; or β can be viewed as moment coefficient (influence) because when F or F_i equals to unity the moment in Equations (11) and (12) equals to β.

In multi-storey buildings when the magnitude of the prestressing force in the beam may be different from one floor to another (or event might be different from beam to beam in a particular floor), the resulting equations may still be used to obtain the prestressing force provided that the ratio of prestressing force are known for every beam. In this case the ratio of prestressing force can be decided based on the external load to be carried by each beam in the structures.

4 Application

A three-storey building is taken as the example. The dead load and live load carried by the structure are shown in Figure 4 along with the cross section of the beam. The size of the beam is 400 x 600 (mm) and the column is 400 x 400 (mm), f_c' = 30 MPa, and f_{ci}' = 25 MPa. The allowable stresses in concrete are as follows:

At the initial stage: $\sigma_{ci} = -0.6f'_{ci}$, $\sigma_{ti} = 0.25\sqrt{f'_{ci}}$; at the final stage: $\sigma_c = -0.45f'_c$ and $\sigma_t = 0.5\sqrt{f'_c}$. For simplicity, the cable profile is assumed to be parabola as in Figure 5. It is assumed also that the magnitude of prestressing force of the beam at the top floor is equal to 0.9 magnitude of prestressing force given in other floors.

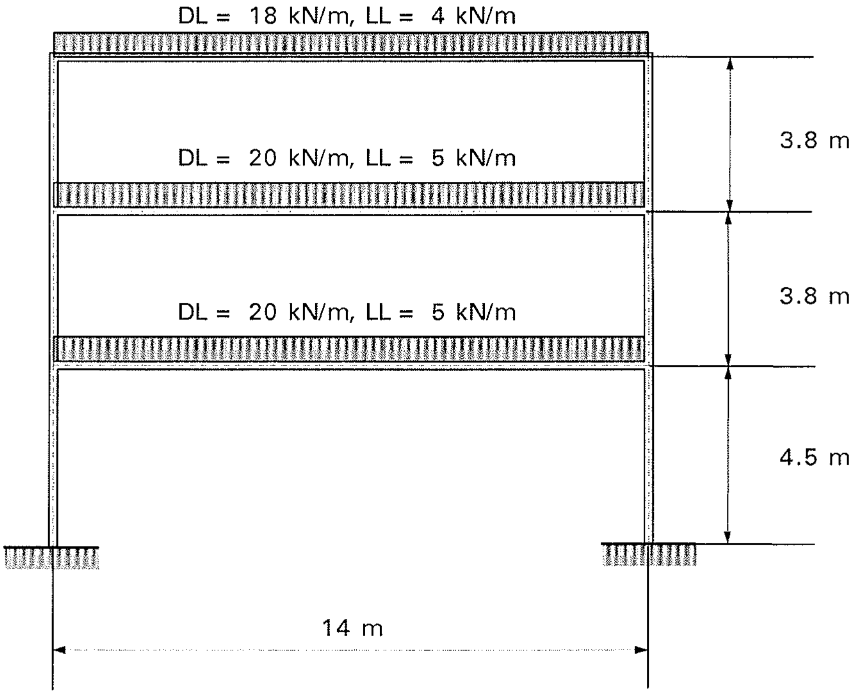
Considering the cable profile in Figure 5, the value of equivalent load acting on the structure at transfer is plotted in Figure 6. From structural analysis, the bending moment of the beam is shown in Figure 7 for dead load, and in Figure 8 for dead plus live load. Figure 9 shows the value of moments of the beam due to prestressing force in Figure 6 with the prestressing force is taken as unity. Therefore, Figure 9 represents the value of β in each beam.

Having obtained the value of moments due to dead load, live load and prestressing force, the magnitude of force at transfer F_i can be determine by utilising Equations (22) – (29) and by assuming that the loss of prestress is 20%, i.e., $\alpha = 0.8$ in Equation (13). When Equations (22) – (29) are employed, the resulting F_i from each beam is depicted in Figure 10 with the assumption that the magnitude of force is constant along the whole span of the beam. Therefore, from the results in Figure 10, the magnitude of prestressing force at transfer that satisfy all conditions can be taken within the largest of F_{imin} and the smallest of F_{imax} of each beam. In this case F_i can be taken as:

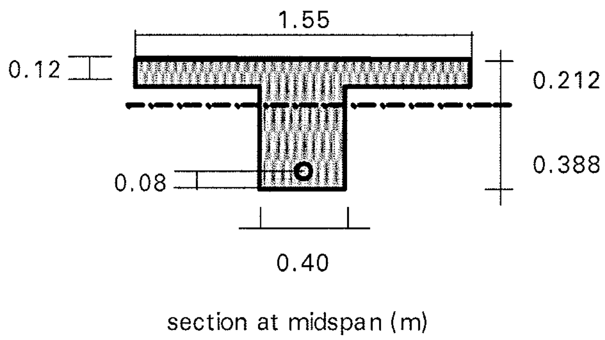
$$1138.9\,\text{kN} \le F_i \le 2501.9\,\text{kN}$$

It can be seen here that the range of F_i is quite large. When optimum design is desired, the range should be taken as minimum.

It can be seen also from this example that the value of prestressing force can be obtained by using the procedure proposed in the previous section and eliminates the computation of secondary moment that would occur in statically indeterminate structures. The method presented here can also be used to determine the prestressing force in statically determinate structures as in this case the value of $\beta = 0$ in Equations (22) – (29).



(a)



(b)

Figure 4. Three storey frame : (a) dead and live load., (b). cross section of the beam at midspan

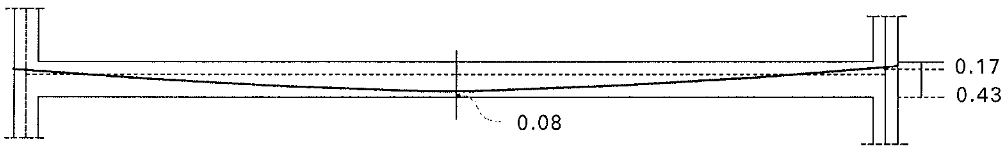


Figure 5. Cable profile

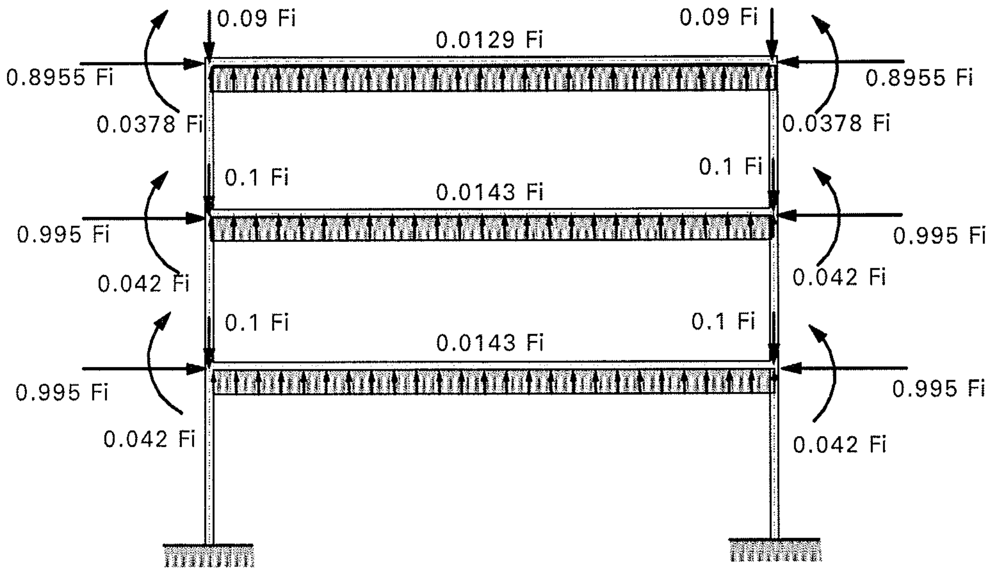


Figure 6. Load due to the prestressing force at transfer

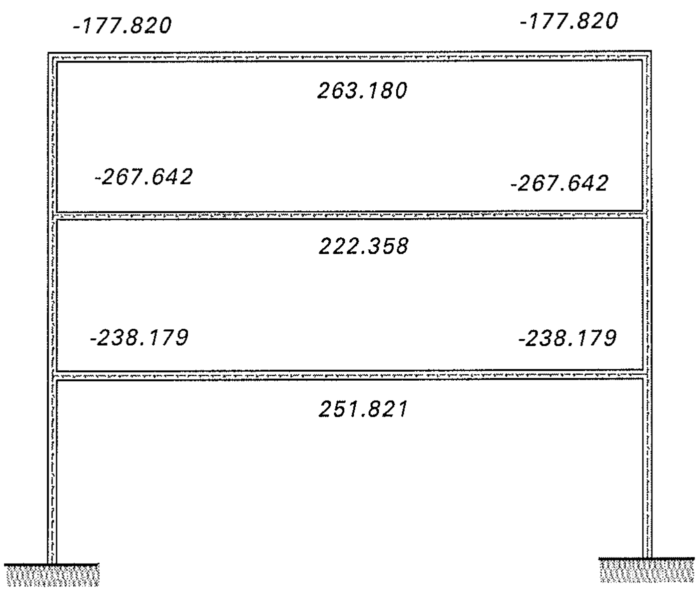


Figure 7. Beam moment due to dead load M_{DL} (kNm)

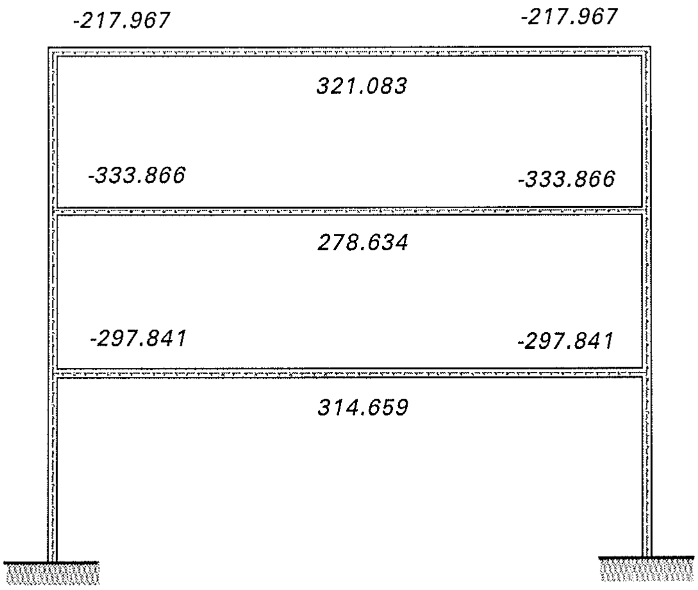


Figure 8. Beam moment to the total load M_{TL} (M_{DL} + M_{LL}) in kNm

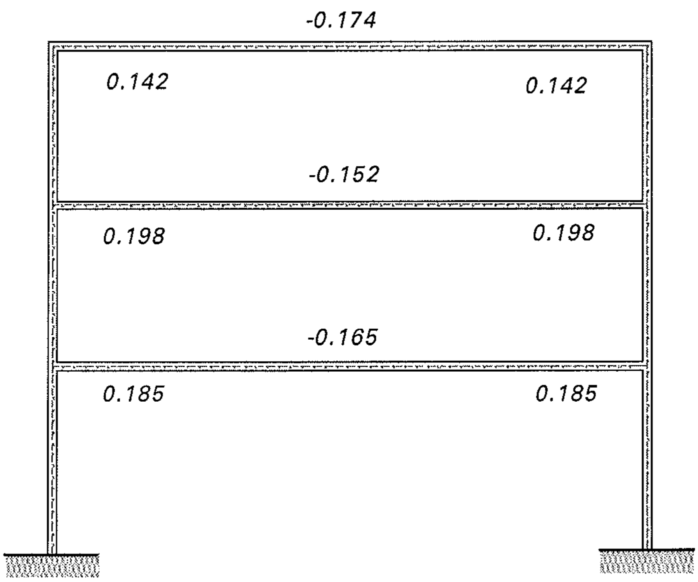


Figure 9. Prestressed moment coefficient (influence) or 'indeterminate eccentricity' β (m)

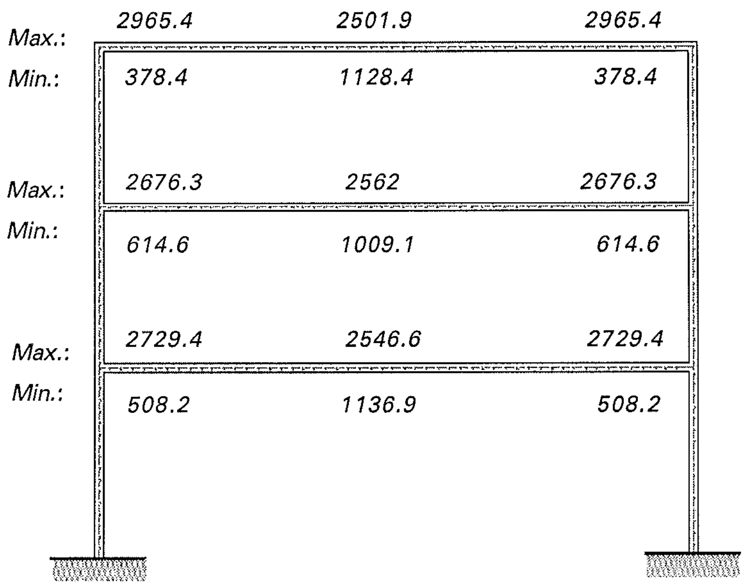


Figure 10. The results of F_i from each floor. (kN)

5 Conclusions

The determination of the magnitude of prestressing force in statically indeterminate structures is discussed in this paper. Equations are derived so that the magnitude of the prestressing force can be obtained directly from those equations. This is achieved by assuming that the value of moment is represented by a coefficient β first so that the structural analysis can be done. Viewed in another way, the coefficient β is the moment coefficient (influence) in statically indeterminate structures when the prestressing force is taken as unity. Similarly, β can be viewed also as the 'indeterminate eccentricity', i.e., the 'eccentricity' in statically indeterminate structures. An example on how to apply the procedure is presented to a three storey building, where the magnitude of prestressing force at the roof beam is taken as 0.9 times the prestressing force of other beams. When optimum design is desired the range of prestressing force obtain from Equation (22)-(29) should be minimum.

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