Nonlinear finite element parametric analysis of prestressed steel reinforced concrete beams

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Abstract: Prestressed steel reinforced concrete beam (PSRCB) is a new type prestressed composite beam which uses prestressing technology in steel reinforced concrete beam (SRCB). The complete failure procedure of PSRCB was analysed by three-dimensional nonlinear finite element method. Numerical results agree well with experimental results. Then the numerical model was used to conduct some parametric studies including tensile rebar ratio, concrete compressive strength, H-section steel ratio, effective stress of prestressing strands and degree of prestressing.

1. Introduction
Prestressed steel reinforced concrete beam (PSRCB) is a new type prestressed composite beam which uses prestressing technology in steel reinforced concrete beam and combines the properties of SRC beam with Prestressing technique. The H-section steel inside increases its flexural strength and prestressing technique improves its working performance. Research indicates that PSRCB has a better serviceable performance by contrast to SRCB[1,2], better resistance to crack, lower strain of tensile rebar and smaller crack width, better crack closing performance, smaller deflection, displacement restoring capacity and higher ultimate bearing capacity.

The complete failure procedure of PSRCB was analysed by three-dimensional nonlinear finite element method. Some parametric studies including compressive strength of concrete, rebar ratio and cover thickness, H-section steel cover thickness and degree of prestressing were considered. The comparison between the numerical results and experimental results states that the analysis approach is valid.

2. Numerical program
Plasticity model were used to simulate rebar and H steel, which met the von Misses yield criterion and simulate the elastoplastic properties of metal materials.

Linear elastic were used to simulate relationship between stress and strain of the prestressed steel strand and Ramberg-Osgood curve[3] were used to simulate its plastic properties.

Elastoplastic damage model provided by ABAQUS were used to simulate concrete, which assumed that the concrete material is mainly due to tensile cracking, compressive fracture and damage[4-7].

PSRCB geometric parameters could be seen in [1,2].
3. numerical simulation results

As shown in Figure 1, the PSRCB numerical simulation has the characteristics as follows: smaller maximum bearing capacity at $P_u$, larger $P$-$f$ curve simulation stiffness values before $P_u$ and faster stiffness decrease after $P_u$. The numerical results agreed well with test results and the numerical model can simulate the PSRCB mechanical performance.

4. Parametrical analysis of PSRCB

PSRCB1 were used as a typical component, and some parametric studies including tension rebar diameter ($D = 14$ mm, 16 mm, 18 mm and 20 mm), the rate of H steel containing ($H_{200 \times 100 \times 4 \times 6}$, $H_{200 \times 100 \times 5.5 \times 8}$, $H_{200 \times 100 \times 7 \times 10}$), the prestressed steel strand effective stress ($A_p = 278$ mm$^2$, $\sigma_{pe}=900$ N/mm$^2$, 977 N/mm$^2$, 1005 N/mm$^2$, 1100 N/mm$^2$ and 1200 N/mm$^2$), the area of prestressed steel strand ($\sigma_{pe}=1005$ N/mm$^2$, $A_p = 197.4$ mm$^2$, 278 mm$^2$, 348 mm$^2$, 427 mm$^2$ and 854 mm$^2$) and strength of concrete ($C_{40}$, $C_{50}$ and $C_{60}$) were carried out.

As shown in Figure 2, tensile reinforcement diameter $D$ changes mainly affect the component P-f curve numerical value and has little influence on the shape of the curve. Before cracking, PSRCB P-f curve has little effect on elastic stage. After cracking, stress of tensile rebar increased rapidly. With the increase of tensile rebar diameter, $P_u$ increased linearly, and the corresponding deflection at $P_u$ decreased within 5%. With the increase of tensile rebar diameter $D$, H steel compressive yield range extended further to the compression flange web at $P_u$. Stress of tensile rebar and prestressed steel strand were basically the same before $P_u$. 
The steel ratio can be expressed as the ratio of the inner H section area to the cross section area of the beam. T4-6 steel steel ratio were 2.9% and T7-10 steel steel ratio were 4.9%.

As shown in Figure 3, steel ratio has little effect on the P-f curve before cracking. With the increase of steel ratio increasement, PSRCB bearing capacity increased, but deflection becomes larger at $P_u$ by about 10%. The increase of bearing capacity was dependent on improving the use of steel tension flange and web area, which increased larger deflection. Steel tensile yield increased range at $P_u$ in order to make full use of H steel. Stress of tensile rebar and prestressed steel strand were basically the same before $P_u$.

As shown in Figure 4, stiffness and bearing capacity of PSRCB increased with the growth of concrete strength. The bearing capacity of PSRCB6 increased by 7.9% and deflection decreased by 4.6% at $P_u$ compared with PSRCB1. Concrete in compression zone of PSRCB was crushed and tensile rebar, the prestressed steel strand and steel flange on the web reached yield stage at $P_u$.

As shown in Figure 5, the increase of steel wire effective stress can delay PSRCB cracking ,but the maximum bearing capacity is same. The increase of effective prestress can reduce corresponding deflection, which improves the PSRCB performance of normal use.

PSRCB prestressing degree can be defined as the ratio of the moment of resistance of the prestressed steel strand to the total flexural capacity of the member [8], and the influence of steel tension flange and web is considered.

$$
\lambda = \frac{M_p}{M_u} = \frac{f_{py}A_{p}}{f_{py}A_{p} + f_{y}A_{y} + f_{xw}(A_{sw} + \alpha A_{sw})}
$$
Where $\lambda$ is prestressing degree, $f_{py}$ is tensile strength of prestressed steel strand, $f_y$ is tensile strength of tensile rebar and $f_{sy}$ is tensile strength of tensile steel. Where $A_p$ is area of prestressed steel strand, $A_s$ is area of the tensile rebar, $A_{ss}$ is area of the tensile steel flange and $A_{sw}$ is area of tensile web area. Where $\alpha$ is equivalent tensile yield area coefficient of steel web.

Based on PSRCB1, $\lambda$ value were improved by increasing the prestressed steel strand area. Take $\lambda=0.35$, 0.49, 0.55, 0.60, 0.65, and 0.75, corresponding to $A_p=197.4$ mm$^2$, 278 mm$^2$, 348 mm$^2$, 427 mm$^2$, 530 mm$^2$, and 854 mm$^2$ respectively.

As shown in Figure6, with the increase of prestressing degree, the anti cracking performance, stiffness and flexural capacity increased, but the mechanical property degenerated more serious after $P_u$. Tensile stress of rebar and prestressed steel strand can yield, when $\lambda \leq 0.6$.

With the increase of $\lambda$, steel tension yield in the range decreased at $P_u$. On the contrary, steel compressive yield range increased. The stress of compression flange developed faster than the stress of tensile flange, when $\lambda=0.6$.

5. Conclusions
1) The comparison between the numerical results and experimental results shows that the nonlinear finite element model can better simulate the mechanical properties of PSRCB.
2) Nonlinear finite element parametric analysis of PSRCB provides a theoretical basis for engineering application.

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