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Effect of Fibres on the behaviour of Bottle shaped strut

Murali Sagar Varma Sagi[1], S Suriya Prakash[2]

[1]Research Scholar, Department of Civil Engineering, IIT Hyderabad, Hyderabad (and)
[1]Assistant Professor, Department of Civil Engineering, MVGR College of Engineering (A), Vizianagaram – 535 005, INDIA,
[2]Professor, Department of Civil Engineering, IIT Hyderabad, Hyderabad, India
Email: muralisagariitr@gmail.com

Abstract: Bottle-shaped struts are the critical elements in the design of D-regions using Strut-and-Tie method. The transverse tension develops due to dispersion of compression load which further leads to splitting crack in bottle shaped strut. Due to this, the strut fails before reaching its ultimate compression capacity. Higher resistance to the transverse tension can improve the strut capacity and its efficiency in load transfer. Transverse tensile stress can be resisted by providing the steel reinforcement or through the addition of discrete fibres in the concrete. Many international codes like ACI, AASTHO, and CSA have suggested guidelines about the addition of steel fibre reinforcement in the bottle-shaped struts for resisting the transverse tension. Still, the influence of the discrete fibres on the performance of the bottle-shaped strut is not well established. The performance of the bottle-shaped strut in terms of efficiency factors, crack pattern and failure mode for different amounts of macro steel fibres and micro polypropylene fibres are studied using experimental investigation. Specimens of 600mm x 600mmx 100mm size were tested under compression. Steel fibres are added in the proportions of 0.7%, 0.9% and 1.1% volume fractions to the concrete. Effect of fibre hybridization also studied by adding micro polypropylene fibres in the proportions of 1% and 2% in addition to the steel fibres. Experimental results showed that adding discrete fibres in concrete significantly improved the resistance to the transverse tension in bottle-shaped struts and led to the increased load-carrying capacity of the specimens. A 75% improvement in the efficiency factor is observed at 0.9% volume of steel fibre addition. Addition of micro polypropylene fibres to the macro steel fibres further enhanced the load-carrying capacity of the bottle-shaped struts. Microfibres in the concrete effectively arrested the micro-cracks and delayed the occurrence of a first splitting crack in the strut region. Due to this the mode of failure changed to ductile through the formation of a greater number of small cracks with less crack width at the ultimate load. Results of this study clearly show that the addition of discrete fibres to the concrete is an effective solution to improve the performance of the bottle-shaped struts in terms of ultimate strength and serviceability.

Keywords: Bottle-Shaped Struts, Steel fibres, Hybrid fibres, Cement and Concrete

1. Introduction

Structural members can be categorized into two portions namely Bernoulli regions (B-regions) and Disturbed regions (D-regions). B-regions are the portion of members where beam theory applies i.e. Bernoulli's hypothesis is valid. In D-regions, the strain profile is significantly non-linear and hence the basic assumption of 'plane section remains plane in an initially straight beam remains plane after bending' is not valid. D-regions forms at the geometric discontinuities, which are adjacent to openings, abrupt changes in the cross-section, or at the statical discontinuities, which are regions near the concentrated loads and support reactions. Structural members with significant extents of D-regions are called Non-flexural members, examples Deep beams, Pile caps, Corbels, Dapped-ends etc. D-regions cannot be designed using elastic theory due to invalidity of Bernoulli’s hypothesis. The Strut-and-Tie method (STM) is a rational method which is useful in the design of both B & D-regions in concrete members. In STM, the complex D-region is modelled as a truss carrying the applied loads to the supports or the adjacent B-regions. This truss is known as the StrutandTie model. The Strut and Tie model consists of compression members and tension members which are connected at nodes. Struts carry compressive forces and denoted using broken lines whereas ties carry tensile forces and denoted with solid lines. Struts represent compressive stress fields with principal stresses are predominantly in the direction of the strut axis. Struts are categorized based on the geometric shapes and load transfer mechanism as prismatic, fan-shaped and bottle-shaped as shown in figure 1. Prismatic struts (figure 1a) have uniform cross-section throughout the length. Fan-shaped struts are formed when compressive stresses flow from a large area to smaller area as in the case of a deep beam subjected to uniformly distributed load as shown in figure 1c. Bottle-shaped strut is diagonal strut which is formed between the concentrated load and adjacent support as shown in figure 1b.

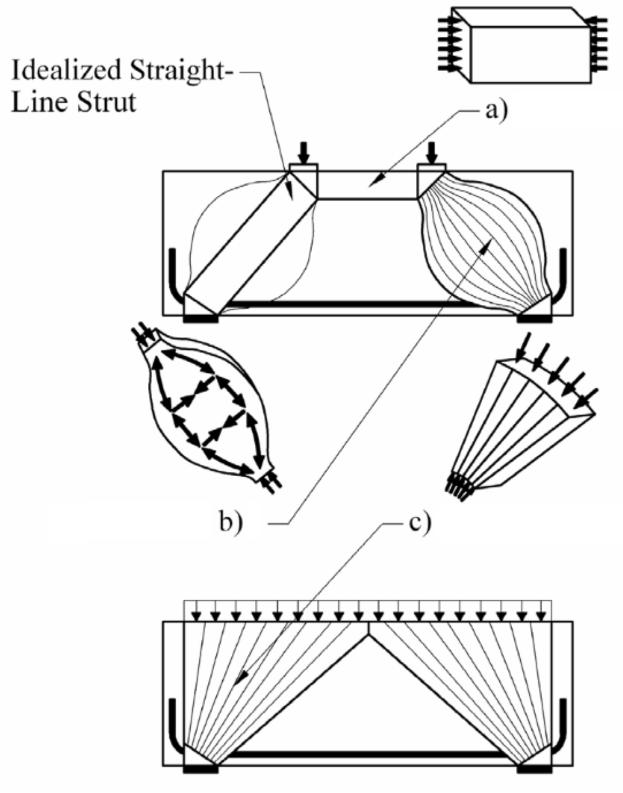


Figure 1. Types of Struts a) Prismatic strut b) Bottle- shaped strut c) Fan-shaped strut

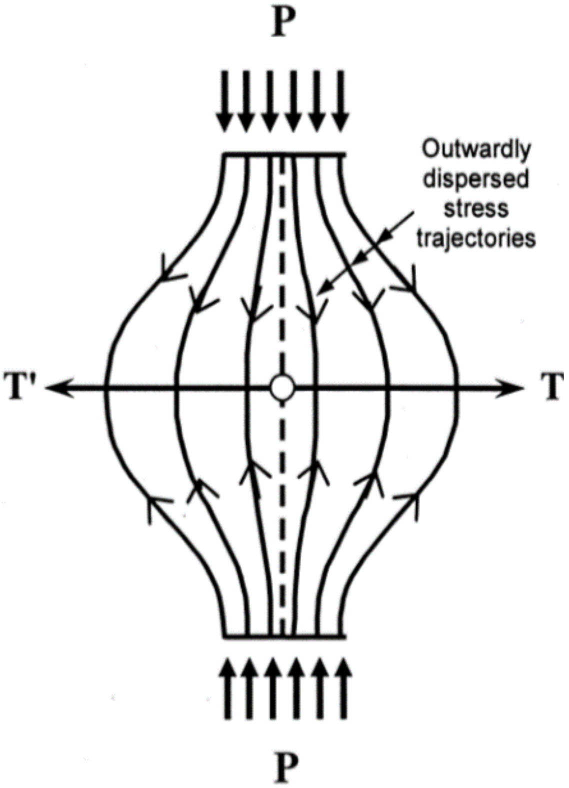


Figure 2. Dispersion of compressive forces in the bottle-shaped strut

1.1 Bottle-shaped strut

Bottle-shaped strut forms when the external load is applied in a relatively small area and the compression disperses as they flow through the member as shown in figure 2. During this dispersion, tension perpendicular to the strut axis develops to counteract the lateral component of the angled compression. Concrete being weak tension, the developed transverse tension in the strut cause longitudinal splitting and failure of the bottle-shaped struts much before the compressive stress reaches the compressive strength of concrete. The behaviour of the cracked concrete strongly influences the compressive strength of bottle-shaped struts in the strut. Compared to prismatic and fan-shaped struts, the bottle-shaped strut is critical due to the existence of transverse tension in the strut region. Resistance to transverse tension is essential in bottle-shaped struts to not only increase its strength but also to control cracking at service loads. The transverse reinforcement provisions in bottle-shaped struts vary from one code of Practice to another. The ACI 318-11 [1] provisions for evaluating the strength and minimum reinforcement requirements of a bottle-shaped strut are discussed here. As per ACI 318-11 [1], the theoretical load-carrying capacity of the bottle-shaped strut is

$$ß_s 0.85 f_c' A_S \quad (1)$$

where
$ß_s$= strut efficiency factor suggested by ACI and is listed in Table 1
f_c' = Compressive strength of cylinder
A_s = Minimum cross-section area of the strut (loaded area)

The ACI (American Concrete Institute) identifies two types of bottle-shaped struts namely reinforced and unreinforced struts and the efficiency factors specified for these two types of struts for normal concrete are 0.75 and 0.60 respectively for cylinder compressive strengths up to 40 MPa. The larger efficiency factor of 0.75 can be used for bottle-shaped struts having minimum reinforcement as per (A-4) of ACI 318-11 [1]. It means ACI allows un-reinforced struts with lesser factors. The efficiency factor of the strut is a very important parameter to design the strut in Strut-and-Tie method. Actual resistance to the transverse tension in the bottle-shaped strut can be understood indirectly from the value of the efficiency factor obtained experimentally.

Table 1. Strut and Nodal efficiency factors in ACI 318-11[1] (American Concrete Institute 2011)

Type of strut	Efficiency factor (β_s)	Type of Node	Node Efficiency factor (β_n)
Prismatic strut	1.00	CCC node	1.00
Bottle-shaped strut with reinforcement as per equation (A-4) of ACI 318	0.75	CCT node	0.80
Bottle-shaped strut without reinforcement as per equation (A-4) of ACI 318	0.60 λ	CTT node or TTT node	0.60
Struts in tension members	0.40		
Other types of struts	0.60 λ		

Note: λ=1.0 for normal weight concrete, 0.85 for sand light weight and 0.75 for all-light weight concrete.

Experimental strut efficiency factor is calculated by equating the theoretical strut capacity to the actual load resisted before it fails. In equation 1, 0.85 f_c' is the design compressive strength of the concrete. So while calculating the experimental efficiency factor, only f_c' will be considered as the compressive strength of concrete. Therefore, the experimental efficiency factor can be calculated as per Equation 2.

$$ß_{se} = P_u / (A_s \times f_c') \quad (2)$$

1.2 Research Motivation

Sahoo et al. [2] found that bottle-shaped struts should be provided with some reinforcement to resist transverse tension. Provision of minimum reinforcement is essential to meet the serviceability requirements. Also, the unreinforced struts will fail in brittle mode with a single splitting crack along the length of the strut, which is not at all advisable. In some structural members like pile caps, beam-column joints etc., providing the steel reinforcement in the strut region may not be possible due to congestion and inaccessibility. Therefore, there is a need to find an alternative solution to steel reinforcement in the strut region for better performance of bottle-shaped strut. Thomas et al. [3] concluded that discrete steel fibres in the concrete improves the tensile strength and develop bridging action after the first crack for better post crack behaviour also. Hsie et al. [4] suggested that microfibres in the concrete help to arrest the micro-cracks and crack widths. Addition of macro and microfibres in the concrete may get the combined advantages of improved tensile strength, reduced crack width and better post-peak behaviour with a ductile mode of failure. Therefore, in this study, it is attempted to use the discrete macro and microfibres in the concrete to study the performance of bottle-shaped struts. Manu other researchers worked on the behaviour of bottle-shaped struts in the recent years ([5], [6], [7], [8], [9] and [11]).

2. Experimental Program

Concrete panels of size 600 mm × 600 mm × 100 mm with different proportions of fibres are tested with in-plane loading as shown in figure 3. Isolated bottle-shaped struts will form in the panel for the adopted loading arrangement. It is observed from the literature that optimum dosage of hooked end steel fibres is around 1% for better tensile strength of concrete and therefore steel fibres are varied around 1% only. Polypropylene fibres are added in 0.1% and 0.2% volume fraction, to mix with optimum steel fibres for higher efficiency factor of a bottle-shaped strut. Table 2 presents the specimen details.

Table 2. Specimen details

Sl. No.	Grade of Concrete	% V_f of macro Steel fibres	% V_f of micro PP fibres
1	M35	0	0
2		0.7	0
3		0.9	0
4		0.9	0.1
5		0.9	0.2
6		1	0
7		1.1	0

3. Materials

The cement of 53 grade, river sand confirming to zone II as fine aggregate, crushed granite of 20 mm nominal size as coarse aggregate is used to make the panels with M35 grade concrete. Mix proportions are calculated as per IS 10262 2009 [12] and the weight of ingredients are mentioned in Table 3 per one cubic meter of the concrete.

Table 3. Mix proportions of concrete(by weight)

w/c ratio	wt. of cement	wt. of water	wt. of FA	wt. of CA
0.5	440.1 kg	220.4 lit.	764.4 kg	1008.4 kg

Macro hooked end steel fibres and Recron 3S micro polypropylene fibres are used in this experimental study. Physical properties of the fibres are mentioned the Table 4 and 5, respectively.

Table 4. Physical properties of hooked end steel fibres

Sl. No.	Property	Details
1	Fibre Length	35mm
2	Fiber diameter	0.60mm
3	Young’s modulus	210000Mpa
4	Tensile strength	1100Mpa
5	Relative density	7.8 g/cm^3

Table 5. Physical properties of Recron 3S microfibres

Sl. No.	Property	Details
1	Specification	Microfiber
2	Colour	White
3	Cut length	12mm
4	Tensile Strength	4000kg/cm^2
5	Relative density	0.9 g/cm^3
6	Modulus of Elasticity	17500 MPa

4. Casting and testing of specimens

Panels were cast under controlled laboratory conditions using standard equipment. For each batch of concrete, the quantities of required materials were kept ready in the required proportion and were mixed well using concrete mixer. The inside surface of the steel mould was coated with shutter-release oil before pouring concrete into the mould. Along with every panel, three cubes and three cylinders were cast for determining the compressive strength of concrete. All the panel specimens were tested after a normal curing period of 28 days. The panel specimens were tested under single point load in a loading frame. The load was applied through hydraulic jack, and the applied loads were read using a 1000 kN capacity digital proving ring. Steel bearing plates of 120 mm × 100 mm × 15mm size are provided at the loading and supporting point as shown in figure 3. The load was applied at the centre for a width of 120 mm only. Loads were applied at small increments to capture the specimen behaviour as closely as possible. A hand-held optical microscope with a least count of 0.1mm was used to measure the crack widths with a least count of 0.1 mm. To observe the crack propagation, the panels were whitewashed and dried before testing. A 100 mm × 100 mm grid was drawn on the panel surface to mark the location of cracks more precisely.

Figure 3. Test set-up of the panel specimen

Table 6. Summary of experimental results

Sl. No.	% SF	% PPF	f_{ck} (MPa)	f_c' (MPa)	Load at First visible crack (kN)	Peak load (kN)	Experimental efficiency factors	% improvement
1	0	0.0	40.1	32.4	249*	249	0.64	--
2	0.7	0.0	43.4	35.2	190	365	0.86	34.9
3	0.9	0.0	43.8	35.7	200	400	0.93	45.8
4	0.9	0.2	44.0	36.1	240	450	1.04	62.2
5	0.9	0.4	44.1	36.7	250	470	1.07	66.6
6	1.0	0.0	40.5	33.1	161	351	0.88	38.0
7	1.1	0.0	44.4	35.7	146	345	0.81	25.7

5. Results and Discussion

The load-carrying capacity of bottle-shaped strut depends on the resistance to the transverse tension developed in the strut. In this study, strut efficiency factors are evaluated for different amounts of fibres in steel fibre reinforced concrete and hybrid fibre reinforced concrete by equating the theoretical strut capacity to the actual load resisted by testing the panels as shown in figure 3. For each fibre volume fraction, 3 panels are tested and the average value is reported for first cracking load, peak load, efficiency and improvement in Table 6.

5.1 Effect of steel fibres on efficiency factors

Based on the peak load, the experimental efficiency factor is calculated as per equation (2) and plotted the variation for a different amount of fibres proportion. Percentage change in the efficiency factor is calculated compared to the controlled specimen which has no fibres in the concrete.

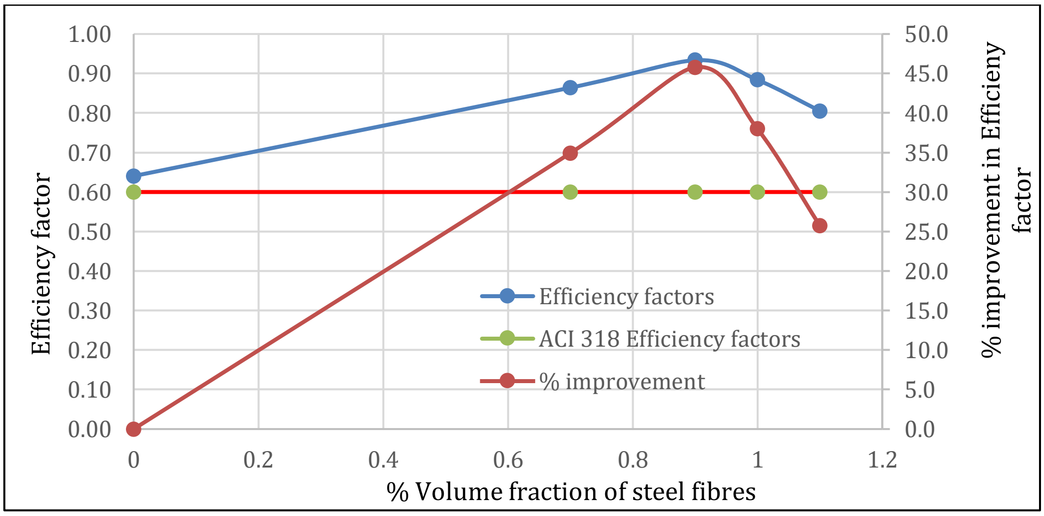
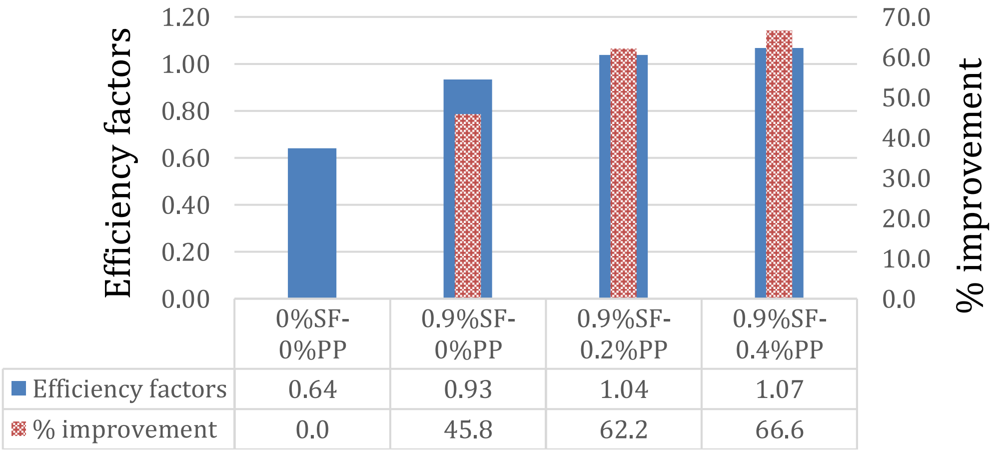


Figure 4. Graph showing the effect of steel fibres on efficiency factors

As shown in figure 3, the efficiency factor increased with the increase in the steel fibres content in the concrete and it has a peak value at 0.9% of the volume fraction. Around 45% improvement in efficiency factor is observed at 0.9% volume of steel fibres. From results shown in figure 4, it is observed that 0.9% volume fraction of steel fibres have shown good efficiency and improvement when compared with different amounts of steel fibres panels. So, the optimum percentage of steel fibres is 0.9% volume fraction.

5.2 Effect of microfibres on efficiency factors

Effect of hybrid fibres has been studied by taking steel fibres with 0.9% and varying polypropylene fibres as 0.1% and 0.2% volume fraction.



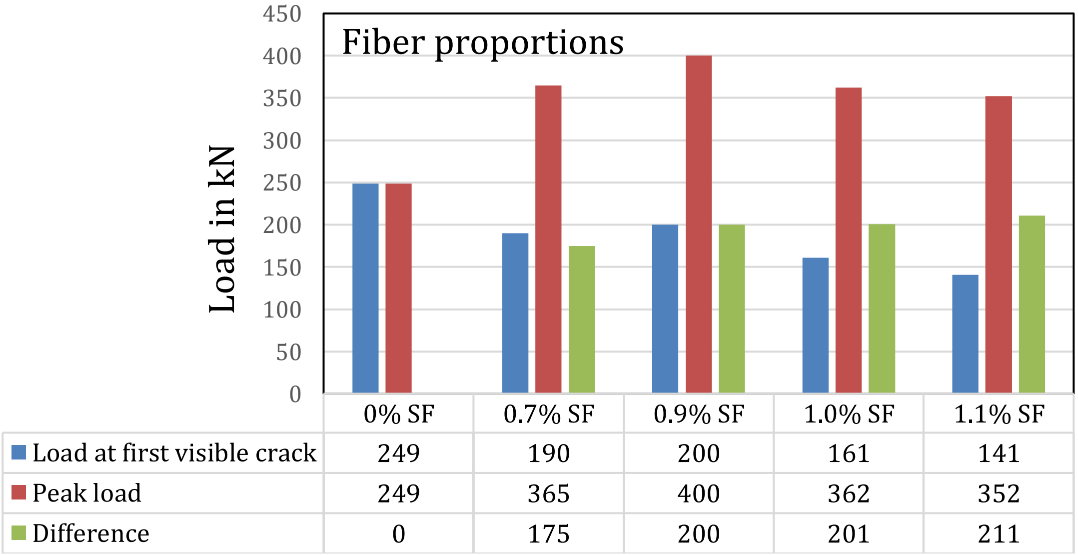
	0%SF-0%PP	0.9%SF-0%PP	0.9%SF-0.2%PP	0.9%SF-0.4%PP
🟦 Efficiency factors	0.64	0.93	1.04	1.07
▨ % improvement	0.0	45.8	62.2	66.6

Figure 5. Effect of microfiber on the efficiency factor

As shown in figure 5, the efficiency of hybrid fibre reinforced concrete has been improved further when compared to mono steel fibre reinforced concrete.

5.3 Effect of steel fibres on crack propagation

Figure 6 represents the first crack load, peak load and the difference between them. Specimens with no fibres fail suddenly with a single splitting crack. Therefore, the same load value is reported for first visible crack and at failure. It has been observed that there is an increase in the ultimate load-carrying capacity of specimens with steel fibres up to 0.9% volume fraction, and from there, the reduction is observed. Though there is a decrease in load carrying capacity beyond 0.9% volume of steel fibres we can observe that the difference in the first crack load and the peak load increased with the percentage of steel fibres which indicates that steel fibres start bridging action once the concrete cracks which delay the ultimate failure after the initial crack and therefore, the ductility is increased.

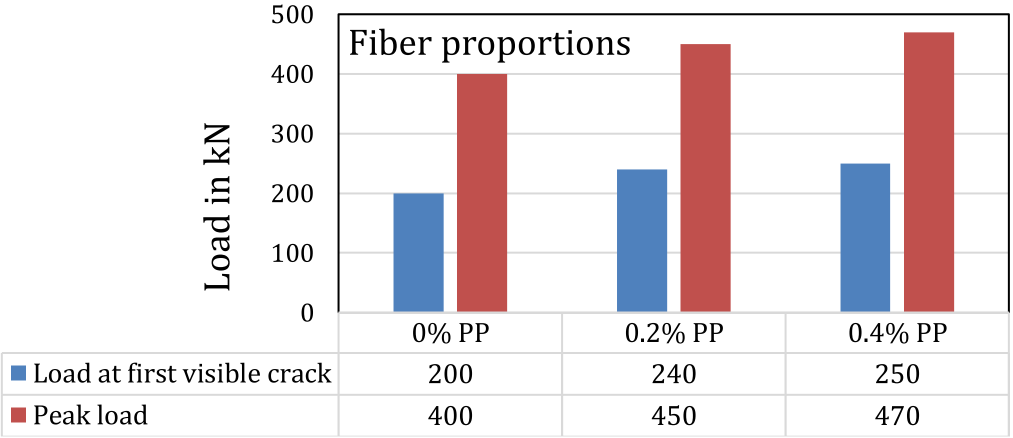


	0% SF	0.7% SF	0.9% SF	1.0% SF	1.1% SF
🟦 Load at first visible crack	249	190	200	161	141
🟥 Peak load	249	365	400	362	352
🟩 Difference	0	175	200	201	211

Figure 6. Effect of steel fibres on crack propagation

5.4 Effect of micro polypropylene fibres on crack propagation

Figure 7 represents the cracking behaviour at 0.9% of steel fibres with varying polypropylene microfibres at 0.1% and 0.2% proportions.



	0% PP	0.2% PP	0.4% PP
🟦 Load at first visible crack	200	240	250
🟥 Peak load	400	450	470

Figure 7. Graph showing the effect of polypropylene fibres on cracking behaviour at 0.9% SF with varying PP fibres

It is observed in figure 7 that, with an increase in the proportion of polypropylene fibres, load carrying capacity has been increased. Due to the addition of micro polypropylene fibres to the macro fibres, load at first visible crack increased compared to the specimens with no microfibres. This shows that the inclusion of microfibres arrests the formation of initial cracks and improves the ductility.

5.5 Crack widths and failure modes

Details of all specimens with crack widths and failure modes are listed below in Table 7. From Table 7, it can be observed that the addition of fibres to the unreinforced bottle-shaped strut changed the failure mode of the bottle-shaped strut and made it more ductile. Specimen with no fibres failed suddenly with a single splitting crack at the centre of the strut and it broken into two pieces as shown in figure 8 to 13. Further, an increase in the fibre percentage in concrete, the width of cracks reduced at service and ultimate load also. Addition of microfibres will further reduce the crack width. Pictures of all the specimens after failure are shown in figure 8 to 13.

Table 7. Crack widths and failure modes

% Steel Fibres	% of PP fibres	Maximum crack width at service load (mm)	Maximum crack width at peak load (mm)	Type of failure
0%	0%	—	--	Splitting failure (brittle failure with single crack)
0.7%	0%	0.4	0.5	Splitting failure with multiple cracks
0.9%	0%	0.4	0.5	Splitting failure with multiple cracks
0.9%	0.2%	0.2	0.3	Splitting failure with multiple cracks
0.9%	0.4%	0.2	0.2	Splitting failure with multiple cracks
1%	0%	0.3	0.5	Splitting failure with multiple cracks
1.1%	0%	0.3	0.5	Splitting failure with multiple cracks

Figure 8. Failure of the panel without fibres

Figure 9. Failure of the panel with 0.7% macro steel fibres only

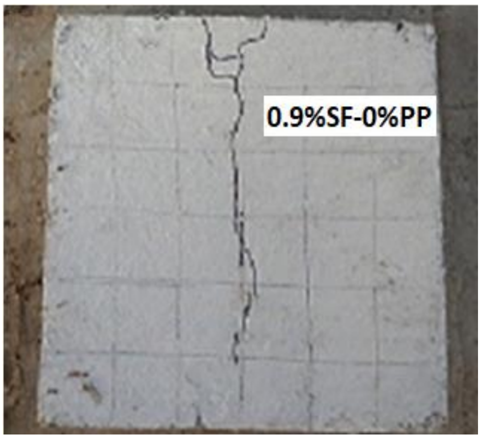


Figure 10. Failure of the panel with 0.9% macro steel fibres only

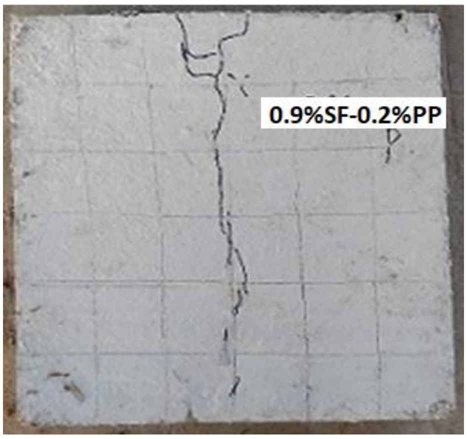


Figure 11. Failure of the panel with 0.9% macro steel fibres and 0.2% micro polypropylene fibres

Figure 12. Failure of the panel with 1% macro steel fibres only

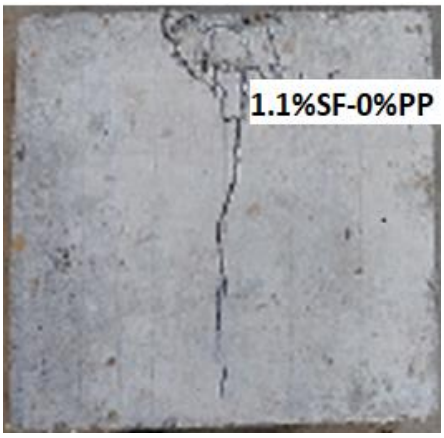


Figure 13. Failure of the panel with 1.1% macro steel fibres only

6. Summary and Conclusions

1. Discrete steel fibres in concrete significantly improved the Efficiency factors of bottle-shaped struts. Around 45% increase in the efficiency factor is observed at 0.9% volume fraction. Macro steel fibres also delayed the ultimate failure of the bottle-shaped strut after the first crack by developing the bridging action after the crack initiation.
2. Plain concrete bottle-shaped strut failed suddenly with single splitting crack. Addition of macro steel fibres develops bridging action after the crack occurs and change the mode of failure to ductile nature.
3. Microfibres in the concrete was found effective in controlling the initial cracks and also the crack width at service and ultimate loads.
4. The good synergy between macro steel fibres and micro polypropylene fibres is observed with the improved performance of bottle-shaped strut in terms of load-carrying capacity and serviceability.
5. Addition of fibres can be considered as the alternative the transverse reinforcement in the bottle-shaped strut to meet the serviceability requirements.

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