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Experimental investigation on the mechanical behaviour of the fiber reinforced high-performance concrete tunnel segment

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ABSTRACT

The main objective of this paper is to investigate the composite effect of macro steel fiber and steel rebar on the mechanical behaviour of tunnel segment with fiber reinforced high-performance concrete (FRHPC). A new experimental method is used for simulating the loading state of the tunnel segment. The experiment including several symmetric-inclination beams with various steel ratios and fiber contents has been carried out. The results indicate that the addition of 50 kg/m^3 steel fibers can partly replace the shear reinforcement, and increases the ultimate load and the energy absorption capacity as well as the toughness. The combination of steel fibers and steel rebars illustrates synergistic response and indicates an optimal choice of reinforcement for tunnel segment.

1. Introduction

The shield tunnel technology is widely used in tunnel construction in soft soil condition, and most of them adopt conventional steel reinforced concrete (RC) tunnel segments. Due to the brittle characteristics and low tensile strength of concrete, traditional RC tunnel segments are prone to crack or damaged during production, transportation, installation and service periods. The safety, the permeability, the serviceability and the durability of the tunnel are strongly influenced by such macro cracks.

The relevant literatures [1–7] describe numerous studies on the fiber reinforced concrete. A common conclusion is that the addition of fibers to the concrete enhances the mechanical behaviour of RC members and it leads to a change in failure mode from a brittle shear failure into a pseudo-ductile failure or even a ductile flexural failure. Steel fibers could be advantageous for the partial or total replacement of stirrups [8]. However, due to the lack of design rules for steel fiber reinforced concrete (SFRC) tunnel segment, engineers have usually designed SFRC tunnel segments by adopting the same rules that valid for conventional RC segments [9]. The investigation of SFRC tunnel segment is far behind the construction and structure demands, while the manufacture of the tunnel segment for lab investigation is difficult and expensive. The method using simply supported beam with exerting axial force by jack at each ends (Fig. 1) [10] is usually adopted for lab investigation to simulate the stress state of tunnel segment, while some problems exist in this method: (1) the axial force exerted by jack offers a constant axial force and cannot reflect the real loading condition of tunnel segment because the normal stress of the tunnel section varies with the vertical rock pressure in the practice; (2) the segments with different central angle and curvature cannot be simulated by simply supported beam.

In order to avoid the unreasonable problems above mentioned, a new test method by name of symmetric-inclination beam (Fig. 2) [10–12] is used to investigate the load-carrying capacity and the toughness of tunnel segment. The method is reasonable and the major advantages are as follows:

- Compared with conventional method using simply supported beam with constant axial force (N_c) (Fig. 1), an inclined support reaction (R) is introduced including axial component (N) (Fig. 2), which increased proportionally with the vertical load.
- Different angle of support reaction with axial component (N) can simulate the segments of different central angle and curvature. The inclination (θ) of symmetric-inclination beam is between 0 and 90°. When θ is equal to 90°, the beam becomes conventional simply supported beam.
- The decrease of θ will enhance the axial component ($N = V \times \cot\theta$), thus result in the increase of the negative moment induced by axial force component ($M_n = V \times \cot\theta \times e_0$). The negative moment can reduce the moment induced by the vertical load ($M_a = V \times a$), so the flexural behaviour will be improved with the decrease of θ (see Figs. 2 and 3). In this program, a constant inclination of 45° is chosen to investigate the mechanical behaviour of symmetric-inclination beam. The beam with 45° inclination of support reaction can simulate the segment with 90° central angle (see Fig. 4).

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Nomenclature

M_n	negative moment induced by axial force
e_0	vertical distance from support to neutral axis
M_a	moment induced by apply load
φ6.5@80	diameter of the stirrups = 6.5 mm, stirrup spacing = 80 mm
φ6.5@150	diameter of the stirrups = 6.5 mm, stirrup spacing = 150 mm
N0-80	stirrup spacing = 80 mm, stirrup ratio ρ_v = 0.55%, without steel fibers
SF25-80	stirrup spacing = 80 mm, stirrup ratio ρ_v = 0.55%, fiber dosage of 25 kg/m^3
SF50-0	beam with 50 kg/m^3 steel fibers, but without stirrups
ε_{80}	tensile strain of longitudinal reinforcement at 80 kN
ε_{120}	tensile strain of longitudinal reinforcement at 120 kN
ε_u	tensile strain of longitudinal reinforcement at ultimate load
D_c	energy absorption by concrete before cracking,
$D_8^f = D_8 - D_c$	energy absorption up to a deflection δ_8
$D_{12}^f = D_{12} - D_c$	energy absorption capacity up to a deflection δ_{12}

- The formwork of symmetric-inclination beam is easy to fabricate and cost saving for lab investigation.

In this study, the combined action of macro steel fiber and steel rebar on the load–strain relationship of longitudinal rebars, load–deflection relationship, ultimate load and energy absorption capacity of the SFRC tunnel segment are investigated by means of the symmetric-inclination beam test. Compared with conventional reinforced concrete, a safe and economic composite material should be found and applied to the underground construction.

2. Experimental investigation

2.1. Materials

The grade of the plain concrete was designed for C60 (Compressive strength of 60 MPa) and the mixture proportions are provided in Table 1. The concrete was made with P·||52.5R Portland cement and first class fly ash. The water to binder ratio was 0.33. The coarse aggregates were crushed gravel with a maximum size of 10 mm, and the fine aggregates were natural river sand.

Macro hooked end steel fibers (Fig. 5) with different fiber contents and conventional steel rebars (Fig. 6) with various reinforcement ratios had been used in this study.

- Macro steel fiber (RC-65/35-BN) (Fiber length l_f = 35 mm, equivalent diameter d_f = 0.55 mm, aspect ratio $\lambda(l_f/d_f)$ = 65), ca. 15,000 pieces/kg, tensile strength was of approximately 1345 MPa. The designed fiber contents were 0 kg/m^3, 25 kg/m^3 and 50 kg/m^3.
- The nominal diameter of the flexural reinforcement for all beams was 14 mm and the diameter of the stirrups was 6.5 mm. The longitudinal rebars and stirrups had a yield stress of 490 N/mm^2 and 282 N/mm^2, an ultimate stress of 692 N/mm^2 and 439 N/mm^2, respectively, which were in accordance with Chinese Code for design of concrete structures [13].

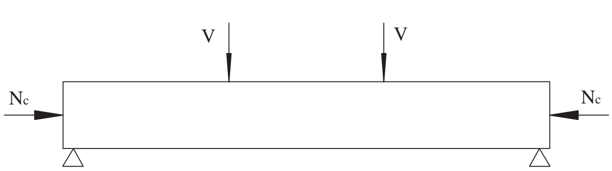

Fig. 1. Traditional methods.

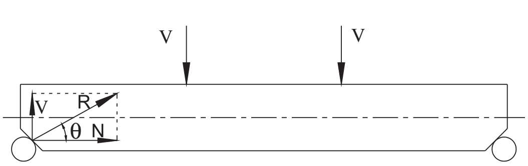

Fig. 2. Symmetric-inclination beam.

2.2. Experimental program

The details of the specimens are listed in Table 2. Two fiber contents and two stirrup ratios were selected for investigating the composite effect of macro steel fiber and steel rebar on the mechanical behaviour of tunnel segment. The first stirrup spacing was 150 mm (the stirrup ratio ρ_v = 0.3%), and the second stirrup spacing was 80 mm (the stirrup ratio ρ_v = 0.55%). The variables of this experiment were fiber content and stirrup spacing. Other parameters, such as shear span to effective depth ratio (a/d) and the longitudinal reinforcement ratio, were kept constant.

Each beam was designated by fiber content and stirrup spacing. RC beam is denoted as N0-80 (stirrup spacing = 80 mm, stirrup ratio ρ_v = 0.55%, without fibers) and marked as the reference beam. The letters SF denote steel fiber reinforced beam; the first two

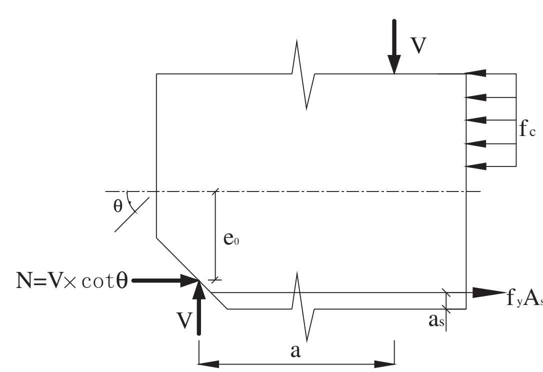

Fig. 3. Forces on portion of symmetric-inclination beam.

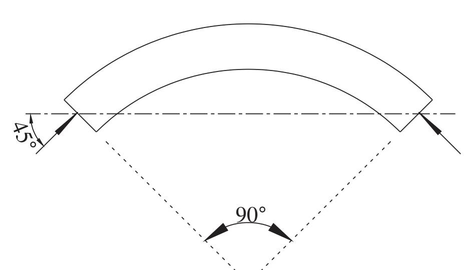

Fig. 4. Tunnel segment with 90° central angle.

Table 1
Mixture proportion of base matrix (kg/m^3).

Cement (C)	Fly ash (FA)	Binder (B)	Sand (0-5 mm)	Coarse aggregate (5-10 mm)	Water (W)	SP	Fiber content (kg/m^3)
390	150 (27.8%)	440	808	808	178	9.72 (1.8%)	25, 50

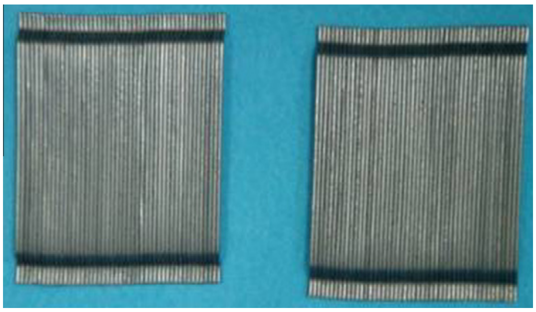

Fig. 5. Macro steel fibers.

Fig. 6. Conventional steel rebars.

digits indicate fiber content and the following number indicates the spacing of stirrups. For example, SF25-80 refers to the beam with 25 kg/m^3 steel fiber and 80 mm stirrup spacing. The beam size was B (width) × H (depth) × L (length) = 150 mm × 150 mm × 1100 mm, tested on a span L_{sp} = 1050 mm, and a 45° inclination at both ends. The shear span length L_{ssp} was 350 mm. The test was conducted in 10000 kN hydraulic servo testing machine and the specimen was subjected to two equal concentrated loads. The beams for load-versus-displacement responses were deformation-controlled and tested when the specimens were 28 days old. The deformation rate of the test was 0.3 mm/min. A linear variable differential transformer (LVDT) was placed to measure the displacement at the mid-span. Strain gauges were glued to the main reinforcement at mid-span to measure the strain of longitudinal rebars under the influence of steel fibers (Fig. 7).

3. Results and analysis

3.1. Compressive strength

In order to investigate the compressive strength of fiber reinforced concrete, uniaxial compression test was carried out on cubic specimens, measuring 150 × 150 × 150 mm, with a constant loading rate of 0.6 MPa/s, after the curing phase according to Chinese guideline [14]. The mean values of compressive strength of all samples after 28 days are illustrated in Table 3. It can be seen that the addition of fibers has no significant influence on the compressive strength of hardened concrete. The addition of steel fibers aims in converting the properties of brittle concrete into a ductile material, generally improving the compressive ductility of concrete [15]. The compressive strength of all the samples exceeded 60 N/mm^2 after 28 days. Therefore, the proposed mix design had produced the concrete that meets satisfactorily the strength requirement of HPC.

3.2. Strain of mid-span longitudinal rebars

Tensile strains in the longitudinal rebars at mid-span of the beams were measured. Fig. 8 shows the load–strain relationship of longitudinal reinforcement in the test beams, and compares the influence of steel fibers and stirrups on the strain of longitudinal reinforcement.

Table 2
Details of test beams.

Beam number	Fiber dosage (kg/m^3)	a/d	Stirrup spacing (mm)	Stirrup ratio (%)	Longitudinal reinforcement ratio (%)
N0-80	0	3	80	0.55	2.6
SF25-80	25	3	80	0.55	2.6
SF25-150	25	3	150	0.3	2.6
SF50-150	50	3	150	0.3	2.6
SF50-0	50	3	∞	0	2.6

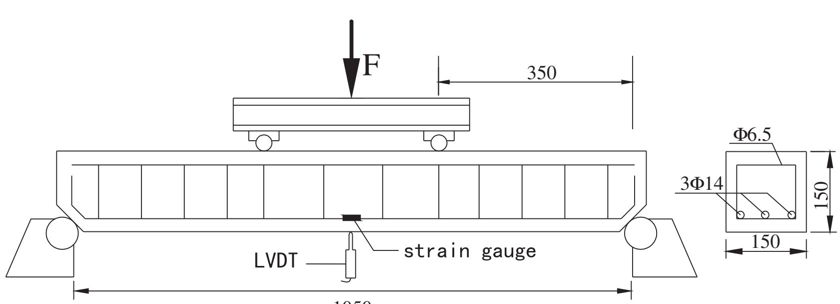

Fig. 7. Details of test setup (Unit: mm).

Table 3
Comparison of compressive strength after 28 days.

	NC	SF25	SF50
Compressive strength in 28 days (N/mm^2)	60.5	61	60

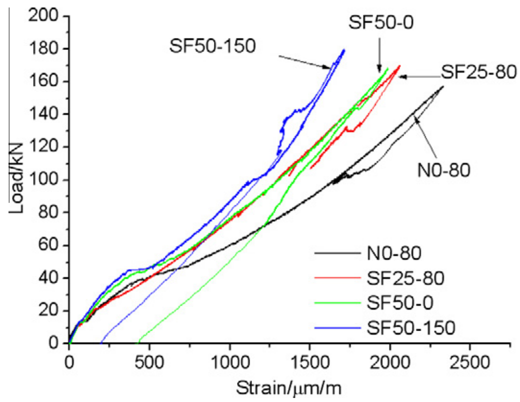

Fig. 8. Load–strain curves of longitudinal reinforcements.

From Fig. 8, it can be seen that the longitudinal reinforcement in all beams did not yield and the addition of steel fibers resulted in a clear reduction in the strain of longitudinal reinforcement.

The difference among these strains were only marginal in the initial loading stage, but with the formation and developing of flexural cracks, the steel fibers crossing the cracks could partially take up the tension released by concrete and restrict the development and the widening of the cracks. Compared to the beams with steel fibers, the strain in the longitudinal reinforcement of N0-80 was relatively large and achieved 2300 micro-strain at ultimate load. The variation of the longitudinal rebar strains of beam SF25-80 and SF50-0 were almost identical and lower than that of RC beam without fibers. One of the reasons could trace back to the fiber influence on reduction of the steel strain. For beam SF50-150 (stirrup spacing = 150 mm, stirrup ratio ρ_v = 0.3%, fiber dosage of 50 kg/m^3), the maximum strain reached only 1700 micro-strain, which was much less than those of other specimens. That pointed a possible positive composite effect of the combination from steel fiber and conventional stirrups on the strain of longitudinal steel rebars.

Table 4 shows the comparison of the corresponding strains in longitudinal steel of beam N0-80, SF25-80, SF50-0 and SF50-150, when the load reaches 80 kN, 120 kN and ultimate load. It can be seen that steel fibers contributed to reduce the strain of steel rebars as the steel fibers increase the tensile capacity of concrete and partially take up the tensile stress of the longitudinal reinforcement.

3.3. Flexural shear performance

The major failure patterns of all beams were caused by diagonal crack. The effect of fiber addition on the load–deflection curves for symmetric-inclination beams are presented in Figs. 9–11.

Table 4
Comparison of strains in longitudinal reinforcement at 80 kN, 120 kN and ultimate load.

Beam number	ε_{80}	ε_{120}	ε_u
N0-80	1340	1898	2326
SF25-80	1034	1507	2057
SF50-150	926	1360	1711
SF50-0	1060	1508	1985

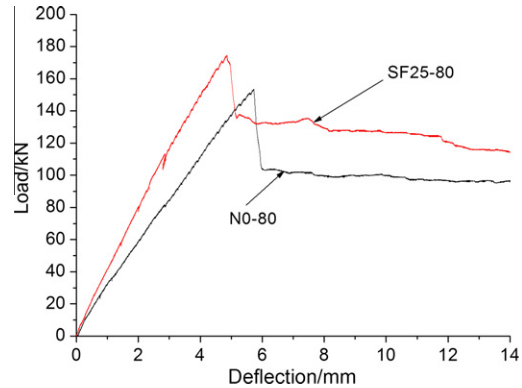

Fig. 9. Effect of steel fibers on the load–deflection curves.

Fig. 9 compares the load–deflection curves between the beams with constant stirrup spacing (stirrup spacing = 80 mm, ρ_v = 0.55%), but with different fiber contents (0 and 25 kg/m^3). Compared with the reference RC beam without fibers (N0-80), the addition of 25 kg/m^3 steel fibers enhanced not only the ultimate load and post-peak load-carrying ability, but also increased the energy absorption capacity over the entire deflection zone.

Fig. 10 shows the comparison of the load–deflection curves of the reference beam N0-80 (stirrup spacing = 80 mm, ρ_v = 0.55%, without fibers) and the beams with reduced stirrup ratio (ρ_v = 0.3%) and different fiber contents (25 kg/m^3 and 50 kg/m^3). Though the stirrup ratio ρ_v decreased 46.7%, the ultimate load

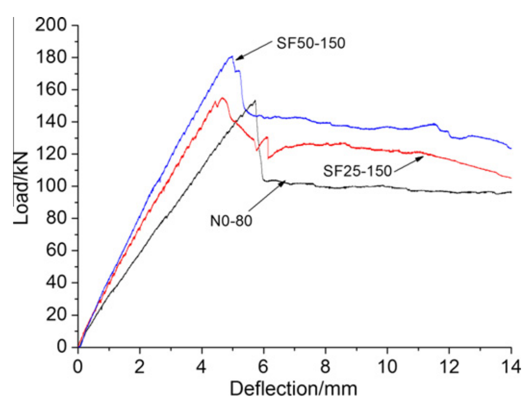

Fig. 10. Load–deflection of the beams with different fiber contents and reduced stirrup ratios.

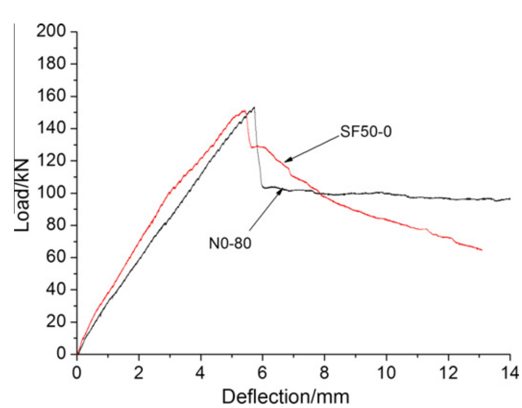

Fig. 11. Load–deflection of the beams with 50 kg/m^3 fibers and without stirrup.

Table 5
Test results of the cracking load, the ultimate load and the corresponding deflections.

	Total applied load F (kN)		Shear load $V = F/2$ (kN)	Corresponding deflection (mm)	
	At first flexural crack (F_{cr})	At failure (F_u)	Ultimate shear load (V_u)	At first flexural crack (δ_{cr})	At failure (δ_u)
N0-80	10.9	153.4	76.7	0.30	5.7
SF25-80	11.1	176.1	88.1	0.24	4.8
SF25-150	12.6	156.2	78.1	0.25	4.7
SF50-150	12.4	180.3	90.1	0.21	4.9
SF50-0	12.6	150.9	75.5	0.20	5.4

(F_u) of beams SF25-150 and SF50-150 increased with fiber contents. Also the stiffness and the energy absorption capacity of beams with steel fibers were enhanced due to the restricted cracking opening. The combined action of steel fibers and stirrups is obviously superior than the beam only reinforced with steel rebars.

Fig. 11 shows the comparison of the load–deflection curves of the reference beam N0-80 stirrup spacing = 80 mm, $\rho_v = 0.55\%$, without fibers) and the beam SF50-0 (without stirrups, but with 50 kg/m^3 steel fibers). Although the stirrups were totally replaced by 50 kg/m^3 steel fibers, the ultimate load capacity of beam SF50-0 only slightly decreased, however, the residual load-bearing capacity after the peak load and energy absorption capacity decreased rapidly compared to N0-80.

The flexural cracking load (F_{cr}), ultimate total applied load (F_u), ultimate shear load (V_u) and the corresponding deflection (δ_{cr}, δ_u) of the beams with different stirrup ratios and fiber contents are summarised in Table 5.

From Table 5, it can be seen that the steel fibers significantly enhanced the ultimate shear load of the symmetric-inclination beams:

(1) When stirrup ratio maintained 0.55% (corresponding stirrup spacing of 80 mm, see Table 2), compared with the reference beam without fibers (beam N0-80), the shear load (V_u) of the beam with 25 kg/m^3 steel fibers (beam SF25-80) increased 14.9%.
(2) When stirrup ratio declined to 0.3% (the stirrup spacing increased from 80 mm to 150 mm, see Table 2), compared with beam N0-80, the shear load (V_u) of the beam with 25 kg/m^3 and 50 kg/m^3 SF (beam SF25-150 and SF50-150) increased 1.8% and 17.4%, respectively.
(3) When stirrup ratio declined to 0% (without stirrups), compared with beam N0-80, the shear load (V_u) of the beam with 50 kg/m^3 (beam SF50-0) slightly decreased 1.6%.

3.4. Toughness

In this study, the post-peak behaviour of RC beams in terms of toughness indexes is evaluated. According to RILEM recommendation [16] and German guideline [17], four toughness parameters (D_8^f, D_{12}^f, $f_{eq.8}^f$, $f_{eq.12}^f$) are introduced to evaluate the energy absorption capacity and the residual load-bearing capacity of the specimens to a deflection $\delta_8 = \delta_{cr} + 8$ or $\delta_{12} = \delta_{cr} + 12$ mm. The typical load–deflection curve is shown in Fig. 13. Similar to [16] and [17], D_8, D_{12} can be defined as the area under load–deflection curve, which is the total energy absorbed up to the certain deflection δ_8 or δ_{12} of the specimen. D_8 or D_{12} consists of two parts: the energy absorbed by plain concrete D_c and the energy absorbed of SFRC D_8^f or D_{12}^f (the shaded area in Fig. 12). The equivalent strength $f_{eq.8}^f$ and $f_{eq.12}^f$ can be determined by means of the following expressions:

$$f_{eq.8}^f = D_8^f L_{ssp}/6bh_0^2 \quad (1)$$

$$f_{eq.12}^f = D_{12}^f L_{ssp}/10bh_0^2 \quad (2)$$

The decreasing ratio of the equivalent strength $\Delta_d = \frac{(f_{eq.8}^f - f_{eq.12}^f)}{f_{eq.8}^f}$ is introduced for evaluation of the variation trend of the residual load-bearing capacity after peak load.

The calculated results of energy absorption and equivalent strengths of symmetric-inclination beams with different reinforcements are presented in Table 6. It can be seen that the beam only

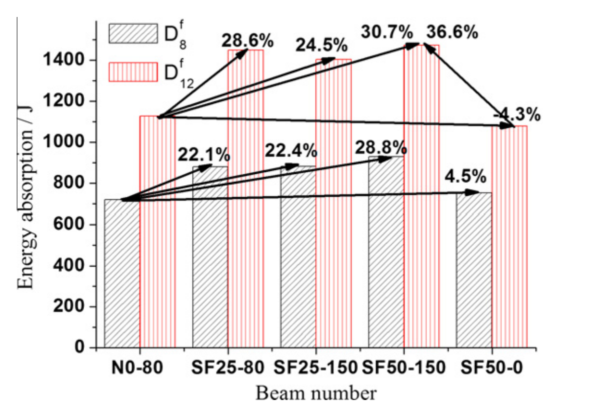

Fig. 13. Energy absorption and increment ratio of the toughness for beams with different reinforcements.

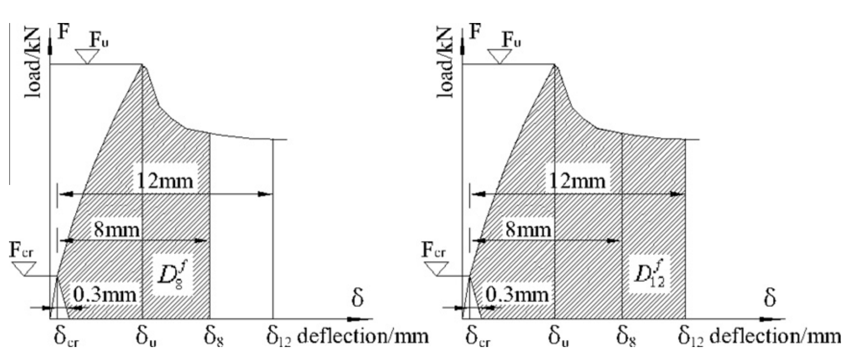

Fig. 12. Typical load–deflection curve and the calculation of energy absorption capacity.

Table 6
Comparison of energy absorption and equivalent strength.

	D_8^f (kN mm)	D_{12}^f (kN mm)	$f_{eq.8}^f$ (N/mm^2)	$f_{eq.12}^f$ (N/mm^2)	Δ_d (%)
N0-80	721.3	1127.1	20.1	18.9	6.2
SF25-80	881.0	1450.0	24.6	24.3	1.2
SF25-150	882.9	1403.4	24.7	23.5	4.6
SF50-150	929.1	1473.3	25.9	24.7	4.9
SF50-0	753.8	1078.2	21.1	18.1	14.2

with stirrups (N0-80) and the beam only with steel fibers (SF50-0) showed relatively low toughness, especially at the large deflections of δ_{12}. Therefore, beam N0-80 and SF50-0 are marked as the reference beam to quantify the hybrid effect of stirrups and steel fibers on toughness.

Fig. 13 shows the comparison of the energy absorption and the increment ratio of the toughness among the beams with various fiber contents and different stirrup ratios. The amounts of stirrups are converted into steel amount in kg/m^3, in order to compare the efficiency of the content of stirrups and fibers per kilogram intuitively. The conversion equation is proposed as follows:

$$m_{s,unit} = m_s/bSh \quad (3)$$

where $m_{s,unit}$ is the steel amount of stirrups in kg/m^3; m_s is the mass of a single-loop stirrups; h is beam depth

The stirrup ratio of 0.3% is equivalent to a steel amount of 38.7 kg/m^3, and the stirrup ratio of 0.55% is equivalent to a steel amount of 71.9 kg/m^3.

It can be seen that:

- Compared to the reference beam N0-80, the addition of 25 kg/m^3 steel fibers enhanced the energy absorption (D_8^f, D_{12}^f) of beam SF50-150 about 22.4% and 24.5%, though the stirrup spacing increased from 80 mm to 150 mm (the stirrup ratio decreased about 46%). It means that the 33.2 kg/m^3 of stirrups can be partially replaced by 25 kg/m^3 steel fibers, whereas the toughness of the member still increased.
- Compared to beam N0-80, the addition of 25 kg/m^3 steel fibers increased the energy absorption capacity (D_{12}^f) of beam SF25-80 about 28.6%. Similarly, the arrangement of 0.3% stirrups could enhance the energy absorption capacity (D_{12}^f) of beam SF50-150 about 36.6%, compared to beam SF50-0. A significant positive synergistic effect on the post-peak properties, energy absorption ability as well as toughness can be achieved by the combination of steel fibers and steel rebars.
- Compared with beam N0-80, the energy absorption D_8^f of beam SF50-0 increased 4.5%, while the energy abortion at large deflection of δ_{12} decreased 4.3%. Meanwhile, the value of Δ_d of beam SF50-0 is higher than that of the other beams from 130% to 1080%. This means that the residual load-bearing capacity after peak load of SF50-0 dropped more rapidly than other beams, so the shear reinforcement (φ6.5@80) in this program cannot be totally replaced by only 50 kg/m^3 steel fibers.

4. Conclusions

In order to investigate the influence of the stirrups and steel fibers on the mechanical behaviour of tunnel segment/symmetric-inclination beam, a series of symmetric-inclination beams were tested. Based on the experimental result above mentioned, the following conclusions can be drawn:

1. The addition of steel fibers results in a clear decrease of the strain in longitudinal rebars for a given load.
2. The combined use of stirrups and steel fibers shows great synergetic effect on load-carrying capacity, energy absorption capacity as well as toughness of symmetric-inclination beam subjected to bending, shear and axial force.
3. The addition of 25 kg/m^3 fiber can partially reduce the amount of stirrups required (the stirrup ratio decreased about 46%, the equivalent steel amount reduced 33.2 kg/m^3), namely enlarging the stirrup spacing from 80 mm to 150 mm in this study. A combination of fibers and stirrups can well satisfy load carrying ability and ductility requirements.
4. The addition of 25 kg/m^3 fibers can partly replace the conventional stirrups and enlarge the stirrup spacing from 80 mm to 150 mm (the equivalent steel amount reduced 33.2 kg/m^3).
5. The arrangement of 0.55% stirrups (equivalent steel amount of 71.9 kg/m^3) can not be totally replaced by 50 kg/m^3 steel fibers.

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