Study on the shear capacity of partially precast castellated steel reinforced concrete beams

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Abstract. This paper focuses on the shear capacity of partially precast castellated steel reinforced concrete (PPCSRC). A test including 7 specimens was carried out and parameters of shear span ratio, cast-in-site concrete strength and castellated steel were analysed. On the basis of the current calculation methods, this paper also proposed an equation to calculate the shear capacity of PPCSRC. By comparing the test results and calculation results, the proposed equation can be considered as reasonable.

1. Introduction

Partially precast steel reinforcement concrete (PPSRC) is a new concept compared with entire precast steel reinforcement concrete (PSRC). PPSRC beams consist of the precast concrete outer part, inner steel shape, longitudinal reinforcement, stirrups and cast-in-site concrete. Several tests and studies had been conducted in a few years before and PPSRC beams show reliable mechanical properties of bending and shearing[1,2]. Partial precast castellated steel reinforced concrete (PPCSRBC) beams are alternative to PPSRC beams, since many studies conclude that the castellated steel reinforced concrete beam shows similar mechanical properties of traditional steel reinforced concrete beam [3,4]. This paper analyses some indicates which have influence on the shear capacity of PPCSRC beam and provides a calculation method for PPCSRC beam.

2. Overview of the test

2.1. Overview of the specimen

7 T-beam specimens are designed for the test, and the cross-section sizes of the specimens are all 200mm×400mm×880mm×100mm. The castellated steel was made of Q235 steel with the size of HN175×90×5×8mm. The detailed mechanical information of the components are listed in Table 1.

| Component        | Yield strength/MPa | Ultimate strength/MPa |
|------------------|--------------------|------------------------|
| Longitudinal rebar | 420                | 578                    |
| Stirrup          | 387                | 545                    |
| Steel flange     | 262                | 436                    |

The diagrams of PPCSRC beam are shown in Figure 1 and Figure 2 and the parameters of specimen are listed in Table 2. The test was a monotonic static loading system. The specimens were loaded with
three-point symmetry and single-point loading in the middle of the span. The test loading device is shown in Figure 3.

![Diagram of PPCSRC beam section.](image1)

![Diagram of castellated steel.](image2)

![Diagram of PPCSRC beam.](image3)

| Table 2 Parameters of Specimens |
|-------------------------------|----------------|--------------------|---------------------------|
| Number |  $f_{cu, out}/\text{MPa}$ |  $f_{cu, in}/\text{MPa}$ | Loading type | Shear span ratio | Failure mode |
| B-1    | 54.0                  | 21.7                | One-point          | 1.0                | Diagonal compression |
| B-2    | 54.0                  | 21.7                | Two-point          | 1.5                | Shear compression |
| B-3    | 54.0                  | 38.1                | One-point          | 1.0                | Diagonal compression |
| B-4    | 54.0                  | 38.1                | One-point          | 1.5                | Shear compression |
| B-5    | 54.0                  | 38.1                | One-point          | 2.0                | Shear compression |
| B-6    | 54.0                  | 38.1                | One-point          | 2.5                | Shear compression |
| B-7    | 54.0                  | 68.0                | Two-point          | 1.5                | Shear compression |

2.2. Overview of test result

As Table 2 shows that only B-1 and B-3 are diagonal compression failure, the other specimens all show shear compression failure. To describe the similar destruction process of the other 5 specimens, B-7 is taken as an example (Figure 4&5). When it loaded to 960kN, the flange slab concrete was crushed and the web surface in the shear span section peeled off. After that, the load began to drop.

![Failure mode of B-7.](image4)

![Internal failure mode of B-7.](image5)
From Figure 4 and 5, it can be observed that the cross-sections of section steel, precast concrete and cast-in-site concrete are well connected without obvious slip marks. The diagonal cracks in the internal core concrete penetrate evenly which shows obvious shear compression failure mode. Besides, the castellated steel did not undergo partial out-of-plane buckling.

3. Analysis and discussion

3.1. Shear span ratio
In terms of Table 2, to analyse the influence of shear span ratio, B-3, B-4, B-5, B-6 can be grouped and contrast their test results. The load-deflection curves of the 4 specimens are shown in Figure 6 and the curve illustrates the relationship between the load and shear span ratio is in Figure 7.

From Figure 6 we can see that when the shear span is small, the shear capacity of the beam is relatively high. With the increase of the shear span ratio, the bearing capacity of the specimen decreases significantly. It can be observed that the influence of the shear span ratio on the shear capacity of the precast castellated steel concrete beam is quite obvious, the larger the shear span ratio leads to the better the deformation performance of the beam. This is similar to the conclusion of ordinary steel concrete beams. From Figure 7 we can see that as the shear span ratio increases, the ultimate capacity of the specimen decreases.

3.2. Compressive strength of cast-in-site concrete
As Table 2 shows, two groups of specimens can be divided to analyse the influence of compressive strength of cast-in-site concrete. B-1 and B-3 are in one group, while B-2, B-4 and B-7 are in the other group. Their load-deflection curves are shown in Figure 8 and Figure 9, respectively. Figure 10 illustrates the relationship between the compressive strength of cast-in-site and ultimate load.

From the figures below we can find that the higher cast-in-site concrete strength leads to the higher shear capacity of the beam.
4. Calculation method

4.1. Calculation method from standards

At present, the domestic calculation method for the shear capacity of the oblique section of steel reinforced concrete members is mainly the superposition method. This kind of method means to calculate the sum of the shear capacity of the steel section and the shear capacity of the reinforced concrete. Zhao et al. [5] confirmed this method is reliable and standard JGJ 138 [6] and YB 9082 [7] both adopted it. The equation is shown below, which includes three parts, shear capacity of concrete $V_c$, shear capacity of stirrup $V_{sv}$ and shear capacity of castellated steel $V_{sw}$. The detailed calculation method of the three parameters are listed in Table 3.

\[ V = V_c + V_{sv} + V_{sw} \]  

(1)

| Standard   | $V_c$     | $V_{sv}$ | $V_{sw}$ | $V_c'$ |
|------------|-----------|----------|----------|--------|
| JGJ 138    | $0.58f_c(h_u - D_k)\gamma \sum f_{sv}A_w$ | $0.8f_bh_b(1-1.6\frac{D_k}{h})$ | $0.8f_bh_b$ |
| YB 9082    | $\gamma'f_{sv}(h_u - D_k)f_{sw}$ | $0.5\sum f_{sv}A_w$ | $0.7f_bh_b(1-1.6\frac{D_k}{h})$ | $0.7f_bh_b$ |

According to the calculation methods in the two standards, the shear capacity of the 7 specimens were calculated and compared with the test results.

Table.4 Comparisons between the results calculated in accordance with the standard and the test results

| Specimen | $V$ (kN) | $V_{JGJ}$ | $V_{JGJ}/V_u$ | $V_{YB}$ | $V_{YB}/V_u$ |
|----------|----------|-----------|---------------|----------|--------------|
| B-1      | 585      | 214       | 0.37          | 209      | 0.36         |
| B-2      | 420      | 235       | 0.56          | 220      | 0.52         |
| B-3      | 670      | 270       | 0.40          | 258      | 0.39         |
| B-4      | 435      | 292       | 0.67          | 269      | 0.62         |
| B-5      | 333      | 336       | 1.00          | 291      | 0.87         |
| B-6      | 250      | 358       | 1.43          | 302      | 1.21         |
| B-7      | 480      | 296       | 0.62          | 273      | 0.57         |

The main reason for the deviation in the table could be that it is too conservative to use the lower concrete strength of the precast beam and the laminated layer to calculate the shear capacity of the specimen [8]. The specimens adopt a prefabricated U-shaped cross-section with transverse ribs, which restrains the cast-in-site concrete. As a result the overall shear resistance of the PPCSRC beam is improved. In conclusion, the calculation methods in the standards are not appropriate to PPCSRC beam.
4.2. Suggested design method and test verification

In order to derive the calculation method of shear capacity, the following assumptions are made:

- The end of the broken oblique section is the section under the point of concentrated load;
- In the calculation, precast and cast-in-site concrete are assumed as a whole;
- The normal stress and shear stress of concrete in the shear zone are evenly distributed;
- The force acting point of the castellated section is at the centre of the oblique section;
- The castellated steel webs and stirrups both reach yield.

With the assumptions, the calculation method of PPCSRC can be derived on the basis of the Equation 1, which means the shear capacity of PPCSRC is the sum of the shear contributions of the three parts of concrete, stirrups and steel.

4.2.1. Shear contribution of the concrete

Equation 2 is used to calculate the concrete equivalent axial tensile strength $f_{tc}$. In order to consider the contribution of the flange of the T-shape beam, flange magnification factor $\gamma_f'$ should also be calculated.

$$f_{tc} = \frac{A_{c1}}{A_{c1} + A_{c2}} f_{t1} + \frac{A_{c2}}{A_{c1} + A_{c2}} f_{t2}$$

$$\gamma_f' = \frac{(b_f - b) h_f f_{t1}}{A_f f_{t1} + A_{c2} f_{t2}}$$

where:
- $b_f$: the width of the flange of the T-beam;
- $h_f$: the height of the flange of the T-beam;
- $A_{c1}, A_{c2}$: the cross-sectional areas of the cast-in-place and precast parts, respectively;
- $f_{t1}, f_{t2}$: the axial tensile strength of the cast-in-place and precast concrete, when $f_{cu} \leq 50\text{MPa}$, $f_{t1} = 0.26 f_{cu}^{2/3}$; when $f_{cu} > 50\text{MPa}$, $f_{t1} = 0.21 f_{cu}^{2/3}$.

As a result, the shear contribution of concrete can be calculated as Equation 4:

$$V_c = (1 + \gamma_f') \alpha f_{wc} bh_0$$

$$\alpha = 1.75/(\lambda + 1)$$

where $\lambda$ is the shear span ratio of the specimen.

4.2.2. Shear contribution of the stirrup

Shear contribution of the stirrup can be calculated as Equation 6.

$$V_s = \varphi \frac{A_s}{s} f_{sv} h_0$$

where $\varphi$: the resistance coefficient of stirrups, which is 1 according to JGJ-138.

4.2.3. Shear contribution of the castellated steel

Two factors should be considered when the contribution of the castellated steel is calculated, the hole position coefficient $\varphi$ and the hole shape coefficient $\eta$.

$$\varphi = \frac{r \cos \alpha}{D_h}$$

where $r$ is the length of the oblique crack passing through the hole, $D_h$ is the diameter of the hole, and $\alpha$ is the angle between the line of the support loading point and the length of the beam.

For low shear span ratio, when $\varphi < 0.1$, take $\varphi = 0.1$. For high shear span ratio, when $\varphi > 1$, take $\varphi = 1$.

The shear capacity of the castellated hole is about 92% to 96% of that of the circular hole beam[9]. Therefore, the section steel with castellated holes should be reduced, take $\eta = 0.9$.

The shear contribution of castellated steel can be calculated as Equation 7.

$$V_s = \beta \eta f_{sh} (h_0 - \varphi D_h)$$

where $\beta = 0.58/\lambda$. Finally, the shear capacity of PPCSRC beam should be calculated as Equation 8 below:

$$V = \frac{1.75(1 + \gamma_f')}{\lambda + 1} f_{wc} bh_0 + \frac{A_s}{s} f_{sv} h_0 + \frac{0.58}{\lambda} \eta f_{sh} (h_0 - \varphi D_h)$$
4.3. Comparison of testing result and calculation result

According to the proposed equation above, the shear capacity of specimens are calculated. Then the calculated results are compared with the test results, which are listed in Table 5 below.

Table 5: Comparisons between the results calculated by the proposed formula and the test results

| Specimen | φ  | $V_{te}$ | $V_{ca}$ | $V_{ca}/V_{te}$ |
|----------|----|----------|----------|-----------------|
| B-1      | 0.10 | 585      | 505      | 0.86            |
| B-2      | 0.37 | 420      | 371      | 0.88            |
| B-3      | 0.10 | 670      | 593      | 0.89            |
| B-4      | 0.37 | 435      | 441      | 1.01            |
| B-5      | 0.88 | 333      | 339      | 1.02            |
| B-6      | 1.00 | 250      | 290      | 1.16            |
| B-7      | 0.37 | 480      | 484      | 1.01            |

$V_{te}$: shear capacity results from the test;

$V_{ca}$: shear capacity results from the proposed equation.

The comparison table shows that the proposed calculation results are similar to the test results, so the proposed can be considered as reasonable.

5. Conclusion

- By removing the concrete at the beam after the test, it is found that there is no slip phenomenon, which indicates that the partial precast method has little effect on the shear capacity of PPCSRC.
- With the decrease of shear span ratio, the bearing capacity of inclined section increases; with the increase of concrete strength, the bearing capacity of inclined section increases.
- According to the comparison results, the calculation results from proposed equation show good agreement with the test results. The proposed equation is reliable.

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