STRAIN RATE EFFECT ON STEEL FIBRE REINFORCED CONCRETE UNDER COMPRESSION

IBRAHIM SM[1], ABADEL Aref[2], ALMUSALLAM Tarek[3], AL-SALLOUM Yousef [4], SIDDIQUI Nadeem[5], ABBAS Husain[6]

Abstract

Although steel fibre reinforced concrete (SFRC) is the widely used in building construction but its behaviour at high strain rate is not understood well. This paper presents experiments to highlight the influence of strain rate on compression behaviour of SFRC. The stress-strain characteristics of SFRC under dynamic compression using Split Hopkinson Pressure Bar (*SHPB*) *tests are studied. SFRC circular disk shaped specimens with different percentage of steel fibres were prepared and tested for the strain rate range of* 25 *to* 125 s^{-1}. *The effect of steel fibre addition in concrete on the failure mode, dynamic increase factor* (*DIF*) *of strength, toughness and strain are studied. Amount of fragmentation of SFRC composite specimens increases with increase in the strain rate. Relatively wider plateau regions in the stress strain curves were observed for fibrous composite specimens at different strain rate ranges. With the addition of fibres, the toughness property of SFRC composites is significantly enhanced. The SFRC composite specimen with* 1.4% *of steel fibres leads to the best performance compared to control.*

Keywords: Steel fibres; Concrete; SHPB; Strain rate; Stress-strain curve; DIF

1. Introduction

Recent disasters around the world have heightened the interest in improving the resistance of structures subjected to seismic, impact and blast load conditions. Fibre reinforced concrete (FRC) has the potential to be a viable solution for improving the resistance of buildings and other infrastructure components because of their high ductility, durability and energy absorption capacity compared with normal concrete. FRC composite structures show better crack resistance properties also. Steel fibres, especially because of their economic viability and relatively higher values of ductility and elastic modulii, are mostly

---

[1] Ibrahim SM, Dept. of Civil Eng., King Saud Univ., Riyadh, Saudi Arabia, srahim@ksu.edu.sa

[2] Abadel Aref, Dept. of Civil Eng., King Saud Univ., Riyadh, Saudi Arabia, aabadel@ksu.edu.sa

[3] Almusallam Tarek, Dept. of Civil Eng., King Saud Univ., Riyadh, Saudi Arabia, musallam@ksu.edu.sa

[4] Al-Salloum Yousef, Dept. of Civil Eng., King Saud Univ., Riyadh, Saudi Arabia, ysalloum@ksu.edu.sa

[5] Siddiqui Nadeem, Dept. of Civil Eng., King Saud Univ., Riyadh, Saudi Arabia, nadeem@ksu.edu.sa

[6] Abbas Husain, MMB Chair for Research and Studies in Strengthening & Rehab. of Structures, Dept. of Civil Eng., King Saud Univ., Riyadh, Saudi Arabia, abbas_husain@hotmail.com

used and the steel fibre reinforced concrete (SFRC) is the extensively used concrete mix in construction industry.

For dynamic loading conditions, the stress-strain behaviour depends on the strain rate and the material/geometric characteristics of different fibres used in the production of FRC. Wang et al. [1] studied the dynamic compression response of steel fibre reinforced concrete using Split Hopkinson Pressure Bar (SHPB). Two types of SFRC composite specimens containing 3% and 6% steel fibres by volume were studied and compared with the control specimens. The influence of the steel fibres and the strain rate in the softening region of stress–strain curve was quite pronounced as compared to their contributions in the initial elastic modulus. Bindiganavile et al. [2] reported the decrease in toughness of SFRC with an increase in the dynamic strain rate observed in drop weight impact tests. Their conclusion was further validated by Lok et al. [3] at even higher strain rates. They reported that the contribution of steel fibres to the toughness of concrete decreases as the strain rate increases. Wang et al. [4] numerically investigated the dynamic compression behaviour of SFRC using finite element analysis. SFRC was modelled as a bilinear elastic–plastic stress-strain material model. Rong et al. [5] studied the effects of strain rate and steel fibre percentage by volume on dynamic compressive behaviour of the high performance cement composite using SHPB. Steel fibres in two volume fractions of 3% and 4% were used. The specimens were tested for strain rate range of 25 to 95 s^{-1}. With increase in the fibre percentage as well as the strain rate, significant improvement in the toughness was observed, however, no appreciable change was observed in dynamic increase factor (DIF). A study of steel fibre reinforced concrete composite was carried out by Wang et al. [6] studied the dynamic behaviour of SFRC cylindrical specimens and found out that the failure mode of fibrous specimens with highest fibre percentage was essentially a spalling type failure of concrete.

SFRC circular disk shaped specimens with different percentage of hooked steel fibres were prepared and tested under dynamic compression using SHPB for the strain rate range of 25 to 125 s^{-1}. The effect of steel fibre on the failure mode, DIF of strength, toughness and strain are studied. Amount of fragmentation of SFRC composite specimens increases with increase in the strain rate. With the addition of fibres, the toughness property of SFRC composites is significantly increased. The SFRC composite specimens with 1.4% of steel fibers lead to the best performance compared to control.

2. Experimental setup

The schematic as well as the experimental setup of SHPB is given in Fig. 1. The details of the experimental setup are given in authors earlier papers [7, 8]. However, for brevity and completeness, only the equations are given here. The time histories of strain, strain rate and stress in the specimen at time *t* can be obtained from the following equations:

$$\varepsilon(t) = \frac{2C_b}{L}\int_0^t \varepsilon_r(\omega)\,d\omega, \qquad (1)$$

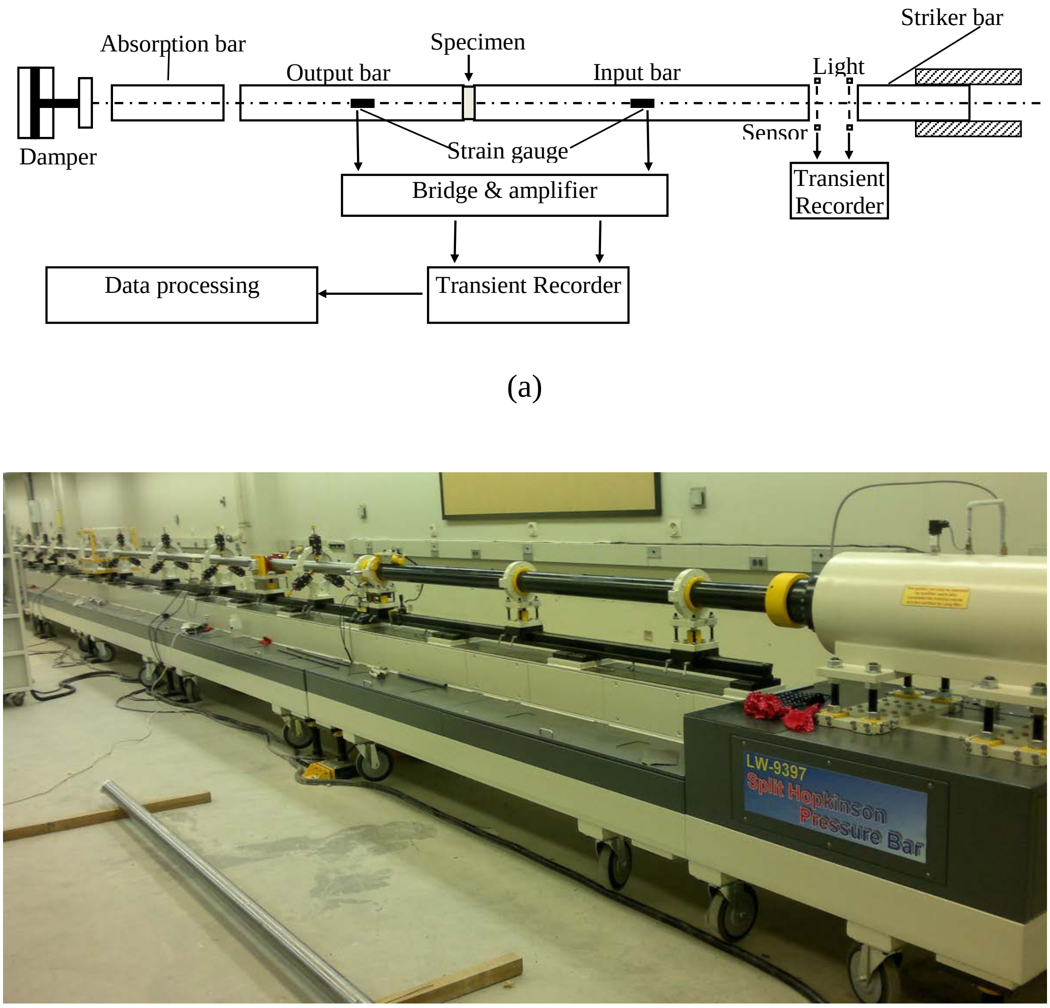
$$\dot{\varepsilon}(t) = \frac{2C_b}{L}\varepsilon_r(t), \text{ and} \qquad (2)$$

$$\sigma(t) = \frac{A_b E_b}{A_s}\varepsilon_o(t). \qquad (3)$$

where ε_i, ε_r and ε_o are incident compressive strain wave, reflected wave and transmitted wave respectively; E_b is the Modulus of elasticity of Hopkinson bars; A_s and A_b are the cross sectional areas of specimen and Hopkinson bars respectively; C_b is the velocity of longitudinal waves in Hopkinson bars; L is the length of specimen. The strain rate and stress history can be obtained as:

$$\dot{\varepsilon}(t)=\frac{C_b}{L}\{\varepsilon_o(t)+\varepsilon_i(t)+\varepsilon_r(t)\}\text{, and} \tag{4}$$

$$\sigma(t)=\frac{A_b E_b}{2A_s}\{\varepsilon_i(t)+\varepsilon_r(t)+\varepsilon_o(t)\}. \tag{5}$$



(a)

(b)

Fig.1: Schematic (a) as well as the experimental setup (b) of SHPB.

3. Experimental Program

3.1 Materials

Plain concrete (without fibres) was obtained from a local ready-mix plant. Type 1 ordinary Portland cement was used in the preparation of concrete. Table 1 shows the details of plain concrete mix.

Hooked ended steel fibre, were used in the preparation of SFRC. The material and geometrical properties of the fibres, shown in Fig. 2, are given in Table 2.

Tab.1: Details of plain concrete mix used in the casting of SFRC composite specimens.

Material	Weight (kg/m^3)
Cement	520
Fine sand	586
Coarse aggregate (Nominal size = 10 mm)	850
Coarse aggregate (Nominal size = 5 mm)	315
Water (water cement ratio = 0.28)	145
Gli-110 (Super-plasticizer)	3 Liters
Retarder LD10	1.5 Liters

Tab.2: Fibre properties.

Fibre length (mm)	Fibre diameter (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Specific gravity	Shape
60	0.75 ϕ	1225	200	7.85	Hooked ends

Fig.2: Hooked-steel fibres used in the study.

3.2 Specimens

The SFRC composite specimens were cast using the fibres percentages given in Table 3. Three cylindrical specimens with ϕ73 mm diameter and an aspect ratio of 0.5 (length of specimen = 36.5 mm) of each SFRC composite mix were cast. These specimens were tested under different strain rates. For each mix, three standard cylindrical specimens were used for quasi-static testing.

Tab.3: Fibre volume fractions in different concrete mixes.

Concrete Mix ID	Steel fibre (SF) percentage by volume, %
M0 (Control)	0
M1	1.2
M2	1.4

4. Results and discussion

The SFRC composite specimens were tested under dynamic compression using SHPB apparatus. Variation in strain-rate was achieved by using striker bars of varying lengths and varying gas pressure. Because of the brittle nature of specimens, relatively long strikers are chosen for the experiments. For relatively lower strain rates, the specimens were tested using 2.2 m long striker at a maintained pressure of 4 bar in the gas gun, whereas for getting the strain rates on the higher side, 1.0 m long striker under a maintained pressure of 6 bar in the gas gun was used. Mid-range strain rates were obtained using 1.0 m striker at 4 bar pressure. The variation of strain rates obtained using the three different striker bars is shown in Table 4. Based on the strain rate values given in Table 4, the testing schemes can be categorized in strain rate ranges: (i) Range 1: 25 – 50 s^{-1} (ii) Range 2: 50 – 100 s^{-1} and (iii) Range 3: 100 – 125 s^{-1}. In the present study, the representative strain-rate is the strain-rate corresponding to the ultimate stress.

4.1 Failure mode

In general, it was observed that the degree of damage has increased with the increase of strain rate, irrespective of the presence of different percentages of fibres. Relatively large size fragments of the specimens were observed for lower strain rates (Strain rate range 1: 25 – 50 s^{-1}) whereas smaller size and crushed fragments were observed for all the SFRC composite specimens tested at higher strain rates (Strain rate range 3: 100 – 125 s^{-1}).

Tab.4: Observed strain rate values using different striker bars and gas pressures.

Concrete Mix ID	Strain rate (s^{-1})		
	2.2 m long striker at 4 bar pressure (Strain rate range 1)	1.0 m long striker at 4 bar pressure (Strain rate range 2)	1.0 m long striker at 6 bar pressure (Strain rate range 3)
M0	36	78	111
M1	32	75	110
M2	24	71	112

Moreover, for the lower strain rates, vertically cracked specimens were observed, quite similar to the failure mode usually associated with static testing. In comparison to the control mix, M0, the specimens with fibres (M1 and M2) sustain comparatively lower degree of damage. This can be possibly due to the binding effect of fibres. This also contributes to the relatively lesser damage in SFRC specimens compared to control. For the case of moderate strain rate (Strain rate range 2: 50 – 100 s^{-1}), fractured fragments of the concrete matrix bound with fibres were also observed.

4.2 Effect of fibres on compressive strength, critical strain and toughness

The stress-strain curves for the control and SFRC composite specimens are plotted in Figs. 3 and 4. The area under the stress-strain curve was calculated to assess energy absorption capacity or the toughness. For calculating toughness, the area under the full curve or the area under the curve up to a maximum microstrain value of 30000, whichever is earlier, was considered. For a better performing concrete mix, higher value of toughness is desirable. The critical strain is the strain corresponding to the peak stress. The critical strain is an important parameter in determining the failure. For structures subjected to strain rate loadings, higher value of critical strain is desirable. The DIF for strength, critical strain and toughness were also calculated. Moreover, percent change in the values of the dynamic compressive strength, f_{cd}, critical strain, ε_{cd} and the dynamic toughness with respect to the control mix, M0 were also calculated. The salient features of the stress-strain plots are summarized in Table 5. The DIF for strength, critical strain and toughness are given in Table 6.

For control concrete, M0, the DIF (strength) is increased by almost 14% when the strain rate range changes from 1 to 2. The change of strain range 2 to 3 causes increase of about 17% in the DIF (strength) whereas this increase is 33% when the strain rate range changes from 1 to 3. Apart from the case of DIF (toughness) at strain rate range 2, similar trend (i.e. percent increase in the range of 14% to 35%) in the DIF (toughness) and DIF (critical strain) was observed.

Tab.5: Summary of test results of different concrete mixes.

Mix	Static critical micro-strain, ε_{cs}	Static strength, f_{cs} (MPa)	Static Tough. ($\times 10^6$ MPa)	Strain rate (s^{-1})	Strain rate range	*Dyn. critical micro-strain, ε_{cd}	*Dyn. Strength, f_{cd} (MPa)	*Dyn. Toughness ($\times 10^6$ MPa)
M0	2930	64.5	0.46	111	3	4086	100.5	2.18
				78	2	3496	86.0	1.94
				36	1	2980	75.3	0.76
M1	3373	73.5	1.09	110	3	11951 (192%)	121.5 (21%)	5.99 (175%)
				75	2	9215 (164%)	96.0 (12%)	4.56 (135%)
				32	1	3968 (33%)	90.0 (19%)	2.27 (197%)
M2	4250	74.4	1.17	112	3	9445 (131%)	128.4 (28%)	5.92 (172%)
				71	2	11244 (222%)	106.0 (23%)	5.05 (160%)
				24	1	6218 (223%)	89.0 (18%)	3.89 (408%)

[* Value within brackets is the percentage increase with respect to the control, M0 at the corresponding strain rate range]

The critical strain is also affected due to the addition of fibres. Although there is a definite increase in the critical strain values for fibrous concrete mixes, however, the increase in the DIF (critical strain) is not consistent with the strain rate ranges. Relatively wider plateau regions in the stress strain curves were observed for M1 and M2 composite specimens at different strain rate ranges.

Tab.6: DIF of different concrete mixes.

Mix	DIF (Critical strain)	DIF (Strength)	DIF (Toughness)
M0	1.39	1.56	4.77
	1.19	1.33	4.26
	1.02	1.17	1.68
M1	3.54	1.65	5.49
	2.73	1.31	4.19
	1.18	1.22	2.09
M2	2.22	1.73	5.03
	2.65	1.42	4.30
	1.46	1.20	3.31

The addition of lower percentage of steel fibres (M1: 1.2%) results in the increase in the DIF (strength) which varies from 12% to 21% at tested strain rate ranges. However, the addition of relatively higher percentage of steel fibres (M2: 1.4%) results in an increase of almost 18% to 28% at different strain rate ranges. With the addition of fibres, the energy absorption capacity or the toughness of SFRC composites is significantly increased. The toughness enhancement is more pronounced for lower strain rate range (Strain rate range 1: 25 – 50 s^{-1}). The maximum toughness enhancement is observed for SFRC composites with 1.4% steel fibres. The average increase in DIF (toughness) for M1 and M2 composite specimens is 170% and 246%, respectively.

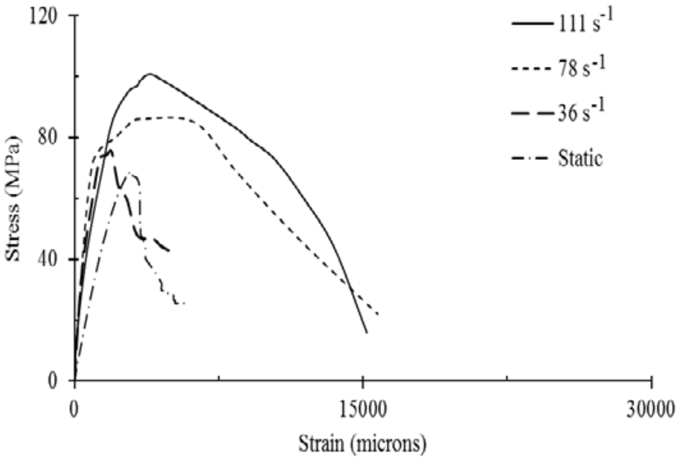
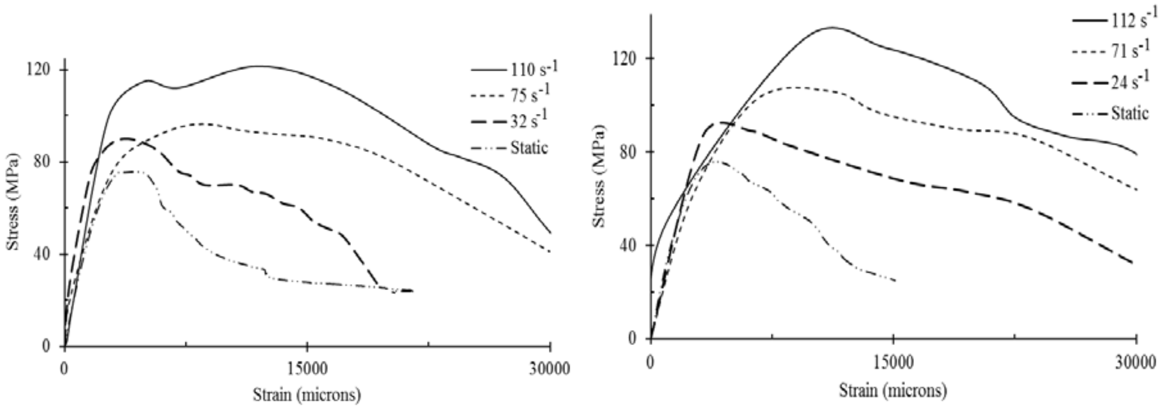


Fig. 3: Stress-strain relationship for plain concrete mix.

Acknowledgements

This work was supported by NSTIP strategic technologies program number (12-ADV2619-02) *in the Kingdom of Saudi Arabia.*



(a) (b)

Fig. 4: Stress-strain relationship for SFRC: (a) Mix M1; (b) Mix M2.

References

[1] Wang ZL, Liu YS, Shen RF. *Stress–strain relationship of steel fiber-reinforced concrete under dynamic compression*. Constr Build Mater, 2008. ISSN 0950-0618. [22:811–819].

[2] Bindiganavile V, Banthia N, Aarup B. *Impact response of ultra-high-strength fiber-reinforced cement composite*. ACI Mater J, 2002. ISSN: 0889-325X. [99(6):543-548].

[3] Lok TS, Zhao PJ, Lu G. *Using the split hopkinson pressure bar to investigate the dynamic behaviour of SFRC*. Mag Concrete Res, 2003. ISSN: 0024-9831. [55(2):183-190].

[4] Wang ZL, Wu LP, Wang JG. *A study of constitutive relation and dynamic failure for SFRC in compression*. Constr Build Mater, 2010. ISSN 0950-0618. [24:1358–1363].

[5] Rong Z, Sun W, Zhang Y. *Dynamic compression behavior of ultra-high performance cement based composites*. Int J Impact Eng, 2010. ISSN 0734-743X. [37:515–520].

[6] Wang ZL, Shi ZM, Wang JG. *On the strength and toughness properties of SFRC under static-dynamic compression*. Compos Part B-Eng, 2011. ISSN 1359-8368. [42:1285–1290].

[7] Al-Salloum Y, Almusallam T, Ibrahim SM, Abbas H, Alsayed S. *Rate dependent behavior and modeling of concrete based on SHPB experiments*. Cement Concrete Comp, 2015. ISSN 0958-9465. [55:34–44].

[8] Al-Salloum Y, Alsayed S, Almusallam T, Ibrahim SM, Abbas H. *Investigations on the influence of radial confinement in the impact response of concrete*. Comp Concrete, 2014. ISSN 1598-8198. [14(6): 675–694].