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Collaborative Optimization Scheme of Mechanical Properties and Engineering Economy of Double T-shaped Vierendeel PEC Beam Based on Abaqus Simulation

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Abstract. A partially encased steel-concrete composite (PEC) structure has high bearing capacity and good seismic performance, but the traditional solid web structure uses a large amount of steel and has a long period. In this paper, a double T-shaped flange open-web PEC beam is proposed. Based on Abaqus parameter analysis and value engineering theory, its shear performance and economy are evaluated. The results show that as the web thickness increases from 6mm to 10mm, the bearing capacity increases by about 13.7%, and the average increase rate is 3.4% per 1mm. As the strength of concrete increased from C30 to C50, the bearing capacity increased by only 6.9%, and the marginal increase of each grade was 1.5%~1.8%. The value coefficient analysis shows that the web thickness of 6~7mm has the best performance-to-price ratio, and the economy of more than 7mm decreases. From C30 to C50, the V value continued to drop to 0.972. When the open-web ratio was 55%~65%, the steel consumption and shear performance were best balanced. Based on the comprehensive specification, the optimization parameters are proposed: web thickness of 6~8mm, concrete C30~C40, and open-web rate of 55%~65%. The open-web full prefabricated assembly can shorten the construction period by 20%~30% and reduce the comprehensive cost by 10%~15%. It is recommended to promote it in industrial plants and large-span public buildings.

Keywords: Double T-shaped flange open-web PEC beam, Shear capacity, Value engineering, Collaborative optimization, Abaqus finite element analysis

1. Introduction

Partially encased steel-concrete composite (PEC) structure has high bearing capacity, high stiffness, and excellent seismic performance. Due to the wrapping effect of concrete, the fire and corrosion resistance performance is better than that of pure steel, which can simplify the surface treatment process, and has been applied in some developed countries. However, current construction is still dominated by the traditional solid web PEC beam and on-site turnover pouring, with a large amount of steel and a long period. For this reason, the proposed "double T-shaped flange open-web PEC beam" removes the steel in the middle of the web, only retains the upper and lower web plates, and

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is connected by tie bars and connecting rods. Concrete is poured in the open-web area to avoid turning over maintenance, shorten the construction period, and reduce the cost.

The mechanical properties have been systematically explored by Abaqus. Chu Liusheng et al. Found through shear test and finite element analysis that when the shear span ratio increased from 1 to 3, the bearing capacity decreased by 44.08%, and when the open-web ratio decreased from 67.4% to 51.1%, the bearing capacity increased by about 8.82% [1]. Chen Yunhui's research on PEC beams with corrugated webs shows that the shear capacity increases by 9.82% when the web thickness increases from 2.5mm to 4mm, while the concrete strength increases by 4.59% from C30 to C45 [2]. The above rules show that increasing the web thickness or reducing the open-web ratio can improve the safety performance, but increase the steel cost. On the contrary, the provincial steel may not meet the requirements of bearing capacity, highlighting the contradiction between mechanics and economy.

At present, there is still a gap in the economic research of the Vierendeel beam. Based on the parametric analysis of Abaqus, this paper systematically investigates the influence of web thickness, open-web ratio, and concrete strength on the shear capacity, and, combined with the assembly comprehensive cost, constructs the value coefficient model of "bearing capacity/unit cost", which realizes the collaborative quantitative evaluation of mechanical properties and economy, and provides the basis for the optimization design and engineering application.

2. Establishment and verification of refined finite element model of double T- shaped Vierendeel PEC beam

2.1. Establishment of finite element model

CDP model was used to simulate cracking, crushing and stiffness degradation of concrete. The uniaxial stress-strain relationship is determined in accordance with code for design of concrete structures (GB 50010-2010) [3]. The compression curve is expressed as follows:

When $x \leq 1$(rising section):

$$y=\alpha_a x+(3-2\alpha_a)x^2+(\alpha_a-2)x^3 \tag{1}$$

When $x>1$(segment):

$$y=\frac{x}{\alpha_d(x-1)^2+x} \tag{2}$$

Where $x=\frac{\varepsilon}{\varepsilon_{c,r}}$, $y=\frac{\sigma}{f^*_{c,r}}$, $\varepsilon_{c,r}$ is the peak compressive strain corresponding to FC, α_a and α_d are the parameter values of the rising section and the falling section respectively. The uniaxial tensile stress-strain curve is expressed as follows:

When $x \leq 1$(rising section):

$$y=1.2x-0.2x^6 \tag{3}$$

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When x>1(segment):

$$y=\frac{x}{\alpha_t(x-1)^{1.7}+x} \tag{4}$$

Where α_t is the parameter value of the tensile descent section.

CDP model parameters are taken as dilation angle 30 °, eccentricity 0.1, biaxial and uniaxial compressive strength ratio 1.16, Kc=0.6667. The viscosity parameter is 0.0005.

The steel (section steel, connecting rod, and reinforcement) adopts the double broken-line elasto-plastic constitutive model, which is ideal elastic before yielding and linearly strengthened after yielding, and complies with the von Mises yield criterion. Constitutive relation:

$$\sigma_s=\begin{cases} E_s\varepsilon_s, & \varepsilon_s\leq\varepsilon_y \\ f_y+E_s'(\varepsilon_s-\varepsilon_y), & \varepsilon_y<\varepsilon_s\leq\varepsilon_u \end{cases} \tag{5}$$

Where E_s is the initial elastic modulus (2.06 × 105Mpa), E_s' is the strengthening modulus ($0.01E_s$), f_y is the yield strength, ε_y is the yield strain, ε_u is the ultimate strain, and Poisson's ratio is 0.3.

Figure 1 shows the assembly process of the model, in which (a) to (c) are the models of each independent component, respectively, and (d) is the overall finite element model after assembly.

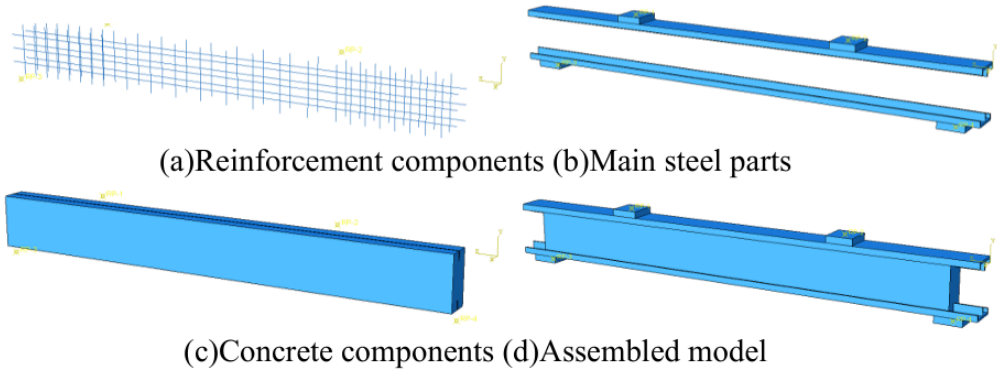


Figure 1. Model assembly process (photo/picture credit: original)

Four node reduced integral shell element S4R (grid 20~40mm) is used for the upper and lower flanges and webs; The concrete adopts an eight-node hexahedron linear reduced-integration solid element C3D8R (grid 30~50mm); a two-node linear three-dimensional truss element T3D2 (grid 10~20mm) is used for the C-shaped connecting rod and tie bar. Steel and concrete face-to-face contact, normal hard contact, tangential penalty function, friction coefficient 0.35; The connecting rod and tie bar are "embedded" constraints. One end of the test piece is fixed with a hinged support (U1=U2=U3=0), and the other end is a sliding hinged support (U1=U2=0). The displacement is controlled for loading, and rigid cushion blocks are set to avoid stress concentration. Figure 2 shows the finite element mesh divided by the above units.

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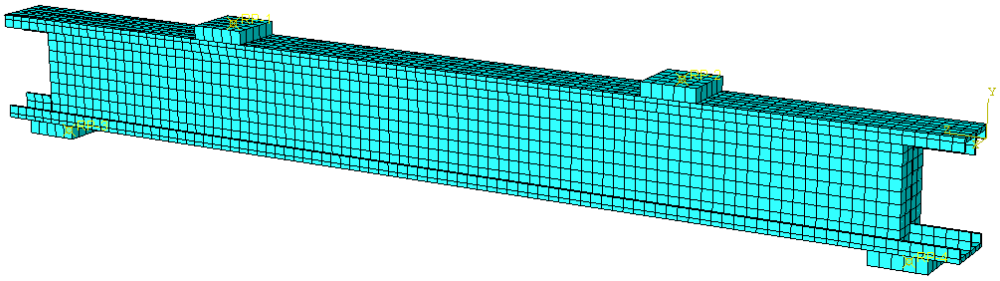


Figure 2. Finite element mesh of cell division (photo/picture credit: original)

2.2. Model validation

The comparison results with the existing PEC Vierendeel beam test are shown in Table 1. The ratio of the finite element simulation value and test value of the specimen with shear span ratio λ=2 and Vierendeel ratio η=0.40 is between 0.96 and 1.06, and the deviation is within 6%, indicating that the model accuracy is good. The tensile damage contour plot of concrete is consistent with the location of the diagonal crack in the experimental web shear, and the distribution of steel stress is reasonable.

Table 1. Comparison between simulated and test values of ultimate load

Specimen Number	λ	Test value(kN)	Analog value(kN)	Analog/Test	Deviation
V1	1	1689.7	1622.1	0.960	-4.0%
V2	2	900.6	936.6	1.040	4.0%
V3	3	372.8	395.2	1.060	6.0%

3. Influence of various parameters on shear capacity

3.1. Stress analysis of steel castings and steel bars

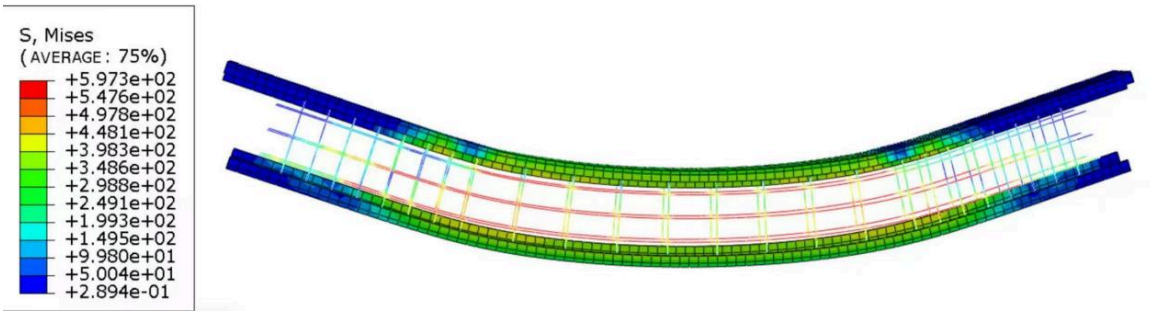


Figure 3. Stress contour plot of main steel parts, connecting rods and tie bars (photo/picture credit: original)

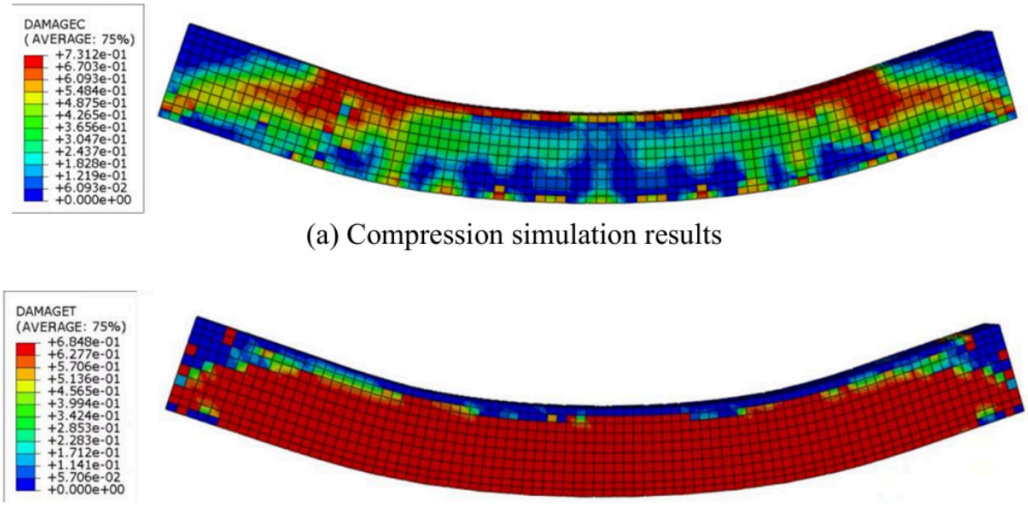
Figure 3 shows the von Mises stress contour plot of steel parts under ultimate load. Under the ultimate load, the stress of the lower flange in the middle of the span and the lower flange of the shear span section is high, and some of them enter the yield (Q355B, about 355MPa). The web stress of the shear span section is significantly higher than that of the midspan; the upper and lower web plates are involved in shear resistance, and the shear stress is evenly distributed along the web

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height. The compression flange is not locally buckled due to concrete restraint. The shear span connecting rod and tie bar yield at ultimate load (about 400MPa) effectively participate in shear resistance, and the stress distribution of tie bar is consistent with the direction of the inclined crack.

3.2. Failure analysis of concrete

Figure 4 shows the tensile damage contour plot and compressive damage contour plot of the concrete under the ultimate load of the finite element model. The tensile damage mainly occurs in the concrete web of the shear span section, and the compressive damage is concentrated below the loading point and near the support. When the shear span ratio is small (λ=1), the compression damage is concentrated in the area of the inclined short column at the end of the inclined crack. When the shear span ratio is large (λ=3), the compression damage is mainly in the compression area of the pure bending section in the middle of the span.



(a) Compression simulation results

(b) Tensile simulation results

Figure 4. distribution of concrete failure (photo/picture credit: original)

3.3. Influence of concrete strength

Take λ=2 as the benchmark model, keep other parameters unchanged, and use C30~C50 concrete. Figure 5 shows the load–mid-span deflection curve. At the elastic stage, the curves basically coincide, and the concrete strength has little effect on the initial stiffness. In the elastic-plastic stage, the slope of the curve increases slightly with the increase in strength, and the bearing capacity increases. The ultimate bearing capacity under different concrete strength grades is shown in Table 2: from C30 to C50, the increase is about 6.9%, and the increase rate of each grade is about 1.5%~1.8%, indicating that the effect of concrete strength on the improvement of bearing capacity is limited, which is consistent with the conclusion that the shear contribution of concrete under open-web structure is small [4].

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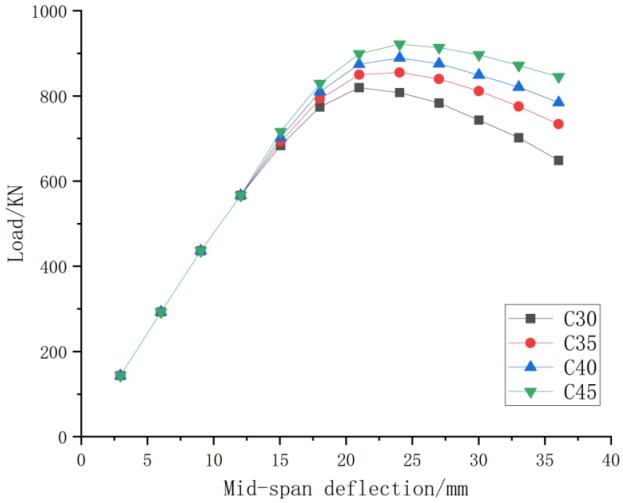


Figure 5. Load–mid-span deflection curve of specimens under different concrete strengths (photo/picture credit: original)

Table 2. Comparison of ultimate bearing capacity under different concrete strength grades

Concrete strength grade	Axial compressive strength f_c (MPa)	Ultimate bearing capacity V_u (kN)	Increase range of bearing capacity
C30	20.1	V0	—
C35	23.4	1.017V0	Approximately +1.7%
C40	26.8	1.033V0	Approximately +3.3%
C45	29.2	1.050V0	Approximately +5.0%
C50	32.4	1.069V0	Approximately +6.9%

3.4. Web influence

The thickness of web is the key factor affecting the shear capacity. The load deflection curve under different web thickness is shown in Figure 6. Elastic stage basically coincides; In the elastic-plastic stage, the thicker the web, the greater the slope of the curve, and the higher the ultimate bearing capacity. Table 3 shows the ultimate bearing capacity of the specimen under different web thickness. The web thickness increases from 6mm to 10mm, and the bearing capacity increases by about 13.7%, with an average increase of about 3.4% per 1mm, which is significantly better than the effect of concrete strength improvement. The safety reserve of thick web (9~10mm) is higher, and the material utilization rate of thin web (6mm) is higher, but the safety reserve is lower. When the open-web ratio decreases from 67.4% to 51.1%, the shear capacity increases by about 8.82%, indicating that appropriate reduction of the open-web ratio is beneficial to the shear performance.

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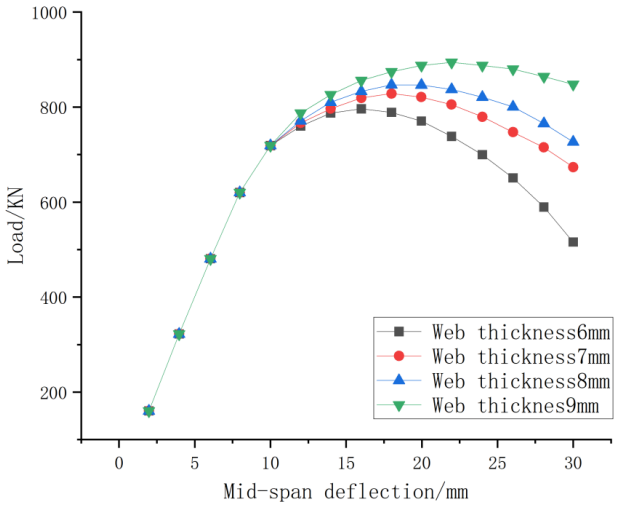


Figure 6. Load deflection curve of specimen under different web thickness (photo/picture credit: original)

Table 3. Comparison of ultimate bearing capacity of specimens under different web thickness

Web thickness t_w (mm)	Ultimate bearing capacity V_u (kN)	Increase range of bearing capacity
6	870	—
7	900	Approximately +3.4%
8	929	Approximately +6.8%
9	959	Approximately +10.2%
10	989	Approximately +13.7%

4. Analysis of mechanical economic collaborative optimization based on value engineering

4.1. Construction of economic evaluation model based on value engineering

4.1.1. Cost composition analysis

The full life cycle cost includes materials, manufacturing, transportation, installation and maintenance. Material cost: the comprehensive cost of main steel Q355B is about 4000 yuan/ton, Reinforcement HRB400 is about 3200 yuan/ton; Concrete C30 is about 350 yuan/m³. The manufacturing cost (cutting, welding, assembly and pouring) is about 1200 yuan/ton, and the labor cost is 700~1000 yuan/ton. The hollow structure can be poured at one time to avoid the turnover process and save labor and formwork occupation [5]. Transportation and installation is about 800

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yuan/ton (transportation 300, installation 500). The maintenance cost is better than that of pure steel due to the wrapping effect of concrete, which can reduce the long-term maintenance cost.

The total cost per unit length (per linear meter) is expressed as:

$$C_{total}=C_{steel}+C_{rebar}+C_{concrete}+C_{fab}+C_{trans}+C_{install} \tag{6}$$

Among them, the proportion of each cost item varies with different design parameters, and the web thickness and open-web ratio are the key variables affecting the steel consumption and total cost [6].

4.1.2. Unit cost accounting model

The standard model of shear span ratio λ=2 (beam height 400mm, width 200mm, t_w=6~10mm, concrete c30~c50, open web ratio η≈ 60%) is taken as the benchmark. Estimation of steel consumption for main steel part:

$$W_{steel}=\rho_s\cdot[2\cdot(b_f\cdot t_f+h_w\cdot t_w)\cdot L] \tag{7}$$

Where ρ_s is the steel density (7850 kg/m ^{3}), b_f and t_f are the flange width and thickness respectively, h_w is the web height, t_w is the web thickness, and L is the beam length. Referring to the current market price, the Q355B steel is 4000 yuan/ton [7]. The cost of reinforcement materials includes C-shaped connecting rod, tie bar, etc. When the reinforcement ratio ρ changes in the range of 0%~1.0%, the amount of reinforcement shall be adjusted accordingly. HRB400 reinforcement is 3200 yuan/ton.

Concrete material cost, concrete web volume is:

$$V_c=(b\bullet h-a_{steel})\bullet l \tag{8}$$

A_{steel} is the main steel section area. C30 concrete is 350 yuan/m ^{3}.

The comprehensive cost of steel structure processing and manufacturing is 1200 yuan/ton. The comprehensive cost of transportation and installation is 800 yuan/ton (about 300 yuan/ton for transportation and about 500 yuan/ton for installation). Thus, the total cost C_m per unit length of beam (yuan/m) can be expressed as:

$$C_m=(4000+1200+800)\cdot\frac{W_{steel}}{L}+3200\cdot\frac{W_{rebar}}{L}+350\cdot\frac{V_c}{L} \tag{9}$$

Simplified:

$$C_m=6000\cdot w_{steel}+3200\cdot w_{rebar}+350\cdot v_c \tag{10}$$

Among them, w_{steel}, w_{rebar} and v_c are the steel consumption (t/m), reinforcement consumption (t/m) and concrete consumption (m ^{3}/m) of the beam per unit length respectively.

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4.1.3. Construction of value coefficient (v) model of "bearing capacity/unit cost"

Define the value coefficient V as:

$$V=\frac{V_u}{C_m} \tag{11}$$

Where V_u is the shear capacity (kN), and C_m is the cost per unit length of beam under the corresponding parameters (yuan/m). The economic meaning of this ratio is "shear capacity per unit cost (kn/yuan)", which is a dimensionless "cost performance" index. The higher the V value, the better the mechanical properties obtained at the same cost [8]. Based on the typical model (t_w=8mm, C30, fasting rate 60%), the V values of each parameter combination were normalized and compared.

The advantage of this model is that it unifies the energy program of mechanical properties and economy, and clearly reflects the asymmetric effects of different parameters on bearing capacity and cost - for example, the web thickness improves significantly, but the cost increases greatly; the contribution of concrete strength is limited, but the cost increases rapidly, and the results are intuitive, which is convenient for rapid comparison and selection of engineering design.

4.2. Collaborative optimization analysis of mechanical properties and engineering economy

4.2.1. Analysis of evolution law of value coefficient (v)

When the web thickness increases from 6mm to 10mm, the changes in shear capacity and unit cost are shown in Table 4.

Table 4. Comparison of bearing capacity, cost, and value coefficient under different web thicknesses

Web thickness t_w (mm)	Bearing capacity V_u (kN)	Increase range of bearing capacity	Unit cost C_m (yuan/m)	Cost increase	Value coefficient *V* (relative value)
6	870	—	100%	—	1.00
7	900	+3.4%	103.5%	+3.5%	1.00
8	929	+6.8%	107.0%	+7.0%	0.998
9	959	+10.2%	110.5%	+10.5%	0.997
10	989	+13.7%	114.0%	+14.0%	0.997

Note: The value coefficient is normalized based on t_w =6mm (V=1.00); The cost calculation is based on 4000 yuan/ton of Q355B steel, 1200 yuan/ton of processing and production, and 800 yuan/ton of transportation and installation.

It can be seen from Table 4 that when the bearing capacity is 6mm → 7mm, the increase rate of bearing capacity (3.4%) is basically synchronized with the increase rate of cost (3.5%), and V is the best; The bearing capacity increase (6.8%~13.7%) was slightly lower than the cost increase (7.0%~14.0%), and V decreased slightly. This shows that 6~7mm is the most cost-effective, and it is no longer economical to exceed 7mm [9]. This conclusion is not contradictory to "the increase of web thickness is mechanically effective", but it may not be optimal economically [1].

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Table 5. Comparison of bearing capacity, cost, and value coefficient under different concrete strength

Concrete strength	Bearing capacity V_u (relative value)	Increase range of bearing capacity	Unit cost C_m (relative value)	Cost increase	Value coefficient V (relative value)
C30	1.000	—	1.000	—	1.000
C35	1.017	+1.7%	1.025	+2.5%	0.992
C40	1.033	+3.3%	1.050	+5.0%	0.984
C45	1.050	+5.0%	1.075	+7.5%	0.977
C50	1.069	+6.9%	1.100	+10.0%	0.972

Note: The value coefficient is normalized based on C30 (V=1.00); The cost increase mainly considers that the unit price of concrete materials increases with the increase of strength grade (C30 is about 350 yuan/m ^{3}, C50 is about 420 yuan/m ^{3}).

It can be seen from Table 5 that the bearing capacity of C30 to C50 increased by 6.9%, the cost increased by 10.0%, and V continued to drop to 0.972. Improving concrete strength has a low contribution to bearing capacity and a large increase in cost, which is uneconomical from the perspective of value engineering. It is recommended to give priority to C30~C40, which is consistent with the literature conclusion [2, 8].

The fasting rate decreased from 67.4% to 51.1%, the bearing capacity increased by about 8.82%, but the steel consumption increased by about 10%~12%, and the V was about 0.97~0.99 [10, 11]. The results show that the optimal open-web ratio range is about 55%~65%, and the steel consumption saving and bearing capacity loss reach the optimal balance [5].

4.2.2. Optimization based on design specification constraints

According to the technical specification for partially encased steel-concrete composite structures (T/CECS 719-2020) and code for design of composite structures (JGJ 138-2016), the structure shall meet the following requirements:

The width-to-thickness ratio of flange of beam section is class 1, class 2 and class 3, and the limits are $9\varepsilon_k$, $14\varepsilon_k$ and $20\varepsilon_k$. For Q355B steel ($f_y=355MPa$, $\varepsilon_k=\sqrt{\frac{235}{355}}\approx 0.814$), the limits of class 3 are 7.3, 11.4 and 16.3 respectively. The flange width-to-thickness ratio in this model is about $\frac{b_f}{2t_f}$, so it is necessary to ensure that the corresponding limit value is not exceeded in the design, so as to ensure that the compression flange does not buckle locally before reaching the full section plasticity [12].

For Q355B steel, the limit value of web height-to-thickness ratio is about $72\varepsilon_k\approx 58.6$. Taking $h_w\approx 300mm$, $t_w=6mm$ as an example, the height-to-thickness ratio is 50, which meets the requirements. When $t_w=5mm$, the height-to-thickness ratio is 60, which has exceeded the limit. This further confirms the conclusion that the web thickness should not be too small from the perspective of norm [12].

The connecting rod diameter should not be less than 8mm, and the spacing should not be more than 300mm. The connecting rod diameter of this model is 8mm, and the spacing is 200mm, which meets the structural requirements.

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The comprehensive value coefficient analysis and specification checking calculation show that the feasible interval to meet the triple constraint of "performance cost specification" is: web thickness 6~8mm, concrete C30~C40, open-web ratio 55% ~65%, connecting rod diameter ≥ 8mm, spacing ≤ 300mm [13].

4.2.3. Discussion on the potential advantages of open-web structure in the context of assembly

Compared with the traditional solid web PEC beam, the double T-shaped Vierendeel structure has many potential advantages in construction technology. For example, the Vierendeel area can be formed by one-time pouring, avoiding the process of double pouring of the solid web structure. The open-web design reduces the dead weight of components, which is theoretically conducive to transportation and hoisting operations. The hollow space can cross equipment pipelines, which is expected to reduce the investment in ceiling decoration. The above advantages are reasonable at the qualitative level, but the specific duration reduction, labor saving ratio and comprehensive cost reduction value need to be verified based on the construction organization design and cost accounting data of the actual project. The cost model (formulas 6~10) established in Section 4.1 of this paper only covers the cost of materials and processing, and does not include the quantitative calculation of indirect benefits such as formwork turnover and construction hoisting. The quantitative evaluation of the above potential advantages needs to be further carried out in combination with specific engineering cases in subsequent studies [14].

4.2.4. Engineering optimization suggestions and design guidelines

On the premise of meeting the bearing capacity, the recommended web thickness is 6~7mm (6mm is the best, 7mm is well balanced), concrete C30~C40 (not recommended above C45), and the open-web ratio is 55%~65% [9]. Connecting rod diameter ≥ 8mm, spacing ≤ 300mm to form a truss effect; Connecting rods shall be added in areas with shear span ratio ≥ 2, and tie bars shall be staggered on both sides and orthogonal to inclined cracks [15]. It is suggested to promote it in industrial plants, large-span public buildings, and prefabricated houses, establish a standardized Atlas (covering 6~12m common span), measure the value coefficient synchronously in the design stage, and include it in the scheme comparison and selection decision.

5. Conclusion

The finite element model of the double T-shaped flange open-web PEC beam based on Abaqus is verified to be in good agreement with the test (deviation ≤ 6%), which can accurately simulate the shear performance. The effect of web thickness on the bearing capacity is much greater than that of concrete strength: the thickness is 6mm → 10mm, the bearing capacity is increased by about 13.7%, and the average increase rate is about 3.4% for each 1mm increase; The concrete strength is C30 → C50, the bearing capacity is only increased by about 6.9%, and the marginal increase rate of each grade is only 1.5%~1.8%. The evolution of the value coefficient shows that a web thickness of 6~7mm has the best performance-to-cost ratio, and V decreases slightly after 8~10mm; When concrete is C30 → C50, V continuously decreases to 0.972; The best balance between steel consumption and shear performance is 55%~65% of the open-web ratio. According to the structural requirements of the specification, the optimization parameters are proposed: web thickness 6~8mm, concrete C30~C40, open-web rate 55%~65%, connecting rod diameter ≥ 8mm, spacing ≤ 300mm, and connecting rod densification in large shear span area.

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The open-web full prefabricated assembly can shorten the construction period by 20%~30%, save labor by 40%, and reduce the comprehensive cost by 10%~15%. It is also convenient for pipeline crossing and reduces the investment in later decoration. It is suggested that it should be popularized in industrial plants, large-span buildings, and prefabricated residences, and the value coefficient should be calculated synchronously at the design stage to be incorporated into the economic decision-making basis.

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