Effect of Shear Studs and Steel Fibers on punching Shear Capacity of Flat Slab

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ABSTRACT

Punching shear is a conspicuous phenomenon of fracture mechanism in R.C Flat slab. To meet high shear and flexural demand at critical shear zones of column supports or point loads of flats slabs, the design codes proposed to construct Column heads (capital) and Slab drops against punching shear failure. But this may lead to decrease head clearance and increase of construction cost. To optimise the slab geometry at critical sections of punching shear zones, an experimental programme conducted on three full scale R.C flat plate slabs (NSF, WSF1, WSF2) constituted with different shear resistant elements(steel fibres and headed shear studs) used in punching shear zone. The flat slabs configurated by NSF is "Flat slab using conventional shear reinforcement bars, and WSF1 is "Flat slab using steel fibre concrete in shear zone and the rest of slab with conventional reinforcement" and WSF2 is "Flat slab with combination of steel fibre reinforcement and shear studs used in punching shear zone only and the rest of slab with conventional reinforcement. Random oriented hooked steel fibres of 1.5% volume fraction used for implicit strengthening of concrete at critical punching shear zone. The test parameters considered in this study are shear performance, load capacity, stiffness degradation, energy dissipation, and crack pattern. The test results indicated that, use of steel fibres and shear studs in critical punching shear zone of flat slab is significantly improves punching resistance mechanism, and load carrying capacity of flat slab (WSF2). Further the punching shear failure at ultimate load was observed by ductile mode with good energy dissipation.

Keywords: Punching shear, Flat slab, Shear studs, Steel fibres, Shear zone

1. INTRODUCTION

Punching shear is a most prominent failure often observed at column supports or point loads of slender slabs that may produce two dimensional brittle failures in R.C Flat slab. Researchers considered that punching shear is an analogous process assessed by one way shear mechanism of R.C beams [1]. In the process of punching shear, cracks are initiated in critical section and progressed in two dimensional mode ,widen up rapidly in around the perimeter of shear zone .To enhance shear capacity and ductile properties of slab, specific improvements are often suggested by designers include strengthening of concrete and increase the effective thickness of slab at critical shear zones. Provision of column heads and slab drop near shear zones are well addressed in the design codes (ACI 318-14, I.S 456-2000, NZS 3101-2006). Further the punching shear can be reduced by increase thickness of slab or arrangement of shear reinforcement in critical zones. Literature study [2] expressed that ratio of flexural reinforcement in flat slab significantly influence the punching shear behaviour in presence of shear reinforcement. Increase the shear reinforcement at critical section of flat slab consist low flexural reinforcement shows limitation on effective improvement of shear resistance. Increase thickness of slab may lead to consume additional material, increase of dead weight, delay in construction process (due to form work) and reduction of head clearance by false ceiling. Hence there is a need for improvement of shear strength and ductile properties of flat slab (column supported regions) without sectional enhancement at shear zones. Research studies [3] mentioned that factors like confinement and tensile strength of concrete significantly improve the shear capacity and ductile parameters of concrete. Previous research expressed that detailing aspects of reinforcement include provision of inclined bars or stirrups in shear zone may significantly contribute against shear resistance mechanism of slab [3], [5]. But the issues of fabrication, placing and concrete cover hindered the application of reinforcement detailing against shear. It is an identified fact that reinforcement ratio of flat slabs does not governed by punching shear failure [4][6] except limiting its deformation. Past research works [5] concluded that a flat slab with good punching shear resistance will allow large horizontal drift and maintain its structural integrity. Further it was identified that [6] provision of shear reinforcement in critical zone was not effectively contributed against punching resistance mechanism or the full yield conditions of steel was not attained during punching failure.

In the context of above remarks, the author comes to a conclusion that unless a good existence of strain compatibility between concrete and steel reinforcement, and omitting the impregnated flaws of concrete due to lack of implicit tensile strength, the shear capacity of concrete can't increase in shear zone. So far less contribution addressed by researchers to improve tensile strength (flexure, splitting, direct) properties of concrete. To meet implicit tensile properties of concrete, steel fibres provides an optional method [7][8] at optimum dosage [8][12] of 1.25%-1.50% (volume fraction of concrete). The fibres provide a bridge action against micro cracking of concrete and delay the formation by tensile resistance. Previous studies [9] [10] observed that provision of headed shear studs in shear zone gives a promising features of improvement in shear capacity of R.C flat slabs[13]. Hence the influence of both steel fibres and shear studs need to be consider for composite mechanism against punching shear. This may produce good contribution against ductility, energy dissipation and shear resistance mechanism of flat slab. In this context an experimental programme conducted on flat slabs using steel fibres and shear studs. The critical zone of shear perimeter is taken as 0.5d (d: effective depth of slab) from column face. The improvement of tensile strength and ductility factors of concrete was verified at limiting flexural reinforcement of slab.

2. OBJECTIVES

This experimentation addressed on punching shear resistance of flat slab using a matrix of steel fibres and shear studs used in punching shear zone. The test parameters considered are shear performance, load carrying capacity, stiffness degradation, energy absorption, and crack pattern of slab under static load conditions. This study is limited to use concentric point load on symmetric application on flat slab under monotonic test conditions. Both column and slab are casted monolithically to meet the conventional design practice.

3. RESEARCH SIGNIFICANCE

An experimental work focused on provision of sectional improvements of slab against punching shear resistance with steel fibres and shear studs. Since the geometric limitations of conventional design practice discourage the use of column head and slab drop in punching shear region, there is a need for design improvements of slab section against punching shear failure and allow the shear failure through ductile mode of fracture. Previous research was not addressed the composite action of steel fibres and shear studs during punching shear of flat. This study focused on the above parameters.

4. EXPERIMENTAL PROGRAMME

4.1. Details of Test Specimens

The test programme constitutes a detailed analysis on punching shear behaviour of three R.C slabs of NSF, WSF1, WSF2 . Typical two way R.C panel flat slab (size:1050x1050x110mm) designated to verify punching shear was monolithically casted with R.C stud column (size 150x150x150mm) by M_{25} grade conventional concrete. The monolithic casting of slab and column (Fig.1) was used to meet conventional practice of slab. The tested slab NSF referred as Flat slab with conventional shear reinforcement, WSF1 referred as Flat slab with hooked steel fibres (1.5% volume fraction) randomly mixed in concrete and used in critical shear zone (260x260mm). The notation WSF2 referred as R.C slab with steel fibre (1.5% volume fraction) reinforced concrete with double headed shear studs used in shear zone (260x260mm) of column support. During this process, steel fibres are randomly oriented in concrete (SFRC) to meet construction feasibility. The design of flat slabs are proceed by yield line method [9] as no design codes or empirical methods available at present to address design of flat slab under point loads. The flat slabs (NSF, WSF1, WSF2) are typically designed without projections of column head or slab drop and designed to meet symmetric service load of 110kN at 1.50 load factor .Due considerations given to meet ultimate failure by punching shear. Boundaries of slabs are considered as simply supported with unrestrained conditions. Based on strength and serviceability conditions, the tested slabs are verified for punching shear, energy dissipation, stiffness, ductility and crack pattern .Flexural reinforcement ratio 1.10% considered in the design of slab and reinforcement detailing is shown in fig 8a, fig 8b and fig 8c.The support conditions of slab was restrained by metal clamps to meet continuous edge conditions of flat slab in real time practice.

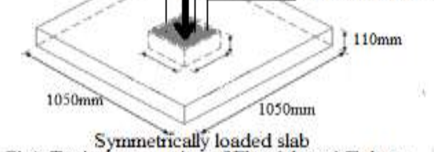


Fig1: Typical connection of Flat slab and Column

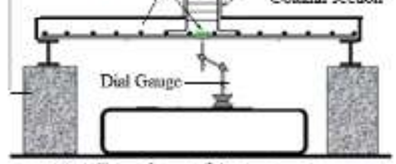


Fig 2 Experimental test setup

Fig:3. Shear Resistance of Steel fibres

Figure.1 Figure 2 Figure 3

4.2. Concrete Design and Testing

M25 grade concrete (designed as per I.S10262-2016) used for the tested slabs of NSF,WSF1,WSF2 with provision of steel reinforcement Fe500 grade .Cement grade OPC-53, Granite coarse aggregate of 25mm size and River sand (confirming to zone II- I.S code) as fine aggregate used and confirmed to material specifications mentioned in I.S.383& I.S.516. The component elements are machine mixed by (1.0: 2.1: 3.0 weight metric proportion) at W/C: 0.46 to prepare M_{25} grade conventional concrete. No admixtures used in the preparation of conventional concrete. The testing of concrete proceed by I.S 516 specifications and concrete strength verified by using compression test (cube specimen size 150x150x150mm), flexural test (prismatic specimen under 1/3 point loads from each end) and splitting tensile test (cylindrical specimen 100x200mm) as shown in fig.4. The test was proceed at different age group of water curing the concrete specimens at 7days, 14days and 28days and results are shown in fig5. The steel fibre reinforced concrete (SFRC) may intended to use in shear zone is prepared by mixing random oriented hooked steel fibres (1.5% volume fraction) with M_{25} design mix and proceed to test the concrete at different ages of 7days,14days and 28days.No admixtures are used during preparation of SFRC .

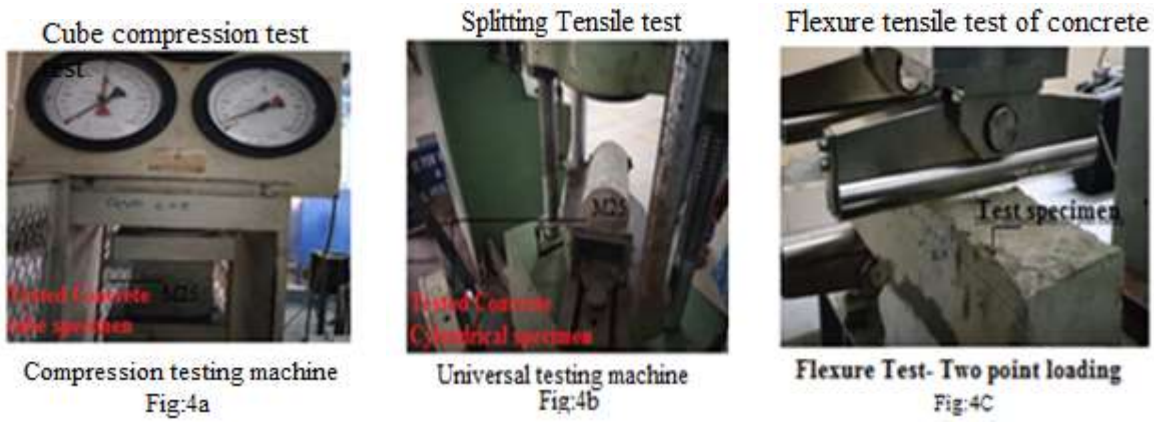


Figure 4. Testing of Concrete Specimens

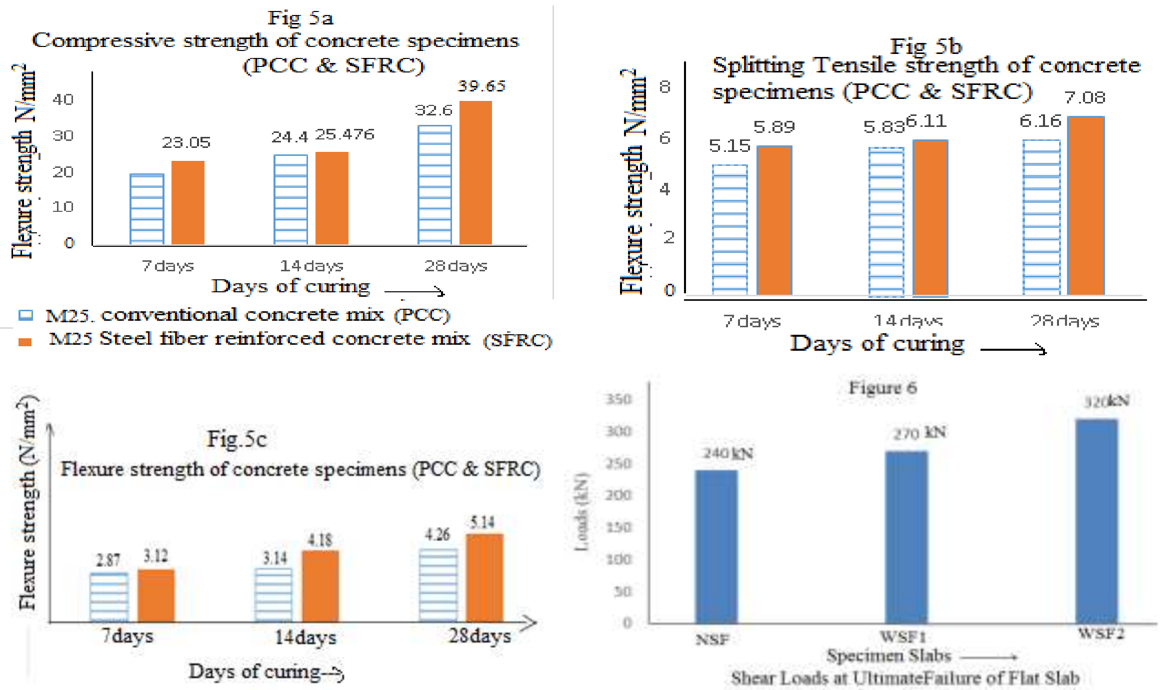


Figure 5 Results of Tested Concrete specimens (PCC & SFRC)

4.3. Reinforcement Properties and Detailing

Slab reinforcement provided in the form of steel bars ,shear studs and fibers. Steel bars of 10mm provides over the entire two way span of all slabs (NSF,WSF1,WSF2) and in addition to conventional bars, steel fiber reinforcement provided in critical shear zones of slabs (WSF1,WSF2) with or without shear studs.The steel reinforcement steel is confirming to Fe_{500} grade HYSD (High yield strength deformed bars) used in the design of flat slab. Bottom bars of 10mm dia at 110mm c/c spacing (11nos) in each direction considered for tensile steel and 8mm dia at 250mm c/c provided in top steel as compression steel in the design of slab. The columns reinforcement (12mm dia-4no) connected to slab reinforcemen with 6mm dia stirrup reinforcement at 100mm spacing. column reinforcement was not provided anchorage with slab as doweling action intended to restrict punching. Punching shear zone is located at 55mm from column face (0.5d: adjacent to column) arround the column periphery of slab.

Table 1 Mechanical properties of Reinforcement steel tested in the Laboratory

Reinforcement type	Diameter of bar (mm)	Cross section (mm^2)	Yield stress (N/mm^2)	Ultimate stress (N/mm^2)
Mild steel	6	28.2	312	410
HYSD	8	50.3	500	580.2
HYSD	10	78.5	510	624.4
HYSD	12	113.10	573	692.3

Table 2 Mechanical properties of Steel fibers tested in the Laboratory

Description (Hooked steel fiber)	Fiber diameter	Length	Tensile strength	Aspect Ratio	Density of fiber
	1mm	30mm	1178 N/mm^2	30	78.5kN/m^3

4.4. Punching Shear Resistance

In this experimental work, Punching Shear Resistance (PSR) is broadly classified and justified as follows. Three R.C flat slabs of NSF,WSF1,WSF2 are considered in the test programme to verify shear resistance mechanism of slab at critical punching shear zone of slab by addition of shear resistance elements . From the experimental test results*, the shear resistance mechanism of steel fibres and shear studs are observed as follows.

PSR of Conventional flat slab NSF = Steel reinforcement bars+ Concrete = (240kN*)

PSR of SFRC flat slab WSF1 = Steel reinforcement bars+ Steel fibres+ Concrete = (270kN*)

PSR of SFRC flat slab WSF2 = Steel reinforcement bars+ Steel fibres+ Shear studs+ Concrete= (320kN*) .

Computations of above test results (Ref fig.6) addressed that steel fibres contributed more shear resistance mechanism (30kN) than shear studs (20kN) as implicit resistance mechanism of fibres against tensile resistance induced in the concrete.

PSR of Conventional flat slab NSF: The tested slab with conventional reinforcement was considered as control specimen as per reinforcement detailing shown in figure7a. The control slab was intended to fail by punching shear mechanism, and the two-way steel reinforcement was designed to meet flexural strength of slab (figure.5).Hence both the concrete and steel are participating in shear resistance mechanism. The design code ACI 318-2014 and I.S 456-2000 mentioned that, shear resistance mechanism of concrete is contributed for 50% of shear force and rest of force compensated by steel reinforcement. But there is no provisions to improve implicit tensile strength of concrete. Hence the NSF slab intended to sudden and brittle failure mode of concrete under two way punching shear. The formation of cracks at ultimate failure (240kN) are widely propagated around the punching shear region of slab by producing large crack width and limited numbers as shown in figure 7a.There is no resistance mechanism for implicit tension failure of concrete under pure shear conditions.

PSR of SFRC flat slab WSF1: The tested slab explicitly designed by conventional concrete (M_{25}) and Fe500 grade steel reinforcement as detailed in figure 7b. In addition to the reinforcement, the punching shear region of slab is strengthened by SFRC concrete for improve the implicit tensile strength of concrete in punching shear region. Punching shear failure of slab at ultimate load (270kN), reveals that the development of multiple cracks are radiated from column periphery with uniform intensity and minimum width as shown in fig.6b .This indicated that shear mechanism of slab posses good energy dissipation and ductility before failure. The punching shear failure of concrete in WSF1 is contributed by combination of steel reinforcement bars, concrete and fibre reinforcement. Since steel fibre shows good tensile properties and intends to enhance implicit tensile properties of concrete. The post cracking phenomenon of slab extended due to good resistance mechanism of steel fibres against tension as shown in fig.3. Hence it may generalized that punching shear mechanism contributed by implicit tensile strength of SFRC under pure shear conditions and explicit resistance by steel reinforcement bars.

PSR of SFRC-STUD Slab.WSF2: The tested slab explicitly designed by conventional concrete (M_{25}) and Fe500 grade steel reinforcement as detailed in figure**7c**. In addition to the conventional reinforcement, punching shear region of slab strengthened by SFRC concrete and headed Shear studs to improve both implicit tensile strength of concrete and external shear resistance mechanism in critical shear zone. From the experimental observations, punching shear failure of slab happened at ultimate load 320kN. Observations noted that controlled development of cracks that radiated punching shear zone with minimum crack width as shown in fig.6c.This indicates shear mechanism of slab posses good energy dissipation and ductility with good improvement of shear resistance before failure. The punching shear failure of concrete in WSF2 is constituted by steel fibres, reinforcement bars, shear heads and concrete. The steel fibre shows good tensile properties and intends to enhance the implicit tensile properties of concrete. Also shear studs possess good resistance of punching shear. Hence the post cracking phenomenon of flat slab (Table.V) shows effective resistance mechanism by implicit strengthening of steel fibres by tension and explicit shear resistance by shear studs (fig.3).Hence the punching shear mechanism of WSF2 contributed by strength of SFRC and SHEAR STUDS in addition to conventional shear resistance mechanism of reinforcement.

5. POST FAILURE CONDITIONS

The post failure conditions of flat slabs NSF,WSF1,WSF2 are observed in terms of load increment and crack pattern during experimentation. This will enables to evaluate the strain energy, stiffness change, and ductility factors of flat slab during punching shear failure. The tested slab shows a good improvement of these parameters when using steel fibres and shear studs. It is observed that the post failure conditions of slab implicitly effected by steel fibres and explicitly improved by shear studs .Experimental results mentioned in Table.3 demonstrated these facts.

Fig.7

Fig 7a

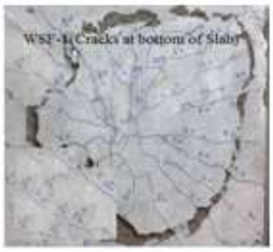


Fig 7b

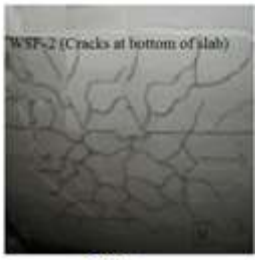


Fig.7c

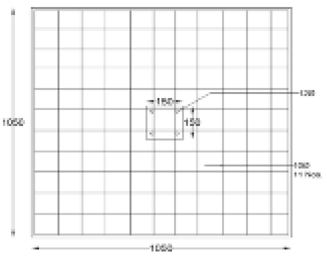
Figure 7. Punching shear failure of flat slabs NSF,WSF1,WSF2

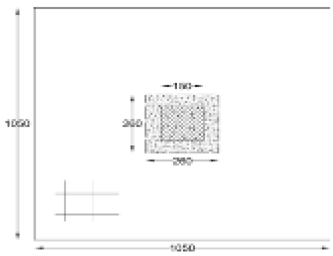
The experimental observation of fig7a,fig7b,and fig7c describes the failure conditions of slabs NSF,WSF1,and WSF2 respectively. It may drawn to conclusions that very few brittle and wide cracks contoured in shear zone during failure of NSF (fig.7a). Similarly multiple thin cracks are observed in WSF-1 which radiated in punching shear zone. Since steel fibers posses good tensile resistance in concrete (fig.7b), the formation of multiple cracks delays punching shear failure.The failure of WSF-2 (fig.7c) concludes that both multiple crack propagation in radial direction and shear failure in punching shear zone are effectively controlled by arranging shear studs in perimeter of punching shear zone and use of steel fibers in punching shear zone.

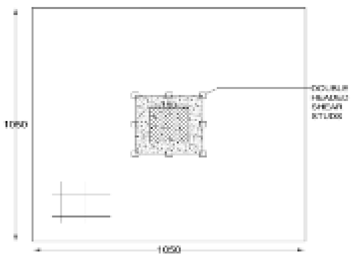
6. EXPERIMENTAL PROGRAMME

The testing of NSF,WSF1, and WSF2 flat slabs constitute arrangement of slab below the loading frame (1000kN) and apply point load at center of pedestal column as shown in fig.8.The tested slabs are simply supported and the corners are clamped by steel section to meet end restraint conditions. Point loads are applied by using hydraulically operated loading frame. Dial gauge fixed below the center of slab used to find the deflection of slab during load increment. Initial load of 50kN applied on slab to meet the test requirements. An uniform load increment of 10kN/min applied on pedestal column and noted the slab deflection using dial gauge fixed at center of slab. The load deflection curves are established to evaluate linear elastic range, ultimate load ,shear failure and stiffness degradation of slab.

Experimental Testing of Flat slabs (NSF,WSF1,WSF2)
Fig.8


NSF . SLAB REINFORCEMENT. **Fig 8a**


WSF.1 SLAB REINFORCEMENT . **Fig8b.**


WSF.2 SLAB REINFORCEMENT. **Fig 8C**

7. ANALYSIS OF TEST RESULTS

The results are analysed by strength and serviceability conditions.As per strength considerations, the flat slabs are evaluated under punching shear failure,energy release,ductility and stiffness degardation .As per serviceability criterion, the slabs are evaluated under crack pattern, service load, ultimate load and ultimate deflection . The limiting deflection of slab at service conditions justified as 4.26mm (I.S456-2000).

Table.3 Principle Test Results

TESTED SLABS	**SERVICE CONDITIONS**		**INITIAL CRACK CONDITIONS**		**ULTIMATE FAILURE CONDITIONS**		**DUCTILITY FACTOR (ρ)**	**STRAIN ENERGY (kN-m)**
Description	Deflection Mm (Δ_y)	Load kN (Ps)	Deflection mm (Δ_{cr})	Load kN (Pcr)	Deflection Mm (Δ_u)	Load kN (Pu)	[(Δ_u)-(Δ_{cr})] (Δ_y)	(Pcr) x (Δ_u)
NSF	4.26	90	4.28	92	13.1	240	2.07	1.20
WSF1	4.26	93	4.34	97	13.84	270	2.23	1.34
WSF2	4.26	98	4.79	100	14.63	320	2.30	1.46

Table.4 Stiffness Change

TESTED SLABS	**Load @ 4mm deflection**	**Load @ 13mm deflection**	**Initial Stiffness Ki**	**Final Stiffness Ku**	**Ratio of Stiffness Degradation**
	kN	kN	kN/mm	kN/mm	Ku/ Ki
NSF	90	238	22.50	18.30	0.83
WSF1	93	262	23.25	20.15	0.86
WSF2	98	293	24.50	22.50	0.92

Table 5 Comparison of Post crack performance of tested slabs (Stiffness - Ductility - Strain Energy)

TESTED SLABS	**(Increase of) INITIAL STIFFNESS**	**(Increase of) FINAL STIFFNESS**	**(Increase of) DUCTILITY**	**(Increase of) STRAIN ENERGY ABSORBED**
NSF	-	-	-	-
WSF1	3.30%	10.10%	7.72%	11.60%
WSF2	8.90%	22.90%	11.10%	20.60%

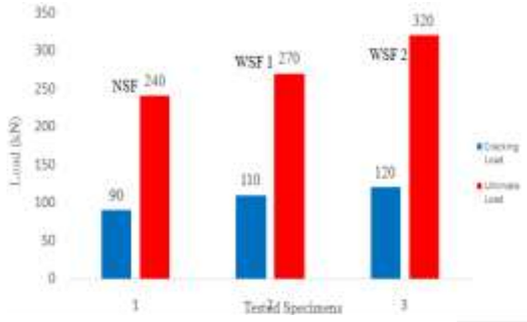


Figure 9 Crack Load and Failure Load of Flat Slabs NSF, WSF1, WSF2

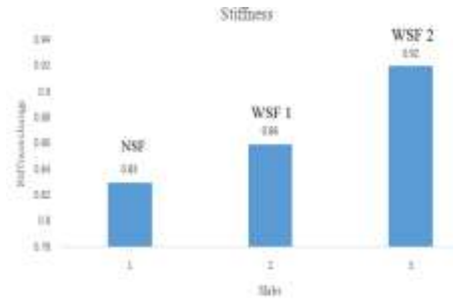


Figure 10 Variation of stiffness in Flat Slab NSF, WSF1, WSF2

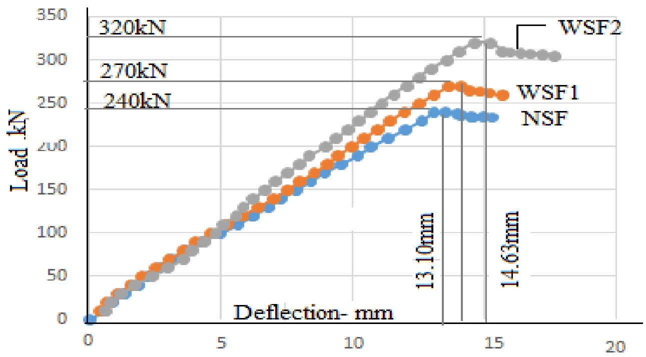


Fig.11.Comparison of Load Deflection Curve

8. RESULT AND DISCUSSIONS

The test results of table 3,4,5 and figure 9,10,11indicated a good improvement of shear resistance parameters in WSF2 as it possess both implicit strengthening of concrete by use of steel fibres in tension and explicit strengthening of flat slab system due to contribution of headed shear studs. The theoretical calculation mentioned for evaluation of punching shear mechanism (Ref. IV) addressed on additional contribution of fibres and shear studs in punching shear mechanism. The contribution of fibres and shear studs exceptionally increased in terms of stiffness and energy absorption during post cracking stage of flat slab WSF2 indicated that there was good punching shear resistance mechanism and ductility by addition of the above addressed material. Following the above test results, the author comes to conclusion that for moderate improvements against punching shear , usage of steel fibres in punching shear zone is suggested, and for expecting higher improvements against punching shear use of steel fibres and shear studs are appropriate. Strain energy absorbed by WSF2 indicate more than 20% that intends delaying of failure against punching shear. Final stiffness improvement of slab WSF2 also noted to be 22% indicated that post cracking phenomena of flat slab WSF2 shows good considerations against ductility and retrofitting measures of damaged slab.

9. CONCLUSIONS

Following conclusions are drawn for strength and serviceability conditions of Flat slabs.

- All the flat slabs (NSF,WSF1,WSF2) are subjected to brittle punching shear failure during the testing but the ultimate load capacity of WSF2 is maximum compared with other slabs.
- There is considerable improvement of punching shear resistance of flat slab WSF2 by 33% compared with conventionally reinforced flat slab NSF.

- The energy absorption of WSF2 increased by 21% compared with conventionally reinforced flat slab NSF
- The final stiffness of slabs WSF1 and WSF2 increased by 10% and 22% respectively compared with conventionally reinforced flat slab NSF.
- The deflection of flat slabs WSF1 and WSF2 increased by 11% and 23% respectively compared with conventionally reinforced flat slab NSF.
- There is an acceptable improvement of ductility in flat slabs WSF1, WSF2 by 7%, and 11% respectively compared with conventionally reinforced flat slab of NSF.

STUDY RECOMMENDATION

This study recommends use of steel fibres and shear studs in critical punching shear zone of flat slab significantly improves the shear resistance mechanism and ductility. Cost incurred for addition of steel fibres and shear studs are nominal as compared to other aspects.

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