

$$\begin{aligned}
\bar{A} \cdot \bar{A} \cdot L &= F_t \\
\bar{B} \cdot \bar{B} \cdot L &= \Delta_t \\
\bar{C} \cdot \bar{A} \cdot L &= \Delta_t \\
\bar{D} \cdot \bar{B} \cdot L &= F_t
\end{aligned} \tag{4}$$

In which \bar{A} and \bar{B} are diagonal matrices as in (5); L is the required lack of fit vector; F_t and Δ_t are the target force and displacement vector respectively for a specific prestressed state. Column j of the productive matrix $\bar{A} \cdot \bar{A}$ and $\bar{D} \cdot \bar{B}$, $\bar{B} \cdot \bar{B}$ and $\bar{C} \cdot \bar{A}$ represent the structural member forces and nodal displacements respectively under -1 unit initial lack of fit of member j (Zhou et al., 2010b).

$$\bar{A} = \begin{bmatrix} f'_{11} & 0 & \dots & 0 \\ 0 & f'_{22} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & f'_{nn} \end{bmatrix}, \bar{B} = \begin{bmatrix} \delta'_{11} & 0 & \dots & 0 \\ 0 & \delta'_{22} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & \delta'_{nn} \end{bmatrix} \tag{5}$$

Simply inverse these productive matrices, Eq. (4) can be directly solved for the required lack of fit L . Then L can be imposed directly on the corresponding member, by back substitution L in Eq. (4), considering the construction sequence. The member forces and/or nodal displacements during the pretension process as well as the tensioning control forces and/or displacements can then be all obtained.

3.2 The iterative solving method

With the definition of the IFM, the mutual relation between member forces and/or displacements during pretension process can be simulated in matrix form (Zhou et al., 2010a) as follows:

$$\begin{aligned}
F_j^i &= X_j^i A_j^i + F_{j-1}^i \\
\Delta_j^i &= Y_j^i B_j^i + \Delta_{j-1}^i \\
\Delta_j^i &= X_j^i C_j^i + \Delta_{j-1}^i \\
F_j^i &= Y_j^i D_j^i + F_{j-1}^i
\end{aligned} \tag{6}$$

In which for the i^{th} round tension: $F_j^i = [f_{j1}^i, f_{j2}^i \dots f_{jn}^i]^T$, $\Delta_j^i = [\delta_{j1}^i, \delta_{j2}^i \dots \delta_{jn}^i]^T$ is the member force, displacement vector respectively when the j^{th} member is tensioned; With $j = 1$, F_{j-1}^i and Δ_{j-1}^i are the member force and displacement vector before pretension; $X_j^i = t_j^i - f_{j-1,j}^i$ and $Y_j^i = u_j^i - \delta_{j-1,j}^i$ are the incremental force and displacement respectively of the j^{th} member; t_j^i and u_j^i are the tensioning control force and displacement of member j ; $A_j^i = [a_{1j}^i, a_{2j}^i \dots a_{nj}^i]^T$, $B_j^i = [b_{1j}^i, b_{2j}^i \dots b_{nj}^i]^T$,

$C_j^i = [c_{1j}^i, c_{2j}^i, \dots, c_{nj}^i]^T$, $D_j^i = [d_{1j}^i, d_{2j}^i, \dots, d_{nj}^i]^T$ are the column j of A , B , C , and D matrices respectively.

The required tensioning control forces and/or displacements to achieve the target prestressed state can be determined by solving Eq. (7) as follows:

$$\begin{aligned} F_n^i &= X_j^i A_j^i + F_{j-1}^i = F_t^i \\ \Delta_n^i &= Y_j^i B_j^i + \Delta_{j-1}^i = \Delta_t^i \\ \Delta_n^i &= X_j^i C_j^i + \Delta_{j-1}^i = \Delta_t^i \\ F_n^i &= Y_j^i D_j^i + F_{j-1}^i = F_t^i \end{aligned} \quad (7)$$

In which for the i^{th} round tension: F_n^i and Δ_n^i are member force and displacement vector after finish tensioning n prestressed members; F_t^i and Δ_t^i are the target force and displacement vector respectively.

For example, in case there are two prestressed members tensioned one time only, the set of Eq. (7) based on A and B matrices are respectively as in Eq. (8) and (9).

$$\begin{aligned} F_1 &= [f_{11} \quad f_{12}]^T = (t_1 - f_{01}) [a_{11} \quad a_{21}]^T + [f_{01} \quad f_{02}]^T \\ F_2 &= [f_{21} \quad f_{22}]^T = (t_2 - f_{12}) [a_{12} \quad a_{22}]^T + [f_{11} \quad f_{12}]^T = [f_{t1} \quad f_{t2}]^T \end{aligned} \quad (8)$$

$$\begin{aligned} \Delta_1 &= [\delta_{11} \quad \delta_{12}]^T = (u_1 - \delta_{01}) [b_{11} \quad b_{21}]^T + [\delta_{01} \quad \delta_{02}]^T \\ \Delta_2 &= [\delta_{21} \quad \delta_{22}]^T = (u_2 - \delta_{12}) [b_{12} \quad b_{22}]^T + [\delta_{11} \quad \delta_{12}]^T = [\Delta_{t1} \quad \Delta_{t2}]^T \end{aligned} \quad (9)$$

By back substitute F_1 into F_2 in Eq. (8); Δ_1 into Δ_2 in Eq. (9), the required tensioning control forces and/or displacements can be obtained by directly solving this set of two equations. The direct solutions of Eq. (8) and (9) are given in the appendix.

It is worth to mention that if there are a large number of prestressed members in the structures, directly solving the set of Eq. (7) is rather complicated. In this case, the iterative solving method is more preferable (Zhou et al., 2010c).

3.1.1 The iterative solving procedure

Step1. Let $i = 1$, the tensioning control forces and/or displacements are set equal to the target forces and/or displacements at the beginning.

$$T^i = F_t, U^i = \Delta_t \quad (10)$$

In which T^i and U^i are the tensioning control force and displacement vector respectively.

Step2. The member forces and displacements after finish tension F_n^i and Δ_n^i can be computed using Eq. (6).

Step3. Check the deviation between the computed forces and/or displacements with the target values as in Eq. (11).

$$\varepsilon_f = 1 - \frac{F_n^i}{F_t}, \quad \varepsilon_\delta = 1 - \frac{\Delta_n^i}{\Delta_t} \quad (11)$$

If the deviation is smaller than a required tolerance, these tensioning control forces and/or displacements are the expected values. Otherwise, they need to be adjusted by adding up with the deviation values as in Eq. (12) and return to step2 for the $(i+1)^{th}$ iteration.

$$T^{i+1} = T^i + (F_n^i - F_t), \quad \Delta^{i+1} = U^i + (\Delta_n^i - \Delta_t) \quad (12)$$

The procedure is repeated until convergence is detected.

4. A NUMERICAL EXAMPLE OF THE INTERDEPENDENT BEHAVIOR OF PRESTRESSED SYSTEM

4.1 Design requirements and pretension schemes

A steel frame column supporting compression load from roof panel and glass façade is as Fig.1. The main frame is tube 100x100x10mm, $f_y = 355 \text{ KN/mm}^2$ (the material nonlinearity is not considered) and $E = 210 \times 10^6 \text{ KN/m}^2$; The prestressed member is 70x35x4mm, $f_y = 550 \text{ KN/mm}^2$ and $E = 210 \times 10^6 \text{ KN/m}^2$. The target forces are 20KN in prestressed members No.11, 14 and 10KN in members No.12, 13. The target horizontal displacements at nodes No.10, 7 are -29mm and nodes No.9, 8 are -61.7mm (inward displacement) at the end.

Considering the structural properties, the design requirements and the capability of the tensioning equipment, four pretension schemes are proposed as follows:

1. **Scheme A:** After constructing the main frame, the prestressed member is assembled and tensioned from member No.11 to 14 in turn. The compression load 100KN is then applied on the column.

2. **Scheme B:** The construction sequence is the same as in scheme A. However, the prestressed members are assembled and prestressed in batches. Batch No.1 included member No.11 and 14 are assembled and tensioned first. Then batch No.2 included member No.12 and 13 are assembled and tensioned later.

3. **Scheme C:** After constructing the main frame, all the prestressed members are assembled and prestressed simultaneously. The compression load is then applied.

4. **Scheme D:** After constructing the main frame, all the prestressed members are assembled first and then prestressed one by one to 10KN in members No.11 and 14 and 5KN in members No.12 and 13. After applying the compression load, the second tensioning phase is conducted to achieve the final design requirements.

4.2 Analysis of the whole pretension process

Under **scheme A**, the prestressed member is assembled and tensioned one by one. Under **scheme B**, they are assembled and tensioned batches by batches. Therefore, the structural stiffness is changed after each tensioning step. On the other hand, under **schemes C and D**, all the prestressed members are assembled first and then tensioned, the structural stiffness remains unchanged. The prestressing forces and displacements are obtained from the finite element analysis programmed in FORTRAN language based on the formulation of lu and Bradford (2012a),(2012b). The direct solving method and the iterative solving method are realized on Visual Basic platform.

For the sake of simplicity, only the final analysis results of the prestressed members are given. The IFMs are first constructed. Then the required lack of fit to achieve the target design forces and/or displacements are determined according to Eq. (4) as in Table 1. The force and displacement variations during pretension process as well as the tensioning control forces and displacements (the bold value) analyzed by the direct solving method using Eq. (4) and the iterative solving method using Eq. (6) are all addressed in Tables 2 and 3. It can be seen that the target forces (the underline values) are all achieved at the end based on this approach. Besides, it is worth to mention that these two solving methods are capable of yielding the same solution as in this numerical example.

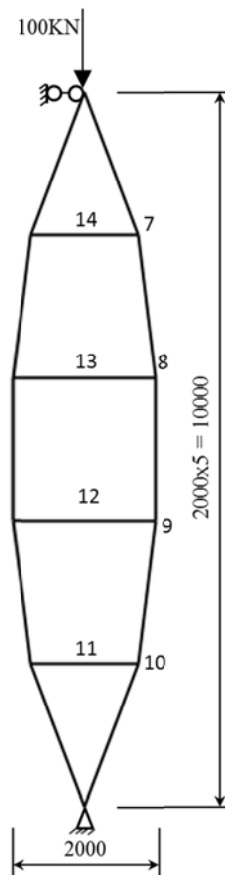


Fig. 1 The structural model of the frame column

IFMs under different pretension schemes are as follows:

Scheme A:

$$A = \begin{bmatrix} 1 & -0.281 & 0.342 & 0.067 \\ 0 & 1 & -0.407 & 0.092 \\ 0 & 0 & 1 & -0.242 \\ 0 & 0 & 0 & 1 \end{bmatrix}, B = \begin{bmatrix} 1 & 0.407 & 0.318 & 0.411 \\ 1.466 & 1 & 0.785 & 1.012 \\ 1.060 & 0.872 & 1 & 1.295 \\ 0.370 & 0.328 & 0.459 & 1 \end{bmatrix}$$

$$C = \begin{bmatrix} -0.0015 & -0.0017 & -0.0012 & -0.0005 \\ -0.0021 & -0.0043 & -0.0029 & -0.0011 \\ -0.0016 & -0.0037 & -0.0037 & -0.0015 \\ -0.0005 & -0.0014 & -0.0017 & -0.0011 \end{bmatrix}, D = \begin{bmatrix} -682.7 & 65.9 & -92.3 & -59.7 \\ 0 & -234.6 & 110.0 & -81.5 \\ 0 & 0 & -270.0 & 215.1 \\ 0 & 0 & 0 & -889.5 \end{bmatrix}$$

Scheme B:

$$A = \begin{bmatrix} 1 & -0.734 \\ 0 & 1 \end{bmatrix}, B = \begin{bmatrix} 1 & 0.353 \\ 1.843 & 1 \end{bmatrix}$$

$$C = \begin{bmatrix} -0.0020 & -0.0022 \\ -0.0037 & -0.0063 \end{bmatrix}, D = \begin{bmatrix} -498.178 & 116.322 \\ 0 & -158.553 \end{bmatrix}$$

Scheme C and D:

$$A = \begin{bmatrix} 1 & -0.799 & 0.317 & -0.067 \\ -0.634 & 1 & -0.738 & 0.251 \\ 0.251 & -0.738 & 1 & -0.634 \\ -0.067 & 0.317 & -0.799 & 1 \end{bmatrix}, B = \begin{bmatrix} 1 & 0.006 & -0.003 & 0.001 \\ 0.008 & 1 & 0.008 & -0.003 \\ -0.003 & 0.008 & 1 & 0.008 \\ 0.001 & -0.003 & 0.006 & 1 \end{bmatrix}$$

$$C = \begin{bmatrix} -0.0004579 & -0.0000037 & 0.0000015 & -0.0000003 \\ -0.0000039 & -0.0005766 & -0.0000045 & 0.0000015 \\ 0.0000015 & -0.0000045 & -0.0005766 & -0.0000039 \\ -0.0000003 & 0.0000015 & -0.0000037 & -0.0004579 \end{bmatrix}$$

$$D = \begin{bmatrix} -2184.1 & 1385.0 & -549.2 & 146.0 \\ 1384.2 & -1734.3 & 1279.8 & -548.9 \\ -548.9 & 1279.8 & -1734.3 & 1384.2 \\ 146.0 & -549.2 & 1385.0 & -2184.1 \end{bmatrix}$$

Table 1. The required lack of fit (in m)

Member	11	12	13	14
Scheme A	0.0197	0.0183	0.0131	0.0071
Scheme B	0.0417	0.0165	0.0165	0.0417
Scheme C	0.0582	0.1235	0.1235	0.0582
Scheme D - Step 1	0.0772	0.1642	0.1642	0.0772
Scheme D - Step 2	-0.0190	-0.0407	-0.0407	-0.0190

Table 2. Forces of prestressed members in various tensioning phases (KN)

Scheme A	Member	11	12	13	14
Assemble and tension member:	11	6.71			
	12	5.23	5.27		
	13	7.13	3.01	5.56	
	14	7.64	3.71	3.71	7.64
Install roof system and glass façade		<u>20.00</u>	<u>10.00</u>	<u>10.00</u>	<u>20.00</u>
Scheme B	Batch	1	2		
Assemble and tension batch:	1	10.36			
	2	7.64	3.71		
Install roof system and glass façade		<u>20.00</u>	<u>10.00</u>		
Scheme C	Member	11	12	13	14
Assemble and tension member simultaneously		7.64	3.71	3.71	7.64
Install roof system and glass façade		<u>20.00</u>	<u>10.00</u>	<u>10.00</u>	<u>20.00</u>
Scheme D	Member	11	12	13	14
First-time tension member:	11	83.49	-52.91	20.98	-5.58
	12	-29.05	88.00	-83.00	39.05
	13	15.58	-15.98	57.91	-73.49
	14	<u>10.00</u>	<u>5.00</u>	<u>5.00</u>	10.00
Install roof system and glass façade		22.36	11.29	11.29	22.36
Second-time tension member:	11	1.78	24.34	6.12	23.74
	12	29.70	-10.62	31.92	12.67
	13	18.63	15.18	-3.04	40.59
	14	<u>20.00</u>	<u>10.00</u>	<u>10.00</u>	20.00

Table 3. Horizontal displacements in various tensioning phases (mm)

Scheme A	Nodal	10	9	8	7	
Assemble and tension member:	11	-9.83	-14.41	-10.42	-3.64	
	12	-18.98	-36.89	-30.03	-11.02	
	13	-25.53	-53.04	-50.62	-20.47	
	14	-29.06	-61.74	-61.74	-29.06	
Install roof system and glass façade		<u>-29.01</u>	<u>-61.70</u>	<u>-61.70</u>	<u>-29.01</u>	
Scheme B	Nodal	10, 7	9, 8			
Assemble and tension batch:	1	-20.91	-38.54			
	2	-29.10	-61.73			
Install roof system and glass façade		<u>-29.04</u>	<u>-61.69</u>			
Scheme C	Nodal	10	9	8	7	
Assemble and tension member simultaneously			-29.06	-61.68	-61.68	-29.06
Install roof system and glass façade			<u>-29.01</u>	<u>-61.65</u>	<u>-61.65</u>	<u>-29.01</u>
Scheme D	Nodal	10	9	8	7	
First-time tension member:	11	-38.23	-0.32	0.13	-0.03	
	12	-38.74	-81.58	-0.51	0.18	
	13	-38.54	-82.22	-81.76	-0.34	
	14	<u>-38.56</u>	<u>-82.09</u>	<u>-82.09</u>	-38.56	
Install roof system and glass façade			-38.51	-82.05	-82.05	-38.51
Second-time tension member:	11	-29.08	-81.97	-82.08	-38.50	
	12	-28.95	-61.81	-81.92	-38.55	
	13	-29.01	-61.65	-61.76	-38.42	
	14	<u>-29.00</u>	<u>-61.68</u>	<u>-61.68</u>	-29.00	

4.3 Discussion

1. Using the proposed approach, the interdependent behavior of all prestressed members in the system is clarified. The tensioning control forces and displacements (the bold values in Tables 2 and 3) to meet the design requirements (the underline values) are all predicted. At the same time, the variation of member forces and displacements according to the construction sequence can also be obtained. These data can serve as a monitoring unit for the whole pretension process.

2. The pretension process analysis based on IFM approach using the direct solving method and the iterative solving method both achieve the design prestressed state. On the one hand, the direct solving method solves Eq. (4) directly for the required lack of fit as a basis to compute the accurate force and displacement variations during pretension process as well as the accurate required tensioning control forces and displacements. On the other hand, the iterative solving method based on Eq. (6) avoids directly solving the set of equation Eq. (7); it repeatedly amends the tensioning control forces and/or displacements to achieve an approximate solution to meet the design requirements.

3. It can be seen that the analysis results from both the direct solving method and the iterative solving method (once the control tolerances are set equal to zero) are the same. Hence, the reliability of these two approaches can be confirmed.

4. Obviously when the number of iteration increases, the result's accuracy of the iterative solving method will also increase. If high accuracy is desired, the convergent criteria can be set really close to or even zero.

5. The two-criterion IFMs prove to be more effective as compared with the one-criterion IFMs if both force and displacement are under control during the construction sequence and a monitoring unit for the whole pretension process is desired.

6. Based on the analysis result, the optimal pretension scheme can also be selected. Through the numerical example, the required tensioning control forces and displacements in **schemes A** and **C** are the smallest. However in **scheme C**, four prestressed members are required to be assembled and tensioned simultaneously. Therefore, high-performance instruments and automatic control technique with computer aid are necessary. This results in high construction cost. As a result, **scheme A** can be considered as the optimal pretension scheme. This confirms that this approach can serve as a platform to optimize the pretension process.

7. Due to the necessity to inverse the productive matrix, the direct solving method cannot be used if the determinant of the productive matrix is equal to zero. On the other hand, if the determinant of the IFM is close to zero, extremely slow convergence or even no convergence was noticed when using the iterative solving method. Therefore, the designer needs to understand the structural property or the IFM characteristic to decide which solving method will be used.

5. CONCLUSION

This paper presents a thorough investigation of the interdependent behavior of all prestressed members in the whole structural system that forms the basis for a complete

analysis of the pretension process. Four different types of IFM and their application in the pretension process analysis are introduced. The direct and the iterative solving method are then proposed to analyze the pretension process.

It can be seen that once the IFM has been constructed, the required initial lack of fit as well as the tensioning control forces and/or displacements in order to meet the design requirement for a specific prestressed state can be obtained. Moreover the variation of prestressed member forces and nodal displacements according to the construction sequence can all be predicted. Therefore a thorough investigation of interdependent behavior of all prestressed members in the whole structural system is essential for a reliable, effective, and optimal pretension process analysis and the IFM proves to be quite suitable to fulfil this requirement. The numerical example shows that this approach can analyze various kinds of complicated batched and repeated tensioning schemes reliably and effectively.

In case, there is a large difference between the theoretical analytical model and the actual structural state, as a result, the IFM constructed by structural finite element analysis in the design stage no longer represent the actual interactions of the real structure. In this situation, the IFM need to be reconstructed based on the measured member forces and/or displacements using the monitoring unit with detective equipment in the construction stage. In this case, the proposed approach can also be used to obtain the correction of the tensioning forces and/or displacements in order to achieve the target prestressed state instead of supplemental tensions by trial and error. The basic differences are the system state parameter (IFM of the real structure) and the system initial value (the member forces and/or displacements that are measured after finishing the pretension phase following the predicted values in the design stage based on the theoretical model). Therefore, this approach is considered as complete and the above numerical example can serve as a benchmark investigation of the interdependent behavior of prestressed system.

APPENDIX

The tensioning control forces and displacements of the structure having two prestressed members are as follows:

$$\begin{aligned}
 X_1 = t_1 - f_{01} &= \frac{a_{22}(f_{t1} - f_{01}) - a_{12}(f_{t2} - f_{02})}{a_{11}a_{22} - a_{21}a_{12}} \\
 Y_1 = u_1 - \delta_{01} &= \frac{b_{22}(\Delta_{t1} - \delta_{01}) - b_{12}(\Delta_{t2} - \delta_{02})}{b_{11}b_{22} - b_{21}b_{12}} \\
 X_2 = t_2 - f_{02} &= -\frac{a_{21}(f_{t1} - f_{01}) - a_{11}(f_{t2} - f_{02})}{a_{11}a_{22} - a_{21}a_{12}} + a_{21}(t_1 - f_{01}) \\
 Y_2 = u_2 - \delta_{02} &= -\frac{b_{21}(\Delta_{t1} - \delta_{01}) - b_{11}(\Delta_{t2} - \delta_{02})}{b_{11}b_{22} - b_{21}b_{12}} + b_{21}(u_1 - \delta_{01})
 \end{aligned} \tag{13}$$

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