Application on large-span reconstructed structure with external prestressing technology

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Abstract. The application of external prestressed reinforcement technology in large-span reconstruction projects is introduced through a project example of drawing columns to increase the use space of existing buildings. Simplified calculation method and midas gen finite element analysis software are used to analyze and calculate the bearing capacity limit state and normal service limit state of GHJL-1 and GHJL-2. In order to ensure the safety and applicability of the large-span reinforcement and reconstruction project, the static load method is used to inspect the serviceability limit state of the structure after the reconstruction. The results show that the deflection and crack width of GHJL-1 and GHJL-2 meet the requirements of the code limits.

1. Introduction
At present, there are demands to change the using function for more and more existing buildings, and some of them need to increase useable space. The existing reinforcement methods such as increasing section area, wrapping steel, sticking steel plate, sticking fiber composite, etc\(^{[1]}\). Above methods have limitations for solving issue which increase space by reducing columns. The advantages for using external prestressed method to solve issue above aren't increase self weight of structure, enough insufficient bearing capacity, and solve excessive deflection and crack overrun efficiently\(^{[2]}\).

2. Project overview
An existing concrete frame building which has one underground floor and four above ground floors. The floors and roof use ribbed beam and the height of building is 19.47 meters. The using function of this building changes from office and business to bar. Therefore, the owner requires to upgrade the local space in the building to increase useable space, which satisfy function demand of entertainment place. The alteration way, as shown belows. The frame columns, frame beams and floors of the second to fourth floors are removed in the area of axis 2 ~ 6 and axis B ~ E of the building, as shown in Figure 1.
3. Reinforcement design of external prestressed

Remove six frame columns from second to fourth floors. The span of frame beam in east-west direction increases from 8000mm to 32000mm and the span of frame beam in south-north direction increases from 8000mm to 23000mm. To reduce deflection and crack width of long-span concrete members, this design chooses steel-concrete composite and external prestressed. The detailed reinforcement design is shown in Figure 2.

4. Structural calculation

4.1. Calculation conditions

Load values: additional dead load 2.5kN/m², live load 0.5kN/m² (non-accessible roof); I-steel Q345B, GHJL-1、GHJL-2 section size are shown in Figure 3. The prestressed tendons are made of 14 steel strands which use 1860 seven-low relaxation steel strands. The span of prestressed floor is 23m×32m. The original structure is ribbed floor, and the beam size is b×h:650×420mm. Now the external prestressing method is used to strengthen the original concrete beam.
4.2. Calculation of internal force

Based on PKPM calculation result: dead load: \( M \) (middle of span) = 1400kN·m, \( V = 666kN \); live load: \( M \) (middle of span) = 80kN·m, \( V = 37.7kN \); standard combination: \( M \) (middle of span) = 1480kN·m, \( V = 703.7kN \); basic combination: \( M \) (middle of span) = 1969kN·m, \( V = 936kN \).

The design value of external prestressing tendons is based on Technical specification for “strengthening building structures with external prestressing tendons” JGJ/T279-2012[3]:

Design value of external prestressing tendons: \( \sigma_{pu} = \sigma_{pe} (\text{Effective prestress}) + \Delta \sigma_p \)

Increasing step of external prestressing: \( \sigma_p = 50N/\text{mm}^2 \)

Effective prestress: \( \sigma_{pe} = \sigma_{con} (\text{Tension control stress}) + \sigma_l (\text{Loss of prestress}) \)

Tension control stress: \( \sigma_{con} = 0.65f_{ptk} = 1860N/\text{mm}^2 \times 0.65 = 1209N/\text{mm}^2 \)

Loss of prestress: \( \sigma_l = \sigma_{l1} + \sigma_{l2} + \sigma_{l4} \)

Prestressing tendons fixed with anchorage:

\[
\sigma_{pl} = \frac{aE}{L}p = \frac{1nm}{23000mm} \times 1.95 \times 10^5 \text{N/mm}^2 = 8.5N/\text{mm}^2
\]

Friction of prestressed tendons:

\[
\sigma_{f2} = (\kappa\sigma + \mu\sigma)\sigma_{con} = (0.004 \times 23 + 0.09 \times 0.054) \times 1209N/\text{mm}^2 = 117N/\text{mm}^2
\]

Relaxation of prestressing tendons:

\[
\sigma_{f4} = 0.125(\sigma_{con} - 0.5)\sigma_{con} = 0.125 \times \left( \frac{1209}{1860} - 0.5 \right) \times 1209N/\text{mm}^2 = 22.67N/\text{mm}^2
\]

The result:

\[ \sigma_{pu} = \sigma_{pe} + \Delta \sigma_p = 1100.8N/\text{mm}^2 \]

4.3. Calculation of bearing capacity of prestressing beam

This reinforcement uses 14 1×7 steel strands with a diameter of 15.2 mm. The lower flange of the newly added I-beam is taken as the tensile reinforcement in this calculation. Effective connection measures should be taken between the I-beam and the original concrete beam to make them work together. The calculated section height of beam is 720mm, the width is 650mm, the calculated rise height of prestressing tendons is 600mm, the I-steel is Q345B, and the design value of tensile strength is 305 N/mm².
Kiang-Hwee Tan and Chee-Khoon Ng\textsuperscript{[4]} studied the influence of the arrangement of the steering block and external tendons on the bearing capacity of the members through six concrete beams strengthened by external prestressing. In order to ignore the secondary effect of external prestressing tendons, the spacing of the external tendons steering device is less than 12m and the calculation refers to “Technical specification for strengthening building structures with external prestressing tendons” JGJ/T279-2012\textsuperscript{[3]}.

\[
\text{Height of compression zone: } x = \frac{f_y A_s - f_y A'_s + \sigma_{pu} A_p}{\sigma_{tcb}} = \frac{305 N / mm^2 \times 10500 mm^2 - 300 N / mm^2 \times 1964 mm^2 + 1100.8 N / mm^2 \times 14 \times 140 mm^2}{1.0 \times 14.3 N / mm^2 \times 650 mm} = 513.3 mm
\]

Calculation of bearing capacity of normal section:

\[
M = \sigma_{pu} A_p (h_p - \frac{x}{2}) + f_y A_s (h - a_s - \frac{x}{2}) + f_y A'_s (\frac{x}{2} - a'_s) = 1100.8 N / mm^2 \times 14 \times 140 mm^2 \times (697 mm - \frac{513.3 mm}{2}) + 305 N / mm^2 \times 10500 mm^2 \times (720 mm - 8 mm - \frac{513.3 mm}{2}) + 300 N / mm^2 \times 1964 mm^2 \times \left(\frac{513.3 mm}{2} - 43 mm\right)
\]

\[
= 2533.8 kN \cdot m > 1969 kN \cdot m \quad \text{Meet the requirements}
\]

Calculation of the bearing capacity of the inclined section (only concrete, reinforcement and steel), the stirrup of the original concrete beam is A8@100/200(4), newly added steels participate in shear calculation.

\[
V = V_{cs} + V_s = \alpha_{cv} f'_t b h_0 + f_{yy} A_{sv} \frac{A_s}{s} h_0 = 0.7 \times 1.43 N / mm^2 \times 650 mm \times 380 mm + 270 N / mm^2 \times \frac{201 mm^2}{200 mm} \times 380 mm + 27100 mm^2 \times 175 N / mm^2 = 5095 kN > 936 kN
\]

Meet the requirements of ultimate bearing capacity.

5. Reverse arch and deflection calculation of prestressing beam

Midas Gen is used to calculate the deformation of prestressing beam. Rigid connection is used between I-beam and original concrete beam, and effective connection measures should be taken between roof concrete beam and I-beam to ensure their cooperation.

5.1. Deformation of prestressing beam under self-weight

![Figure 4: Deformation of prestressing beam under self-weight](image)
The maximum deformation is 55mm (downward), which is less than the specification requirement $L/300 = 76.7\text{mm}$. The result is shown in Figure 4.

5.2. *Deformation of prestressing beam under additional dead load*

![Figure 5: Deformation of prestressing beam under additional dead load](image)

The maximum deformation is 24mm (downward), which is less than the specification requirement $L/300 = 76.7\text{mm}$. The result is shown in Figure 5.

5.3. *Deformation of prestressing beam under live load*

![Figure 6: Deformation of prestressing beam under live load](image)

The maximum deformation is 5mm (downward), which is less than the specification requirement $L/300 = 76.7\text{mm}$. The result is shown in Figure 6.
5.4. Reverse arch deformation of prestressing tendons

![Figure 7: Reverse arch deformation of prestressing tendons](image)

The maximum deformation is 23mm (upward), which is less than the specification requirement $L / 300 = 76.7$mm. The result is shown in Figure 7.

5.5. Total deflection under standard combination

![Figure 8: Total deflection under standard combination](image)

The maximum deformation is 62mm (downward), which is less than the specification requirement $L / 300 = 76.7$mm. The result is shown in Figure 8.

So the deformation of prestressing beam meets the requirements.

6. Static load test

According to “Standard for test method of concrete structures” GB/T50152-2012[5], the representative GHJL-1 is selected for serviceability limit state inspection.

6.1. Loading mode

GHJL-1 adopts in-situ loading mode, which adopts suspended point load, and the load is standard steel block. The point load value and layout position make the internal force of the structure equivalent to the internal force of the main structural section under the actual load. The specific loading layout is shown in Figure 9-10.
Three displacement meters are used to monitor the deformation of the middle span and beam end continuously. After adding the loading of each level, the deformation of the test beam is observed continuously for more than 20 minutes. The maximum deformation of the middle span is recorded and the next level load is applied. In addition, in the process of loading test, continuous observation is made to see whether there are cracks in the concrete of the test beam and whether there are cracks, deformation and other abnormal conditions in the welded joints of the I-beam. Stop the test immediately if any abnormality is found. Loading curve of CHJL-1 is shown in Figure 11.

6.2. Test result
Recording the vertical deformation of mid span and beam end under each level of load, and calculating the maximum mid span deflection of test beam CHJL-1 after eliminating the influence of settlement of
supports according to article 12.2.12 of “Technical standard for in-site inspection of concrete structure” GB/T50784-2013[6], as shown in formula (1).

\[ a^0_q = u^0_m - \frac{u^0_1 + u^0_2}{2} \]  

(1)

In formula: \( a^0_q \) stands for maximum mid span deflection of test beam CHJL-1 after eliminating the influence of settlement of supports \( u^0_m \) stands for measured value of mid span deflection of test beam CHJL-1 including settlement of supports, \( u^0_1 \) stands for measured value of settlement of left supports, \( u^0_2 \) stands for measured value of settlement of right supports.

The calculation results of the maximum deflection in the middle of the span under each level of load are shown in Table 1 and Figure 12. After complete unloading, the residual deformation in the middle of the span is 0.02mm, so the loading process is in CHJL-1 elastic stage.

Table 1 Measured deflection in the middle of the span under each level of load

| Load Level | Load value (kN) | Deflection (mm) |
|------------|-----------------|-----------------|
| Level 1    | 1.500           | 0.16            |
| Level 2    | 3.000           | 0.32            |
| Level 3    | 4.500           | 0.45            |
| Level 4    | 5.250           | 0.54            |
| Level 5    | 6.000           | 0.62            |
| Level 6    | 6.750           | 0.71            |
| Level 7    | 7.125           | 0.75            |
| Level 8    | 7.500           | 0.78            |
| Unload     | 0               | 0.02            |

![Figure 12: Deformation curve of CHJL-1](image)

The deformation rate of the mid span deformation curve of the test beam CHJL-1 is calculated as shown in Figure 13. It can be seen that the test beam CHJL-1 enters the elastic-plastic stage when the sixth level load is loaded, and at this time, the test beam CHJL-1 begins to produce plastic deformation.

![Figure 13: Deformation rate curve of CHJL-1](image)
According to article 12.2.12 of “Technical standard for in-site inspection of concrete structure “GB/T50784-2013[6], the maximum deflection of mid span after considering self-weight is calculated according to formula (2) and formula (3):

\[ a^0_{sb} = (a^0_{sb} + a^c_{sb}) \phi \]  

(2)

In formula: \( a^0_{sb} \) stands for the maximum mid span deflection after considering the self-weight of test beam CHJL-1, \( a^c_{sb} \) stands for mid span deflection of test beam CHJL-1 due to self-weight and multi-stage distributed loading equipment weight, \( \phi \) stands for correction factor of concentrated load replacing uniform load.

\[ a^c_{sb} = \frac{M_s}{M_b} a^0_{sb} \]  

(3)

In formula: \( M_s \) stands for mid span bending moment value of test beam CHJL-1 due to self-weight and loading equipment weight, \( M_b \). \( a^0_{sb} \) stands for measured value of mid span bending moment and deflection produced by the level load which is previous at inflection point of the load deflection curve.

Considering the influence of self-weight and long-term load, the mid span deflection of the test beam CHJL-1 is 57.5mm, which meets the requirements of article 3.4.3 of “Code for design of concrete structure”GB 50010-2010(2015 edition)[7].

7. Conclusion
Through the in-site static load test, the results show that the deflection considering the influence of self-weight and the long-term effect of load are consistent with the results of MIDAS Gen finite element analysis, and no cracking due to insufficient bearing capacity is found in the loading process, so the calculation results are reliable.

The external prestressing reinforcement can effectively improve the bearing capacity, reduce the deflection and crack width without increasing the weight of the structure. It can be used in the reconstruction projects of similar reducing column and increasing the useable space.

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