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Seismic Performance Analysis of Bonded Prestressed CFRP Bar with Mixed Steel Reinforcement Frame-Supported Shear Wall Structure

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Abstract: Under the effect of vertical load and horizontal-low-cyclic load, the whole process of nonlinear finite element numerical simulation analysis of one specimen for bonded fullly prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure and one specimen for bonded partially prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure were conducted. It analyzed the whole process of the structure from concrete cracks to transfer beam yielding until the damage of transfer beam. The analysis also included hysteretic characteristics and skeleton curves. It then studied the plastic strain of full and partially prestressed CFRP bars with mixed steel reinforcement frame-supported shear wall structures and their cracks development law, damage modes, load capacity, ductility performances and seismic performances.

Keywords: *Prestressed, Carbon fiber reinforced plastics bar (CFRP bar), Mixed reinforcement, Frame-supported shear wall, Seismic performance*

1. Introduction

Carbon fiber reinforced plastics (CFRP) bar have several characteristics. They include high tensile strength, good corrosion resistance, and small density. Besides, relevant studies from different countries showed that CFRP bar replaced prestressed reinforcement, which is one of the most effective ways to solve the durability problems of prestressed concrete structures [1-3]. However, for the elastic modulus was slightly lower than the stress-strain relationship of ordinary reinforcement and linear elastic, it led to brittle failure, large crack width and deflection of CFRP bar concrete member under services. These deficiencies limited its promotion and application in the field of civil engineering. Prestressed CFRP bar with mixed reinforced concrete structure comprehensively applied the characteristics of high ductility of reinforcement as well as high tensile strength and corrosion resistance of FRP bar[4-5]. So, prestressed CFRP bar and reinforced mixed reinforcement concrete structure was an ideal reinforcement form.

In 1974, the studies on prestressed glass fiber reinforced plastics (GFRP) reinforced concrete beams were first conducted by people like Rehm[6] from University of Stuttgart. In 1990, the comparative tests of seven post-tensioned prestressed CFRP reinforced concrete beams were conducted by people like Mutsuyoshi [7]. In 1999, the studies on three two-meter GFRP prestressed concrete beam and one full-size twenty-meter prestressed beams were conducted by people like Houssam Toutanji[8]. After the year of 2000, flexural performances of prestressed carbon fiber reinforced concrete beams were studied by people like Rizkalla.S [9].People like Stoll. F [10] conducted relative studies on CFRP prestressed concrete beams. They took concrete strength and pre-stressed level as variables. Patrick [11] analyzed and compared various indicators of ductility and flexural deformation capacity of prestressed FRP bar concrete structures. Through monotonic loading static test of six specimens, people like Xue Weichen[12] studied flexural capacity, displacement ductility and failure modes of bonded prestressed CFRP bar concrete beams. In addition, they conducted nonlinear finite element analysis of teat beam by ANSYS engineering analysis software. In Hunan University, Yang Jian [13] conducted the study of sixteen pre-tensioned prestressed T-shaped section of beams. People like Mohamed [14-16] studied the bending properties of aramid fiber bar with bond, partially bonded and unbonded prestressed beams. Zhang Peng [17] conducted the study of eighteen partially bonded and partially pre-stressed CFRP bar concrete beams. The variable parameters were the ratio of prestressed degree, unbonded prestressed reinforcement length and specimen span.

The frame-supported shear wall structure was a new kind of structure form. It was designed and developed to meet the parking garage under the building, the hall or the road across the city, fire escapes, underground pipe networks and functional requirements of other large spaces. The structure must be set wall transfer structure and convert the upper small bay shear wall structure into the large bay frame structure at the bottom. In this structure, the beam transfer member, namely transfer beam, was widely applied [18]. For transfer beam had clear force-bearing, increased housing height and had simple constructions. However, compared with the general structure layer, for the transfer beam tend to bear the weight of the top wall, it had the characteristics of large structural weight, big structural layer stiffness, larger geometric size, complex loading, more reinforcement quantity and construction difficulties. It affected the application and development of frame-supported shear wall structure.

Therefore, the study proposed that, in the beam transfer member of frame supported shear wall structure, fullly bonded prestressed and partially prestressed carbon fiber reinforced plastics (CFRP) bars with mixed steel reinforcement should be applied. To some extent, this could reduce the reinforced volumes of transfer beam, improve the load capacity of the structure, and then ensure the seismic performance of frame- supported shear wall structure. Under the effect of vertical load and horizontal-low-cyclic load, the whole process of nonlinear finite element numerical simulation analysis of one specimen for bonded fullly prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure and one specimen for bonded partially prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure were conducted. It studied cracks development law, damage modes, load capacity, ductility performances and seismic performances of bonded prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure from concrete cracks to transfer beam yielding until the damage of transfer beam.

2. Specimen Design:

The nonlinear numerical analysis model of two specimens for bonded prestressed CFRP bar with steel mixed reinforcement frame shear wall structures came from the practical engineering structure according to the reduced-scale of 1: 3. It included specimen YZHL-4Q of bonded fullly prestressed CFRP bar with mixed steel reinforcement frame shear wall structure as well as specimen YZHL-4B of bonded partially prestressed CFRP bar with steel mixed reinforcement frame shear wall structure. The dimension of the specimen is showed as following (Fig.1).

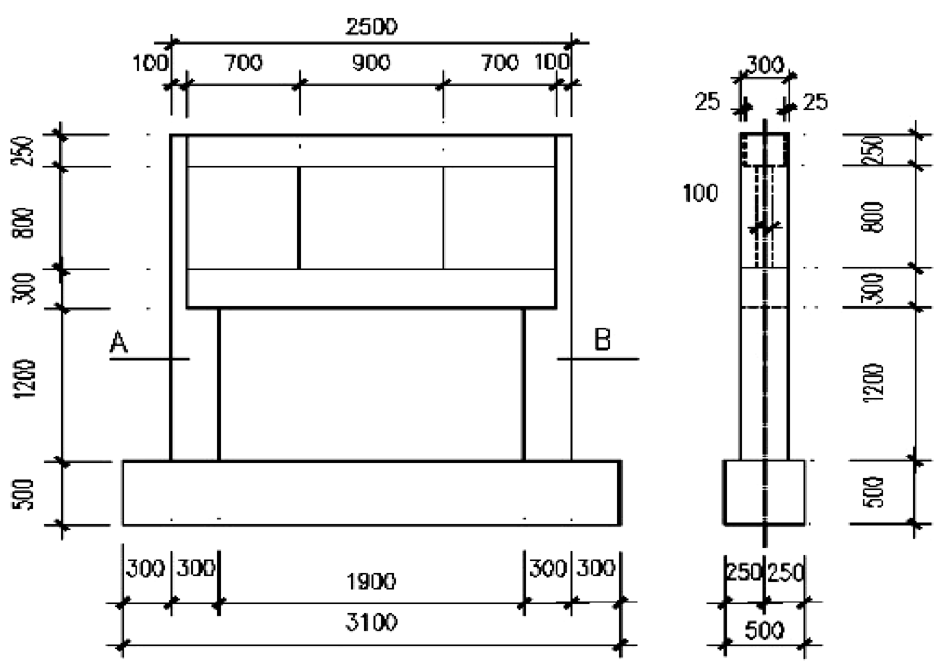


Fig.1: *Specimen Dimensions*

The section dimensions of two specimens were the same. Transfer girders, shear walls, columns and beams were consistent with reinforcement form and reinforcement quantity. Transfer beam applied the form of prestressed CFRP bar with mixed steel reinforcement. The stirrup still all applied reinforcement. However, the longitudinal reinforcement of transfer beam was different. The transfer beam of specimen YZHL-4Q applied the form of bonded fully prestressed CFRP bar with steel mixed reinforcement. The transfer beam of specimen YZHL-4B applied the form of bonded partially prestressed CFRP bar with mixed steel reinforcement. The distributions of two specimens for transfer beam force reinforcement are showed as following (Table 1).

Table 1: *Main Parameters of Transfer Beam*

Specimen Code	Size of Transfer Beam (mm)	Concrete Strength	Prestressed Form	Construction Method	Tension Forces	Main Bearing Reinforcement of Transfer Beam
YZHL-4Q (Fully prestresed)	200*300	C40	Bonded	Post-tensioning method	93kN	Above:$3\varphi_f10$ Below: $3\varphi_fY10$
YZHL-4B (Partially prestressed)			Bonded	Post-tensioning method	62kN	Above: $3\varphi_f10$ Below: $2\varphi_fY10+1\varphi_f10$

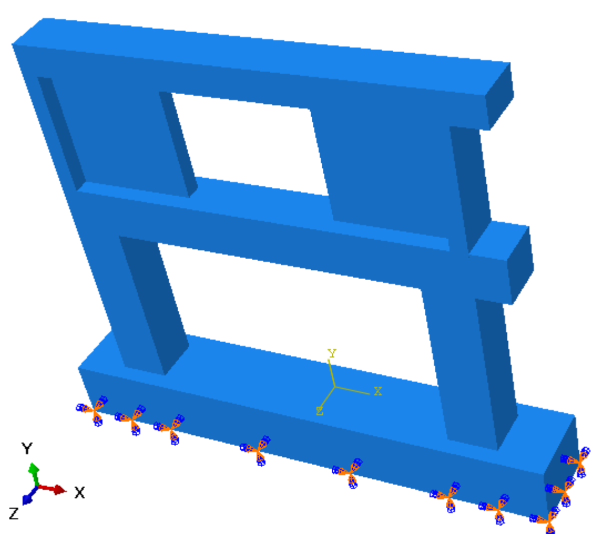
f stands for CFRP bar, Y stands for Prestress

3. Nonlinear Numerical Analysis:

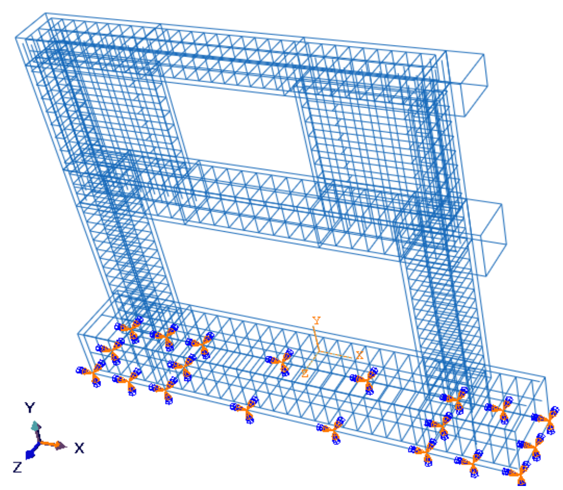
ABAQUS is currently one of the most advanced and large finite element numerical analysis software. It has a wide range of simulation performances and large solution functions [19]. The study applied ABAQUS finite element analysis program, conducted quasi-static simulation analysis on two specimens (YZHL-4Q, YZHL-4B) for bonded prestressed CFRP bars with mixed steel reinforcement frame supported shear wall structure.

3.1 Establishment of Nonlinear Numerical Model:

When simplified nonlinear numerical model, finite element analysis applied separated model [19]. It was found in test that, the bonding between the concrete and the reinforcement performed well, and did not appear slip phenomenon. Therefore, the bonding effects of both could be ignored in the process of simulation. The numerical analysis model is showed as following (Fig.2).



a. Model for Concrete



b. Reinforcement Skeleton

Figure 2: *Numerical analysis model*

3.2 Boundary Conditions and Loading Mode:

3.2.1 Boundary Conditions:

It should ensure that the entire member did not appear overall movement when imposing horizontal reversed cyclic loading. When the finite element model was imposed constraints, all nodes freedom at the bottom surface of the base beam were limited to zero, namely, U1 = U2 = U3 = UR1 = UR2 = UR3 = 0.

3.2.2 Loading Mode:

The fig of loading device is showed as following (Fig.3(a)). When vertical load was imposed, in order to ensure the vertical load could be evenly applied to the specimen, two steel distributive girders were placed above transfer girder, and then the vertical load was imposed by two 1000kN hydraulic jacks. The vertical load was transmitted to transfer girders through steel distributive girders, and then was transmitted to members. The hydraulic jack was placed just above the heart-shaped of short pier shear wall. In order to make the specimen do free horizontal displacement under horizontal load level, the roller bearing was set between the vertical jack and steel girder. The loading way of horizontal load applied two-point loading scheme. It distributed total horizontal load to transfer girder and transfer beam by distributive girder according to the ratio of 1.625:1.

A. The Simulation of Vertical Load:

During finite element analysis, vertical load was imposed to transfer girder above the short-leg shear wall. Given that the weight of the specimen had little effect on load capacity, the influence of self-weight on the structural internal force distribution could be ignored. The vertical load value could be confirmed as axial load ratio 0.3.

$$\frac{N_k}{f_{ck}A} = 0.3 \qquad (1)$$

$$P_v = \frac{N_k}{A_v} \qquad (2)$$

Among these,

N_k— Standard value of vertical load

f_{ck} —Concrete compressive strength value

A — The upper shear wall area

A_v — Vertical load surface

P_{vk} — Standard value of vertical uniform load

B. The Simulation of the Horizontal Load:

During finite element analysis, when imposed concentrated load, it was easy to make concrete cause partial stress concentration phenomenon. Therefore, a steel cushion block was added in the imposed loading section, and then applied uniform load to emulate horizontal load.

$$P_{hk} = \frac{F_k}{A_h} \qquad (3)$$

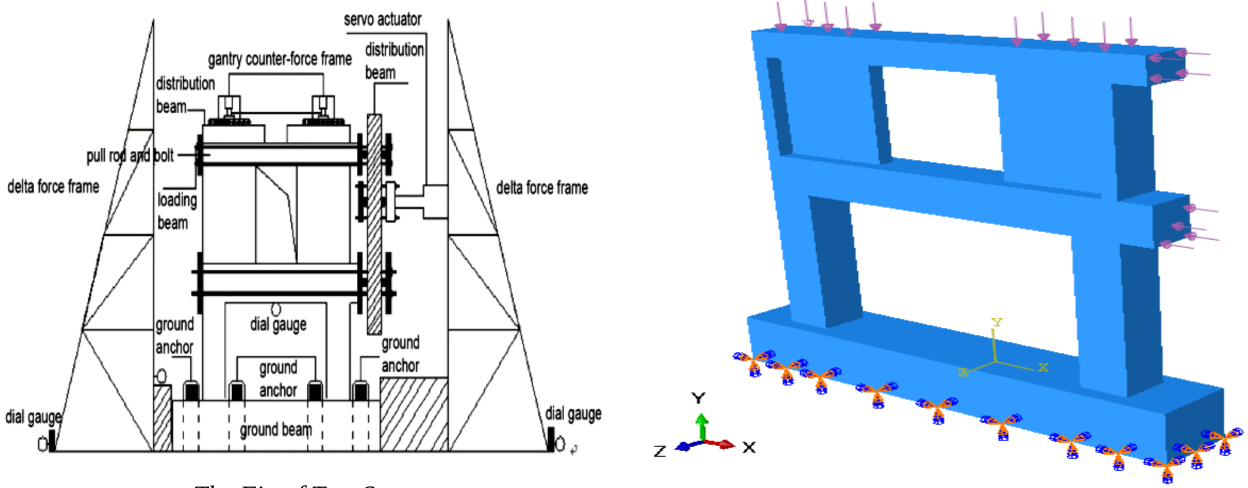
Among these,

P_{hk} — *Standard value of horizontal load*

F_k —*Standard value of horizontal concentrated load*

A_h —*Horizontal concentrated load surface*

The load was divided into two load steps. The first load step was imposed vertical load with a load of 490kN. The second load step maintained the same vertical load, hierarchically imposed horizontal load. The loading system of horizontal load applied hybrid control method of load and displacement, namely, it applied load control before the specimen yielded and applied displacement control after yielding. In this study, each stage of load reciprocated once before yielding and twice after yielding. The loading simulation of numerical analysis is showed as following (Fig.3(b)).



a. The Fig of Test Set-up

b. Loading Simulation by Numerical Analysis

Fig.3: *Loading Mode*

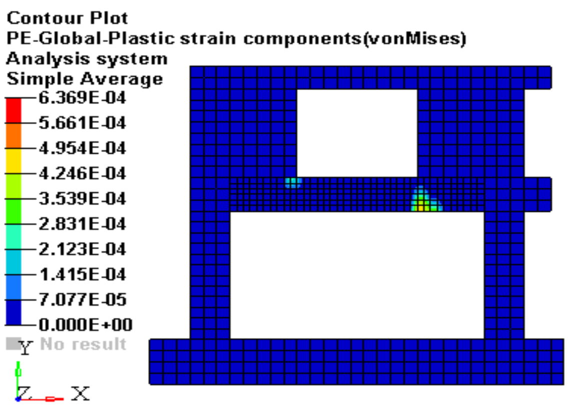
4. Analysis of numerical simulation results:

4.1 Comparative Analysis in the Cracking Process of Specimen:

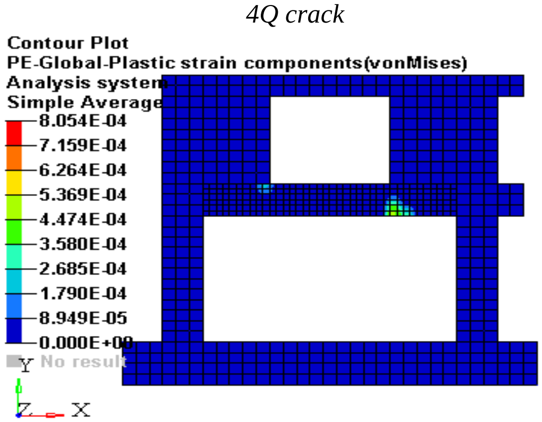
Through the finite element software ABAQUS, the following described the plastic strain development, crack development and distribution of a few key moments (cracking, yielding, damage) in the whole process of nonlinear numerical analysis.

4.1.1 Comparative Analysis of Cracks Distribution When Specimen Cracked:

The following is the distribution contrast cloud picture of the plastic strain. It derived from numerical analysis of the specimen ZHLY-4B and ZHLY-4Q crack (Fig.4). Numerical analysis specimen ZHLY-4Q first produced the cloud picture of plastic strain. It showed that specimen ZHLY-4Q produced larger plastic strain under transfer beam. The transfer beam was under wall limb hole of short-leg shear wall. The plastic strain reminded that the first cracked fracture appeared in this place (Fig.4(a)). Specimen ZHLY-4B first produced the cloud picture of plastic strain (Fig.4(b)). It showed that specimen ZHLY-4B first appeared larger place of plastic strain, namely, the place of first cracked fracture. The place was completely in accordance with that of specimen ZHLY-4Q. The difference was that the maximum plastic strain (8.054×10^{-4}) produced by specimen ZHLY-4B was greater than that (6.369×10^{-4}) of specimen ZHLY-4Q. However, the cracking load of specimen ZHLY-4B (P_{cr}=120kN) was smaller than that (P_{cr}=130kN) of specimen ZHLY-4Q. It showed that imposing full prestress could better improve the crack resistance of CFRP bar with mixed steel reinforcement frame supported shear wall structure than imposing partial prestress.

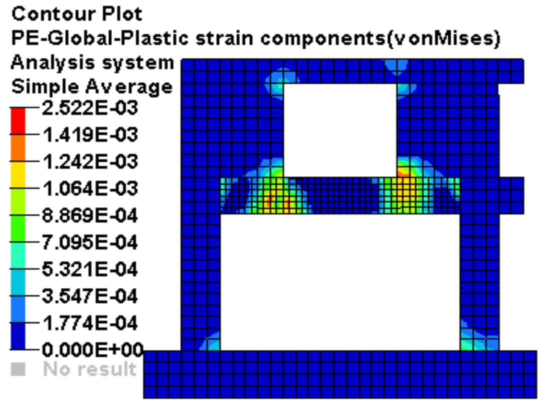


a. The plastic strain distribution cloud picture of ZHLY-4Q crack

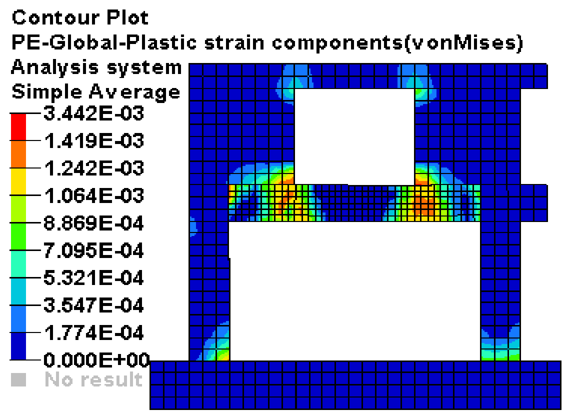


b. The plastic strain distribution cloud of ZHLY-4B crack picture

Fig.4: *The plastic strain distribution contrast cloud picture of crack*



a. The plastic strain distribution cloud picture when ZHLY-4B yielded



b. The plastic strain distribution cloud picture when ZHLY-4Q yielded

Fig.5: *The plastic strain distribution contrast cloud picture of yield*

4.1.2 Comparative Analysis of the Plastic Strain Distribution When Specimen Yielded

The following (Fig.5) comparatively analyzed the distribution and development situation of plastic strain and crack. The plastic strain and crack were achieved by numerical analysis when specimens ZHLY-4B and ZHLY-4Q yielded.

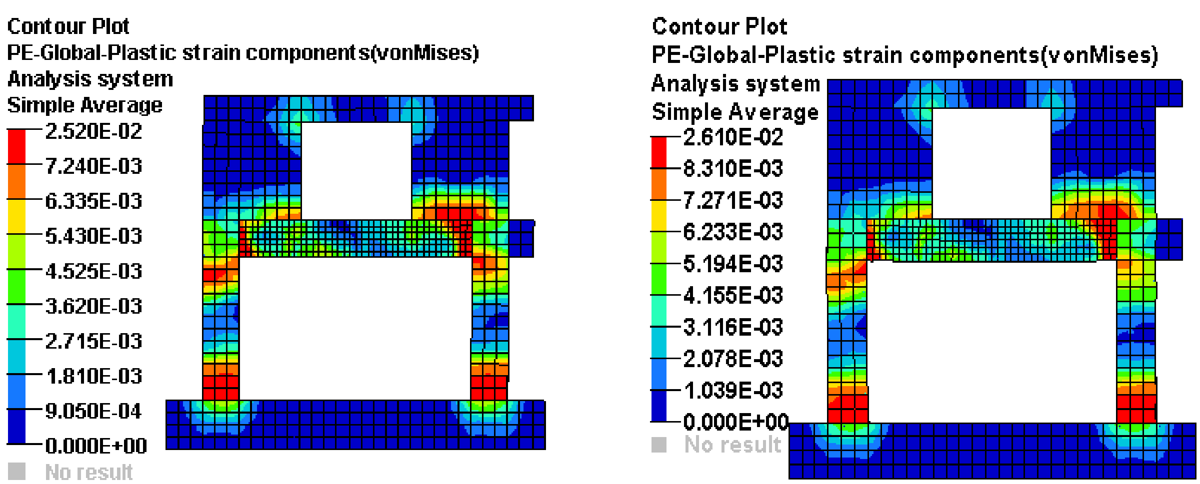
Compared Fig.5(a) and (b), when the specimens ZHLY-4Q and ZHLY-4B were loaded horizontally to the specimen yield, the plastic strain development of two specimens was similar, namely, the cracking development situation was similar. The part of transfer beam plastic strain development was the main place of crack. The crack was under short-leg shear wall, between the frame-supporting column and the hole. The development of the crack was that the original cracks constantly extended to beam-column joints and produced a number of new cracks in the same direction. The cracks were produced dramatically than the previous stage. It was the beginning of the transfer beam longitudinal reinforcement to yield. Both below and above frame-supporting columns appeared plastic strains and a few cracks, while it was not obvious like the plastic strains and cracks in transfer beam. The cracks in short shear wall were mainly extended from transfer beam and was at 45 degree toward the hole. At this time, the maximum plastic strain (3.442×10^{-3}) of specimen ZHLY-4B was greater than that (2.522×10^{-3}) of specimen ZHLY-4Q. While the yield load of specimen ZHLY-4Q and ZHLY-4B was closed to each other.

4.1.3 Comparative Analysis of the Crack Distribution when Specimen Damaged:

The following (Fig.6) comparatively analyzed the distribution and development situation of plastic strain and crack when specimens ZHLY-4Q and ZHLY-4B were in the state of destruction.

Compared Fig.6(a) and (b), when the specimen ZHLY-4Q and ZHLY-4B were loaded horizontally to its damage, the two specimens had some similarities in plastic strain, crack distribution and development. In this stage, the similarities of two specimens were that when transfer beam closed to frame-supporting column, the plastic strain enlarged, cracks were dense, concrete strain reached ultimate strain at the joint of transfer beam and column A and B, the damage became worse, beam-hinge and column-hinge all formed. Members under transfer beam had obvious lateral displacements. The cracks on short-leg shear wall continued to extend from inclined cracks of transfer beam. The cracks under positive and negative loading crossed and extended. The cracks reached nearly half the height of the wall pier. However, they were not serious like transfer beam and columns. Plastic strains below and above frame-supporting column enlarged, cracks appeared and developed widely. The difference of two specimens cracks were that, after the yield, the plastic strain of specimen YZHL-4B was bigger than that of specimen YZHL-4Q. The cracks extended earlier and more from transfer beams to shear walls. It showed that after imposed full prestress, the deformation capacity of transfer beam slightly improved.

In general, when the specimens ZHLY-4Q, ZHLY-4B were loaded horizontally to the final damage of specimen, the plastic strain and cracks all shown such a law that, plastic strain on transfer beam and cracks occurred mainly below short-leg shear wall and near the support of frame-supporting column, while cracks were few in mid-span section of transfer beam. Cracks on frame-supporting column were mainly gathered above and below column, while central column had few cracks. However, the plastic strain and cracks on short-leg shear wall were mainly gathered in the 3/4 position crossed transfer beam, there were almost no cracks in its upper part. What’s more, no matter transfer beam, frame-supporting column, or short-leg shear wall, they all showed strong symmetry.



a.The plastic strain distribution cloud picture when ZHLY-4Q damaged

b.The plastic strain distribution cloud picture when ZHLY-4B damaged

Fig.6: *The plastic strain distribution contrast cloud picture when damaged*

4.2 Comparative Analysis of Load Capacity

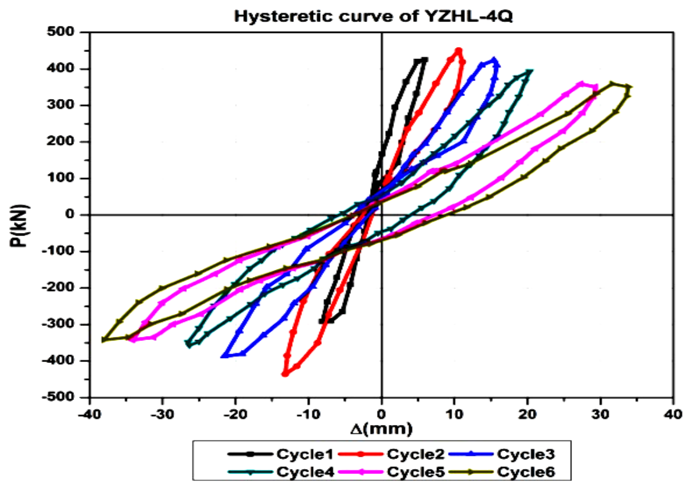
The cracking load, yielding load and ultimate load of specimen were listed as above during numerical analysis (Table 2). For ZHLY-4Q, when the positive and negative loads were respectively loaded to 130kN and 130kN, the first cracks came out from transfer beam. While for ZHLY-4B, the cracking loads were respectively 120kN and 120kN. The cracking load of ZHLY-4Q was higher than ZHLY-4B in positive and negative horizontal loads. For ultimate load, the positive and negative ultimate loads of ZHLY-4Q were respectively 440kN and 400kN during numerical analysis. The positive and negative ultimate loads of ZHLY-4B were respectively 388kN and 365kN. It showed that the ultimate load of ZHLY-4Q was higher than ZHLY-4B in positive and negative horizontal loads.

After analyzing the reasons, it indicated that imposing full prestress had more obvious effects on improving cracking load and anti-crack performances of CFRP bars with mixed steel reinforced frame shear wall structure. It also had more obvious effects on improving load capacity. While applying partial prestress didn't have the same effects.

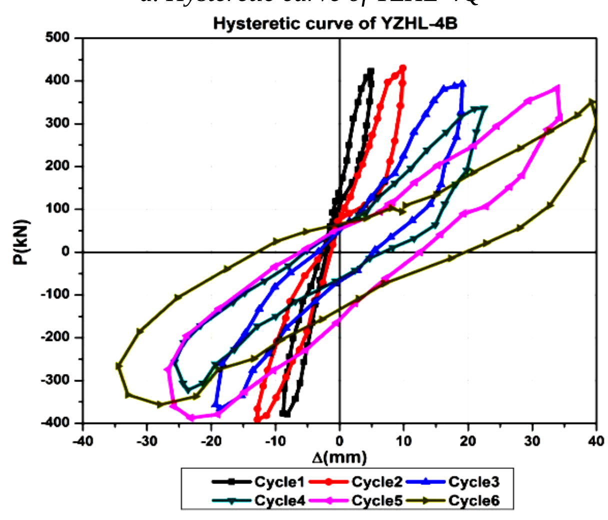
***Table 2*：** *cracking load, yield load, ultimate load of specimens*

No.	P_{cr}(kN)			P_y(kN)			P_u(kN)		
	Forward	Reverse	Mean	Forward	Reverse	Mean	Forward	Reverse	Mean
ZHLY-4Q	130	130	130	270	268	269	440	400	420
ZHLY-4B	120	120	120	275	273	271.5	388	365	376.5

P_{cr}—cracking load; P_y—yield load; P_u—ultimate load



a. Hysteretic curve of YZHL-4Q



b. Hysteretic curve of YZHL-4B
Fig.7: *Hysteretic curve*

4.3 Analysis of Hysteretic Curve under Cyclic Loading:

The following (Fig.7) are the hysteretic curves of transfer beam P-△. P(horizontal force) is the total load applied by tension and compression jack. △ (horizontal displacement) is the horizontal displacement on the left and center of transfer beam.

The two were at the beginning of specimen loading. The hysteretic curve of transfer beam P–Δ was roughly a straight line, the residual deformation was small. It indicated that at this time the specimen was in a state of flexible working. After the crack appeared, the curve began to bend down with the advent of plastic properties of concrete. Under repeated cyclic loading, the transfer beam longitudinal reinforcement yielded, and then the specimen stiffness gradually decreased. At this time, the load increased slightly, while the specimen had obvious displacement, and the hysteretic curve began to appear cyclic annular. Therefore, in order to confirm the yield load or yield displacement of transfer beam, it was determined whether transfer beam longitudinal reinforcement reached yield strain and judged whether hysteretic curves appeared obvious bending. These were more accurate distinguishing methods [20].

In the hysteretic curves controlled by the process of displacement, under repeated loading, from the entire curve form, the hysteretic curves of two specimens all exhibited some pinching phenomenon in positive and negative loading stage. However, the hysteretic curve was quite plump. The phenomenon showed that bonded prestressed CFRP bars with mixed steel reinforcement frame-supported shear wall structure had better seismic performance. However, the hysteretic curve form of specimen ZHLY-4B was more plump than that of ZHLY-4Q. It indicated that partially prestressed CFRP bars with mixed steel reinforcement frame-supported shear wall structure had better ductility and energy dissipation capacity than fullly prestressed CFRP bars with mixed steel reinforcement frame-supported shear wall structure.

4.4 Skeleton Curve Analysis under Cyclic Loading:

It can be seen from the skeleton curve (Fig.8) that, in the test, when specimen YZHL-4B reaches its peak load, the curve remains relatively flat. While when the specimen YZHL-4Q reaches the maximum limit load, the curve has a certain decline, the entire curve trend is not as smooth as specimen YZHL-4B. However, overall curve is relatively flat and has no steep drop. It indicates that bonded prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure have a certain plastic deformation capacity. The load capacity of fully prestressed CFRP bars with mixed steel reinforcement frame-supported shear wall structure is higher than that of partially prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure, while its ductility and plastic deformation capacities are lower than that of partially prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure.

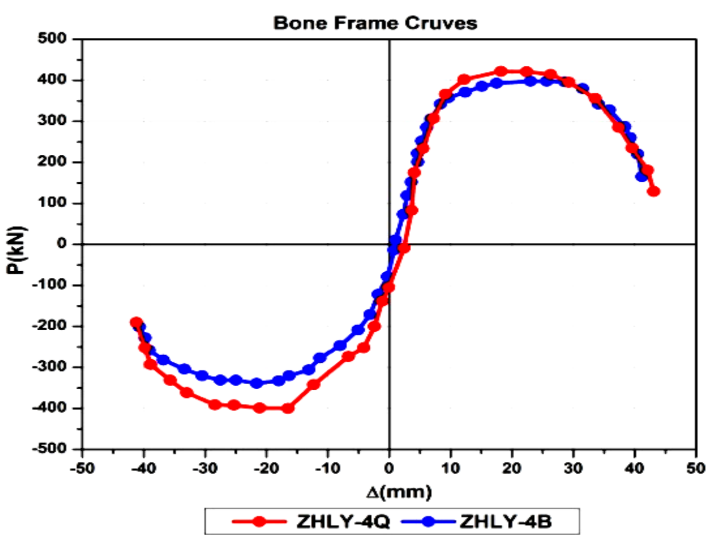


Fig.8: *Skeleton curve comparison of ZHLY-4Q and ZHLY-4B*

5. Conclusion:

Through the above comparative analysis of nonlinear finite element numerical, compared bonded fully prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure and bonded partially prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure, the conclusion can be achieved as the following. The comparison includes plastic deformations, the law of crack development, load capacity, hysteretic curves, skeleton curves and failure mechanism.

- Under positive and negative horizontal loads, the cracking load and ultimate load of bonded fully prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall were bigger than that of bonded partially prestressed CFRP bars with mixed steel reinforcement frame-supported shear wall structure. It indicated that improving prestressed degree could enlarge the crack resistance and load capacity of bonded prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure.
- Properly designed bonded fully prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure member and bonded partially prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure member had similarities from cracking, yielding to damaged plastic strain, crack distribution and development. Besides, they also exhibited the same failure mechanism, namely, beam crossed first, and then column crossed.
- It was seen from the comparative analysis of hysteretic curves and skeleton curves that, bonded fully prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure was similar to bonded partially prestressed CFRP bars with mixed steel reinforcement frame-supported shear wall structure. Both ends of hysteretic curve were plump, skeleton curves decreased smoothly. Prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure had better seismic performances.
- The ultimate displacement of bonded fully prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure member was smaller than that of bonded partially prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure member. It indicated that bonded partially prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure had better ductility and energy-dissipating capacity than that of bonded fully prestressed CFRP bar with mixed steel reinforcement frame-supported shear wall structure.

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