Static test study on precast concrete frame beams with large-diameter and high-strength steel bars

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Abstract. The paper is focused on the mechanical properties of precast concrete frame beams with large-diameter and high-strength steel bars. The full-scale static tests and nonlinear finite element analysis were carried out on the two proposed beams with steel bars of HRB500 Ø32-Ø25 and Ø40-Ø32 to study the load-carrying capacity, flexural capacity and plastic rotational capacity. The influence of steel bar diameter on mechanical properties were explored. On the basis of equal-strength principle of flexural capacity at the same time, the finite element model of the cast-in-place concrete frame beam with large-diameter of HRB500 and ordinary steel bars of HRB400 were compared. Results indicated the properties of the precast concrete frame beams with large-diameter and high-strength steel bar. The load-carrying capacity of the prefabricated concrete beam with steel bars of Ø40-Ø32 was higher. The coefficient of plastic rotational capacity was 3.41 and 2.88 of specimens with steel bars of HRB500 Ø32-Ø25 and Ø40-Ø32, respectively. The positive section yield bending moment could be calculated by the current concrete codes. The properties such as yield load, flexural bearing capacity and the plastic rotational capacity were similar to the cast-in-place concrete frame beam, and could be verified by the current standard.

1. Introduction

The precast concrete structures with small-diameter and low-strength steel bars and various joint of the on-site consolidation leads to the cumbersome installation procedures and the lack of compactness of concrete pouring, which are hard to ensure the quality of concrete pouring and construction efficiency [1, 2]. To address these shortcomings, the paper proposes a precast concrete member with large-diameter and high-strength steel bars. Yin Xiaoli et al., proposed a series of design methods and structural suggestions of precast composite beams and precast frame beam-column joints experimentally and numerically, which can be found in [3 - 5]. The method of at the end of proposed beam in the paper supplement the content of the above-mentioned assemble method. The full-scale static tests and numerical simulations monotonic were carried out on two full-scale precast concrete frame beams with steel bars of HRB500 Ø32 and Ø40, which provide a basis for. Based on the results, the application gist of large-diameter and high-strength steel bars in prefabricated construction have been proposed.

2. Test survey

2.1. Specimen design

Figure 1 shows the detail on the experimental specimens had a net span of 3200 mm, the section was
The concrete strength grade of precast part and post-pouring part was C40 and C45, respectively. The thickness of concrete cover was consistent with the diameter of stressed steel bar. In order to ensure the quality of connection, shear keys for surface roughness treatment were reserved at the end of prefabricated frame beam, and grouting sleeve was used for connection of stressed longitudinal bars [6]. The end of double-sided welded anchor bars was used for anchorage of stressed longitudinal bars in joint area.

| Specimens  | Tensile reinforced | Compressed reinforced | Middle reinforced bars | Stirrups | Additional reinforcement |
|------------|--------------------|-----------------------|------------------------|----------|-------------------------|
| KL-32-25   | 2 Ø 32             | 2 Ø 25                | 3 Ø 12                 | Ø 10@100 | No                      |
| KL-40-32F  | 2 Ø 40             | 2 Ø 32                | 3 Ø 12                 | Ø 10@100 | Lay out                 |

Note: The additional reinforcement was Ø 12, and the strength level of stirrups, middle reinforced bars and additional reinforcement were HRB400.

2.2 Material Properties

The average measured mechanical properties of the HRB500-grade steel bar and concrete are listed in table 2 and table 3, respectively. More detail about the material properties can be found in [7 - 9].

2.3. Test loading device and loading system

The support end of the specimen beam was fixed on the reaction wall through a steel beam, and the monotonic load was exerted on the beam end by an actuator. The experimental loading device is shown in figure 2.
Table 2. Mechanical properties of steel bars.

| $D$(mm) | $\sigma_y$(MPa) | $\sigma_b$(MPa) | Grain fineness | $A_r/%$ | $A_{gt}/%$ | $E_S$(MPa) |
|---------|----------------|-----------------|----------------|---------|-----------|------------|
| 25      | 543            | 725             | 1.34           | 12.4    | 22.0      | $1.83 \times 10^5$ |
| 32      | 548            | 735             | 1.34           | 13.4    | 20.0      | $1.82 \times 10^5$ |
| 40      | 542            | 704             | 1.30           | 13.2    | 23.0      | $1.81 \times 10^5$ |

Note: $\sigma_y$ is the yield strength; $\sigma_b$ is the tensile strength; $A_r$ is the total elongation rate of maximum load; $A_{gt}$ is the elongation after fracture.

Table 3. Structural parameters of concrete.

| Batchs  | Design strength | $f^0_{cu}$ | $f^0_c$ | $f^0_t$ | $E_S$(MPa) |
|---------|----------------|------------|---------|---------|------------|
| First   | C40            | 47         | 35.7    | 3.28    | 34033      |
| Second  | C45            | 43         | 32.7    | 3.13    | 33256      |

Note: $f^0_{cu}$ is the cubic compressive strength of measured strength; $f^0_c$ is the axial compressive strength of estimating value; $f^0_t$ is the axial compressive strength of standard value.

3. Experimental phenomena and failure modes

The figure 3 shows the ultimate failure pattern. The experimental phenomena and failure modes of the two specimens were very similar. Bending failure in the end of the beams. The first crack appeared about 350mm away from the column edge. With the increased of load, more flexural cracks formed and propagated, and the original vertical cracks developed into shear diagonal cracks. The number and length of hair cracks developed rapidly, the crack range gradually extended from beam root to beam end. After the longitudinal bars yielded, the displacement loading was adopted. At this stage, the steel bars were mainly stressed, and concrete gradually drops out of bearing capacity. Therefore, the number and length of cracks in beam body tend to be stable, and crack width starts to develop after the longitudinal reinforcement is yielded, the displacement is applied. Ultimately, the beam deflection exceeded 1/25 of the beam span and reached 1/16 [10], and the concrete at the lower end of the beam is crushed with large pieces falling off, and the concrete at the upper end is slightly damaged.

Figure 2. Test loading device.

(a) KL-32-25 (b) KL-40-32F

Figure 3. The most damaging pattern of specimens.
4. Test results and analysis

4.1. Displacement-load curve

Figure 4 displays the load-displacement curve. Similar development trend is observed among the two specimens, and both had obvious yield steps. After yielding, the growth rate of bearing capacity gradually decreased. Ultimately, the beam deflection exceeded 1/25 of the beam span and reached 1/16, and the bearing capacity had no obvious decline trend. The ductility of the specimen was good and the overall reinforcement structure was reasonable.

It can be seen that the initial stiffness of specimens KL-40-32F was higher than specimens KL-32-25 and the bearing capacity of specimens KL-40-32F also shows obvious advantages, which increases by 22%. It shows that the bearing capacity of the structure can be obviously increased by increasing the diameter of steel bar appropriately.

![Figure 4. Displacement-load curve.](image)

4.2. Crack load calculation and analysis

The cracking bending of beam is shown in table 4, more detail about the calculation method can be found in [11-13]. It can be seen that the measured cracking moment of specimens was smaller than the calculated by the standard due to the concrete cover thickness was consistent with the diameter of tensile steel bar (32/40mm). Therefore, the anti-crack performance of specimens decreases with the increase of the concrete cover thickness.

![Figure 5. Moment-rotation curve.](image)

| Specimens | Experimental value | Calculated value of Gu Xianglin method | Calculate value of Hydraulic code method |
|-----------|---------------------|---------------------------------------|----------------------------------------|
| KL-32-25  | 92                  | 193                                   | 140                                    |
| KL-40-32F | 137                 | 238                                   | 153                                    |

Table 4. Comparison of actual cracking load of test beam and theoretical calculation results.

Note: Superscript t is the test value; superscript c is the calculated value; $M_{cr1}^{t}$, $M_{cr1}^{c1}$ are the yield moment calculated by measured value; $M_{cr2}^{t}$, $M_{cr2}^{c2}$ are the yield moment calculated by standard value.

4.3. Crack width under service load

It can be seen that the maximum crack width under the service load, the measured value is more than 300% of the calculated value (table 5). The results show that anti-crack performance of specimens decreases with the increase of the concrete cover thickness. It is suggested that add steel mesh or reduce the stirrups spacing in order to enhance their anti-crack performance in practical engineering applications.
Table 5. Maximum crack width of test piece under load.

| Specimens  | $M_y$ (mm) | $\omega_s$ (mm) | $\omega_l$ (mm) | $\omega_l^c$ (mm) | $\omega_l^c / \omega_l$ |
|------------|------------|----------------|----------------|----------------|------------------|
| KL-32-25   | 435        | 0.45           | 0.675          | 0.22           | 3.07             |
| KL-40-32F  | 605        | 0.35           | 0.525          | 0.15           | 3.50             |

Note: $\omega_s, \omega_l$ are the short-term and long-term maximum crack width test values of test beams under service loads, respectively; $\omega_l^c$ is the calculation value of maximum crack width.

4.4. Analysis of normal section bending bearing capacity

Table 6 summaries the comparison between the yield moment ($M_y$) and the failure moment ($M_u$) in the measurement and calculation, respectively.

The average value of $M_y^c / M_y^{c2}$ is 1.05, so the yield moment can be calculated by the current concrete codes. It is not significant to calculate ultimate moment by the current codes due to the bearing capacity of specimens decrease unconspicuous during the test. The mean value of $M_u^c / M_u^{c2}$ is 1.24, which indicates that the flexural capacity calculated by current concrete codes has sufficient safety reserve.

Table 6. Flexural bearing capacity of test beam.

| Specimens     | Yield (kN.m) | $M_y^c$ | $M_y^{c2}$ | Failure (kN.m) | $M_u^c$ | $M_u^{c2}$ |
|---------------|--------------|---------|------------|----------------|---------|------------|
| KL-32-25      | 563          | 563     | 455        | 1.00           | 1.23    | 661        | 751        | 0.88 |
| KL-40-32F     | 883          | 835     | 672        | 1.09           | 1.24    | 920        | 1072       | 0.86 |

Note: $M_y^c$ and $M_y^{c2}$ is the yield moment calculated by measured value and standard value, respectively.

4.5. Calculation and Analysis of Plastic Rotation Capability

Figure 5 shows the moment-rotation curve of test beam. Table 7 displays that the plastic rotation capacity of the steel reinforcement diameter 32 was better than diameter 40.

Table 7. Calculation of plastic turning ability of test beam (unit: rad^{-1}).

| Specimens     | $\theta_y$ (10^{-2}) | $\theta_u$ (10^{-2}) | $\theta_p$ (10^{-2}) |
|---------------|----------------------|----------------------|---------------------|
| KL-32-25      | 1.06                 | 4.47                 | 3.41                |
| KL-40-32F     | 1.59                 |                      | 2.88                |

Note: $\theta_y$ is the yielded rotation angle; $\theta_u$ is the failure rotation angle; $\theta_p$ is the plastic rotation angle.

5. Experimental finite element verification

5.1. Moment-turn curve comparison

It can be illustrated that the development trend of test curve is similar to the simulation curve in figure 6 and table 8 show that the simulation results were in good agreement with the test results. Therefore, the finite element model can simulate the bearing capacity of the test specimens better.

Table 8. Comparison of measured eigenvalues and simulated analytical eigenvalues.

| Specimens   | Yield load $M_y^t$ (kN.m) $M_y^c$ (kN.m) | $M_y^t / M_y^c$ Relative Error (%) | Ultimate load $M_u^t$ (kN.m) $M_u^c$ (kN.m) | $M_u^t / M_u^c$ Relative Error (%) |
|-------------|------------------------------------------|-----------------------------------|-----------------------------------------------|-----------------------------------|
| KL-32-25    | 563                                      | 0.98                              | 661                                           | 1                                 | 0.10 |
| KL-40-32F   | 883                                      | 1.05                              | 920                                           | 0.98                              | 2.17 |
5.2. Stress and strain cloud analysis

The stress cloud of specimens is shown in figure 7 and the maximum stress of the component can be seen at the root of beam. Tracking changes of cloud shows that the tension zone of concrete specimen quits work before the shear-compression zone, the bearing capacity was mainly provided by the tensile reinforcement. But the shear-compression zone was still supported by concrete and steel. Until the concrete was crushed, and the neutral axis of the beam moved down to 100 mm from the lower edge of the beam, the bearing capacity of the shear-compression zone was provided by the steel bar and the concrete in the hear-compression zone. The above process was consistent with the test phenomena.

5.3. Fracture contrast

The failure crack state of specimens is depicted in figure 8. The cracking damage of the concrete on the upper side of the beam root is almost complete.

The damage area of the beam body develops from the beam root to the end of the beam with a slope-like reduction, which was basically consistent with the phenomena observed in the experiment.

According to the simulation result, it is shown that the finite element model can accurately simulate the static test study on precast concrete frame beams of large-diameter and high-strength steel bars, and the finite element model of relevant parameters can be used to analyze the model.
6. Finite element comparison analysis

6.1. Basic model parameters

Based on the principle of strength of flexural capacity, the model of the cast-in-place concrete beam with small-diameter steel bars of HRB400 was compared with the experimental model.

The stirrups were Ø10@100 and the basic parameters are shown in figure 9 and table 9.

Table 9. Comparison of measured eigenvalues and simulated analytical eigenvalues.

| Group      | Specimens | Sectional (mm) | Tensile reinforced | $A_s$ (mm$^2$) | Compressed reinforced | $A'_p$ (mm$^2$) |
|------------|-----------|----------------|--------------------|----------------|-----------------------|----------------|
| First group| KL-32-25  | 350×700        | 2 Ø 32             | 1607.68        | 2 Ø 25                | 981.25         |
|            | XKL-32    | 350×700        | 2 Ø 32             | 1607.68        | 2 Ø 25                | 981.25         |
|            | XKL-20(25) | 350×700   | 2 Ø 25+2 Ø 20      | 1609.25        | 2 Ø 25                | 981.25         |
| Second group| KL-40-32F| 350×700        | 2 Ø 40             | 2512.00        | 2 Ø 32                | 1607.68        |
|            | XKL-40    | 350×700        | 2 Ø 40             | 2512.00        | 2 Ø 32                | 1607.68        |
|            | XKL-22(25)| 350×700        | 2 Ø 25+4 Ø 22      | 2501.01        | 2 Ø 25+2 Ø 20         | 1609.25        |

Note: XKL-32 and XKL-40 are integral casting models with small-diameter reinforcement as test specimens KL-32-25 and KL-40-32F; XKL-20 (25) and XKL-22 (25) are the models of integral pouring of small-diameter reinforcing bars with strong bending capacity of test specimens KL-32-25 and KL-40-32F.
6.2. Moment-turn curve comparison
Figure 10 shows that the stiffness of specimens and the development trend of the moment-corner curve was approximately the same. It shows that the stiffness and bearing capacity of the large-diameter steel precast concrete frame beam can meet the requirements of the overall pouring concrete frame beam.

![Figure 10. Comparison of the second set of load-displacement curves.](image)

6.3. Comparative analysis of bearing capacity
It can be seen that the yield load and ultimate load calculated by the finite element model are compared with the test results in Table 10. The median ratio of each group is approximate to 1, which indicates that the bearing capacity of large-diameter precast reinforced concrete frame beams was basically consistent with monolithic concrete frame beams.

| Group     | Specimens      | $M_y$ (kN.m) | $M_y^t/M_y$ | $M_u$ (kN.m) | $M_u^t/M_u$ |
|-----------|----------------|-------------|-------------|-------------|-------------|
| First group | KL-32-25         | 563         | 1.00        | 661         | 1.00        |
|           | XKL-32           | 563         | 1.00        | 655         | 1.01        |
|           | XKL-20(25)       | 569         | 0.99        | 701         | 0.94        |
| Second group | KL-40-32F      | 883         | 1.00        | 920         | 1.00        |
|           | XKL-40           | 852         | 1.04        | 944         | 0.97        |
|           | XKL-22(25)       | 861         | 1.03        | 941         | 0.98        |

Note: $M_y$ is the yield load; $M_u$ is the failure load.

6.4. Comparative analysis of plastic rotation capacity
The compare result between the finite element model and the test are listed in Table 11.

| Group     | Specimens      | $\theta_y$ ($10^{-2}$) | $\theta_u$ ($10^{-2}$) | $\theta_p$ ($10^{-2}$) |
|-----------|----------------|------------------------|------------------------|------------------------|
| First group | KL-32-25 | 1.06 | | 3.41 |
|           | XKL-32 | 1.05 | | 3.42 |
|           | XKL-20(25) | 1.12 | 4.47 | 3.35 |
| Second group | KL-40-32F | 1.59 | | 2.88 |
|           | XKL-40 | 1.40 | | 3.07 |
|           | XKL-22(25) | 1.55 | | 2.92 |
The plastic rotation angle in each group is close, which indicates that the plastic rotation capacity of precast concrete frame beams large-diameter meets the requirements of current codes.

7. Conclusion
In this paper, the following conclusions are provided:

- the bearing capacity and plastic rotation capacity of large-diameter and high-strength precast concrete frame beams with steel bar Ø40-Ø32 are superior;
- after the beam-end deflection exceeds 1/25 of the beam span and reaches 1/16, the trend of bearing capacity without obvious falling, which indicates that the ductility of precast concrete members with large-diameter reinforced was excellent;
- for large-diameter reinforced precast concrete frame beams, the yield moment of normal section can be calculated by current concrete codes. The cracking moment and the ultimate moment are quite different from those calculated by the codes. The flexural capacity calculated by current concrete codes has sufficient safety reserve. The plastic rotation capacity coefficients of the specimens with steel bar of Ø32-Ø25 and Ø40-Ø32 are 3.41 and 2.88, respectively.
- There is no crack and mutual dislocation between the prefabricated and cast-in-place joint interface concrete of the test beam, which shown that it was feasible to set up rough surface and shear keys at the assembly interface. The effective transmission of force can be ensured by using double-sided bonded anchor bars and sleeve splicing in the beam-column joint area.
- The anti-crack performance of the large-diameter steel bar specimens decreases with the increase of the concrete cover thickness. It is suggested that add steel mesh or increase the density of transverse stirrups in order to enhance their anti-crack performance in practical engineering applications.

Reference
[1] Yin X W Huang X K Tian C Y Li Y Liu Q and Liu L 2016 Experimental study on flexural performance of RC composite beams with large spacing HRB500 high-strength longitudinal rebar Journal of Building Structures 37 pp 291-296
[2] Yin X W Huang X K Tian C Y Li Y Liu L and Liu Q 2016 Experimental study on seismic behavior of RC columns with large spacing and high strength longitudinal reinforcements Journal of Building Structures 37 pp 41-47
[3] Wang J Tian C Y Yan F Gao J and Tan Y A 2015 Experimental Study on Bending Performance of Full-tale Superposed RC Beam with Cast-in-place Joint Building Technology 31 pp 57-61
[4] Li G Q Huang X K Tian C Y Yin X W and Li Y 2015 Experimental study on shear performance of reinforced concrete superposed beams with overlapping hoops Journal of Building Structures 36 pp 286-291
[5] Gao J Tian C Y Hao W and Tan Y A 2015 Experimental study on seismic behavior of precast concrete layered slab and beam to column interior joints Journal of Building Structures 36 pp 196-202
[6] Liu L 2015 Experimental study on seismic performances of precast concrete frame connections with rebars of large diameter and enlarged spacing (Beijing: Chinese Academy of Sciences)
[7] Ertas O Sevket O and Turan O 2006 Ductile Connections in Precast Concrete Moment Resisting Frames PCI Journal 51 pp 66-76
[8] Gao Y F Liang X B and Deng X L 2010 Metallic materials - Tensile testing - Part 1: Method of test at room temperature (Beijing: China Architecture & Building Press)
[9] MOHURD 2014 Standard for test method of concrete structures (Beijing: China Architecture & Building Press)
[10] Liu Y L Chu D H Liu J J and Zhong X 2015 Comparative study on calculation formula of crack load for reinforced concrete beam Building Structure 45 pp 14-17
[11] Gu X L 2011 Basic Principles of Concrete Structures (second edition) (Shanghai: TongJi Univ. press)
[12] National Energy Administration 2009 *Design specification for hydraulic concrete structures* (Beijing: China Electric Power Press)

[13] MOHURD 2010 *Code for design of concrete structures* (Beijing: China Architecture & Building Press)