Shear Strength of Conventional and Lightweight Concrete I-Beams with Fibrous Webs

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ABSTRACT

This study investigates the behavior of the shear strength of fibrous concrete I-beams made from normal and lightweight concrete that have the same compression strength, of about 30 MPa. Lightweight aggregate concrete was made by replacing 75% of the coarse aggregate with lightweight aggregate (Bonza stone). Fourteen concrete I-beams with dimensions of 1000×210×175 mm were divided into two groups. In the first group, the web area was reinforced with steel fiber added in 0.5%, 1%, and 1.5% of the mix volume. The second group was reinforced with glass fiber added in the same percentage as the steel fiber. The results showed that the shear strength of a Normal Concrete Beam with Steel Fibers (NCSF) is increased by 3.5%, 13.5%, and 13.3% for the addition ratios of 0.5%, 1%, and 1.5%, respectively, compared to the Normal Concrete Beam without Fibers (NC). Webs with glass fibers gain an increase of about 3.7% and 14.05% for the addition ratios of 0.5% and 1%, respectively, while the shear strength decreased by 6.21% for the addition ratio of 1.5%. On the other hand, the Lightweight Concrete Beam with Steel Fibers (LWCBSF) achieved greater shear strength than the Lightweight Concrete Beams without Fibers (LWCB) by 4.8%, 13.5%, and 10.9%; for the three additional percentages, respectively. The shear strength increased by 8.4% and 11.04% for the Lightweight Concrete Beam with Glass Fibers (LWCBGF) at 0.5% and 1% ratios, while the shear strength decreased by 11.9% for the 1.5% glass fibers ratio compared to the Lightweight concrete Beam without Glass Fibers (LWCB). The best performance, according to the ultimate load, was achieved when fibers were added at a ratio of 1% in normal and lightweight concrete compared to other ratios.

Keywords-shear of I-beam; glass fibers; steel fibers; lightweight concrete

I. INTRODUCTION

One of the principal structural components in the construction field is the concrete I-beam, which is the combination of steel and concrete to create a load-bearing member. It has been chosen for many years for bridges, buildings, and other large infrastructure projects because it is strong, inexpensive, and durable. When used in construction to support loads, reinforced concrete I-beams are primarily meant to support heavier loads than non-reinforced concrete beams; they also help to absorb bending stresses that may occur during their life span. The vertical web joining the bottom with the top horizontal flanges accomplishes this. The vertical web reinforcement consists of steel rods or bars, while the top and bottom flanges consist of cement [1]. In this context, I-shaped cross-section beams are widely used in long traverse and pre-stressed concrete constructions [2]. However, LWC offers the benefit of reducing the weight of large projects while also providing superior insulation properties and being environmentally sustainable. Fiber-Reinforced Concrete (FRC) has become more popular in building construction because of its improved tensile strength, impact strength, flexural strength, and failure mode. Additionally, adding fibers somewhat affects the concrete's compressive strength and elasticity modulus [3, 5]. The traditional goal of engineers is to design structures that are both affordable and secure. Nonetheless, there is growing awareness of sustainability and the need of protecting the environment. Today, more than ever, engineers must choose eco-friendly materials by incorporating the right materials to enhance these structures' mechanical properties and fire resistance [6, 7]. LWC has drawbacks, such as poor tensile strength, brittleness, and relatively high cement content. Continuous enhancements address these weaknesses, including fiber reinforcement and the partial substitution of more cost-effective cement binder materials [8]. Utilizing fibers in LWC helps enhance its strength properties, which are typically low, without compromising its low density [9, 10]. This paper demonstrates the progression of shearing stress in reinforced concrete I-beams connected to a single target capacity. Specifically, it examines the behavior of the beams when subjected to shear stress failure and the associated costs. Two factors were used to configure a supported concrete I-beam, the type of concrete and the percentage of steel and glass fiber added to the concrete admixture. The concrete used was regular and lightweight (by replacing 75% of coarse aggregate with bonza stone [11]), with the same compressive strength. this allows for configuring lighter and smaller members while reducing dead weight. Furthermore, the I-shaped cross's narrow web effectively transmits shear stress.

II. OBJECTIVE OF THE STUDY

The major objective is to use steel and glass fibers to reinforce the web region of I-shaped beams made from two distinct types of concrete (lightweight and regular) with the same compressive strength. This will allow researchers to understand better how adding fibers to the web area alone affects shear failure in these beams.

III. EXPERIMENTAL PROGRAM

A. Materials

OPC type CEM I 42.5 R complies with Iraqi standard specifications IQS No. 5 [12]. Table I lists the component weights required to create one cubic meter of concrete, where NC is normal concrete without fibers (reference mix) and LWC is lightweight concrete without fibers (reference mix).

TABLE I. DETAILS OF THE SUCCESSFUL TRIAL MIX FOR NORMAL AND LIGHTWEIGHT CONCRETE.

Concrete Type	Cement (Kg/m^3)	Sand (Kg/m^3)	Gravel (Kg/m^3)	Lightweight Aggregate (Bonza) %	W/C %
Normal	365	725	1050	0 %	0.48
Lightweight	550	550	950	75 %	0.42

B. Reinforcing Bars

This study's reinforcing steel bars and wire had diameters of 16 mm, 6 mm, and 10 mm. The bottom reinforcement of the section utilized steel bars by 2Ø16 mm in the longitudinal direction to withstand the tensile stresses caused by bending.

TABLE II. TEST RESULTS OF STEEL BAR REINFORCEMENT

Bar diameter (mm)	Yield stress (MPa)	Ultimate stress (MPa)	Modulus of elasticity (GPa)
6	460	684	200
10	522	712	200
16	590	747	200

Additionally, 6 mm diameter steel bars were employed as stirrups at 150 mm center to center spacing to prevent shear failure. Furthermore, 2Ø10 mm steel bars were employed longitudinally in the top reinforcement of the section to facilitate the formation of the necessary steel cage. Three specimens of each bar diameter were examined to ascertain the properties of steel bars. The steel modulus of elasticity was assumed to be 200 GPa. The test results are shown in Table II, which conform to the ASTM A615 [13] requirements (ASTM A615/A615M, 2004).

C. Steel Fibers

The steel fibers used in this research are crimped (corrugate-shaped) and made 3 cm long by the Bekaert company, as shown in Figure 1. Three fiber ratios 0.5%, 1% and 1.5% were used for each type of concrete. Table III shows the specifications of the steel fibers used.

TABLE III. STEEL FIBERS SPECIFICATIONS.

Commercial name	Configuration	Property	Specifications
LSF0525	Corrugate pattern	Density	7860 kg/m^3
		Ultimate strength	1345 MPa
		Modulus of elasticity	210×10^3 MPa
		Strain at proportion limit	6.4×10^{-3}
		Poisson's ratio	0.28
		Average length	30 mm
		Nominal diameter	0.55 mm
		Aspect ratio (L_f/D_f)	55

Fig. 1. Steel fibers used.

D. Glass Fibers

This study used the Owens Corning Cem-FIL® 54 Company glass fibers, as illustrated in Table IV. For each type of concrete used, three ratios of fibers 0.5%, 1%, and 1.5% were utilized after the fibers were cut to a length of 30 mm, as shown in Figure 2. The fibers in question stand out due to their exceptional mechanical performance, ease of unwinding, easy chopping, high split-efficiency, safety, ease of handling, and easy incorporation into the matrix. Alkali-resistant glass has been used for over 50 years worldwide. Concrete is strengthened by using glass fibers, reducing the steel reinforcing requirement. As a result, steel reinforcement in hydraulic structures and maritime environments experiences less corrosion. Glass fibers lower the crack width, increasing flexure strength and fatigue resistance while also changing the fracture pattern [14].

TABLE IV. GLASS FIBER SPECIFICATIONS.

Commercial name	Configuration	Property	Specifications
Cem-FIL® 54	Straight Pattern	Density	2450 kg/m^3
		Electrical conductivity	Very low
		Material	Alkali-resistant glass
		Softening point	860°C–1,580°F
		Chemical-resistance	Very high
		Average length	30 mm
		Modulus of elasticity	72 GPa–10×106 psi
		Tensile strength of Input	>1,000 MPa–>145×103 psi

Fig. 2. Glass fibers were used in this work.

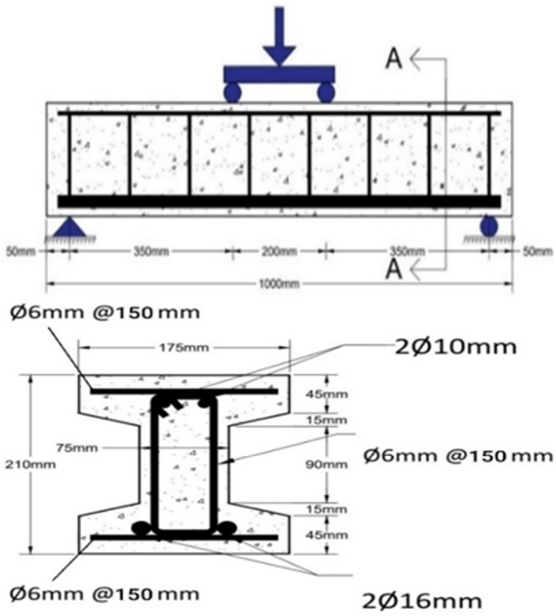

Fig. 3. Dimensions and reinforcement details of reinforced beam.

IV. BEAM DETAILS

The experimental program includes casting fourteen concrete beams divided into two groups. Six specimens with two reference specimens were tested for failure in each group. They were designed to fail in shear, as shown in Table V, where the general details and variables of the test beams are provided. The steel and glass fiber ratio in beams was equal to 0.5%, 1%, and 1.5% in each concrete type. Through the possibility of the preparation of the appropriate model by the appliance of the laboratory medium and the design calculations, the proposed model was tested. The length of the model 1000 mm, its depth is 210 mm, the thickness of the upper flange and lower flange is 45 mm, the width of the flange is 175 mm, the width of the web is 75 mm, the length of the web is 90 mm, and between the flange and web is 1.5/5 mm, as shown in Figure 3. The ratio of shear to depth remains constant, $a / d = 1.89$.

V. TEST SETUP AND DEVICES

SANS (Machine Testing Universal) used the apparatus, which had a 2000 kN capacity and a 1.5 kN/s load rate, to test the shear strength of beams. The vertical deflection of beam specimens at the mid-span was measured by using Linear Variable Differential Transformers, or L.V.D.Ts. The bottom face of the tested beam is below the gauge. The dimensions of the beam were 175 mm width, 1000 mm effective length, and 210 mm depth. In the apparatus, beams were placed on the designated cushions and extended to the sample loaded four times from the top two loading points. Additionally, A 300 mm steel plate was employed to transmit the central load produced by the hydraulic system to two equidistant loading points on the upper surface of the beam, as depicted in Figure 4. The locations and progression of the cracks were visibly apparent on the lateral surfaces of the shear beams [15].

VI. RESULTS AND DISCUSSION

A. Test Results

All tested beams were elastic during the early loading phases, showing no visible structural flaws or cracks and exhibiting modest mid-span deflections in line with the applied load. It was evident how the hollow affected the beam's strength. Upon increasing the load, the control beam exhibited a shear failure, one type of failure that can occur. All types of failures were shear failures. In the early stages of loading, cracks appear in the lower flange of the area near the supports. These cracks are inclined at an angle of 45° and continue to rise to the web area and then to the upper flange, to the deflection caused by cracking, and to the loads at which cracking occurs, Table V presents the maximum deflection of the tested beams.

Fig. 4. The beam under the test device.

TABLE V. TEST RESULTS OF SPECIMEN BEAMS

Beam group	Beam symbol	Fibers Vf %		Ultimate Load (KN)(Pu)	Increase %	Deflection (mm) (Δu)
		Steel	Glass			
Normal Concrete	NC	0	0	98.2	0	2.79
	NCSF 0.5%	0.5	0	101.7	3.5	2.81
	NCSF 1%	1	0	111.5	13.5	3.26
	NCSF 1.5%	1.5	0	111.3	13.3	3.31
	NCGF 0.5%	0	0.5	101.9	3.7	2.84
	NCGF 1%	0	1	112	14.05	2.045
	NCGF 1.5%	0	1.5	92.1	- 6.21	3.80
Light Weight Concrete	LWCB	0	0	92.4	0	2.03
	LWCBSF 0.5%	0.5	0	96.9	4.8	3.35
	LWCBSF 1%	1	0	104.9	13.5	2.83
	LWCBSF 1.5%	1.5	0	102.5	10.9	2.73
	LWCBGF 0.5%	0	0.5	99.8	8	2.69
	LWCBGF 1%	0	1	102.6	11.04	2.30
	LWCBGF 1.5%	0	1.5	81.4	- 11.9	2.013

B. *Mechanical Properties*

1) *Ultimate Load (Pu)*

The results showed the ultimate load for normal concrete as shown in Figure 5. The NCSF of 0.5%, 1% and 1.5% ratio is greater than NC by 3.5%, 13.5%, 13.3%, and the NCGF of 0.5% and 1% ratio is greater than NC by 3.7% and 14.05%. Also, for glass fibers, 1.5% ratio is less than of the normal concrete by 6.21%. The results revealed the ultimate load for lightweight concrete beam as shown in Figure 6. The LWCBS.F is greater than LWCB by 4.8%, 13.5% and 10.9%. LWCBG.F of 0.5% and 1% ratio is greater than lightweight concrete beam without fibers by 8% and 11.04% while glass fibers of 1.5% ratio were less than LWCB by 11.9%.

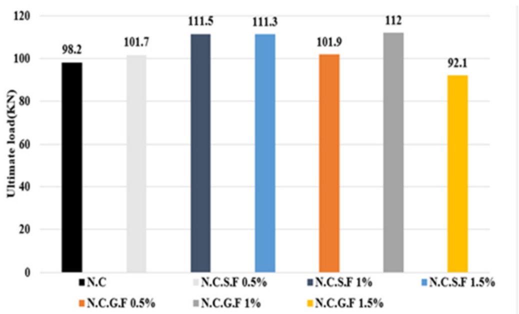

Fig. 5. Ultimate load for normal concrete with steel and glass fibers.

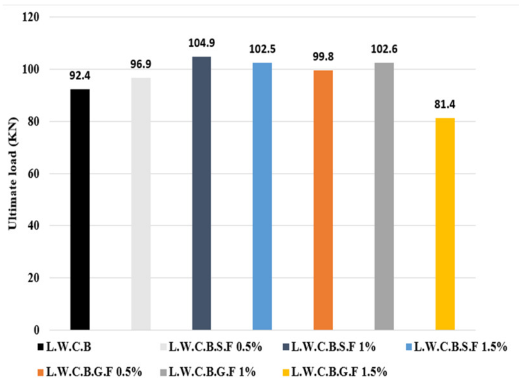

Fig. 6. Ultimate load for lightweight concrete with steel and glass fibers.

2) *Load-Deflection Relationships*

LVDTs measure the deflection at the mid-span of concrete beams to determine whether they will break when the last loads are applied. Once the first crack appears, every curve (the beam is in an elastic condition) transforms from its initial linear form to a nonlinear shape with varying slope. Next, the third phase commences as the applied load steadily rises to its maximum value until failure, accompanied by a rapid increase in deflection. Table V demonstrates the impact of fiber presence in normal and lightweight concrete on the load mid-span deflection response. It is evident that the deflection of the NCSF of 0.5%, 1% and 1.5% ratio, increased by about 0.7%, 16.84% and 18.63% compared with the NC as shown in Figure 7, and for NCGF of 0.5% and 1.5% ratio, the deflection increased from 1.79% to 36.34% and decreased by 36.4% for 1% of glass fibers compared with the NC as shown in Figure 8. For LWCBSF of 0.5%, 1% and 1.5% ratio, the deflection increased by about 65.02%, 39.4% and 34.4% compared with the LWCB as shown in Figure 9. For LWCBGF of 0.5% and 1% ratio, the deflection increased by 32.3% and 13.2% but for 1.5% of glass fibers it had no effect compared with the LWCB as shown in Figure 10.

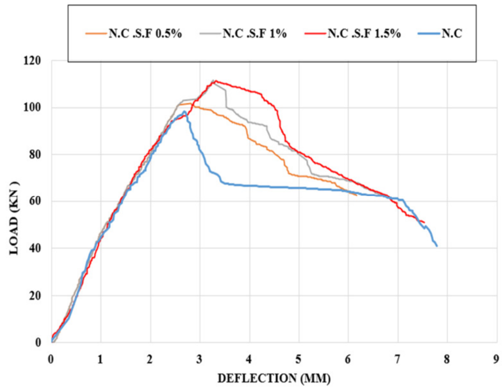

Fig. 7. Load-mid span deflection curve normal concrete with steel fibers.

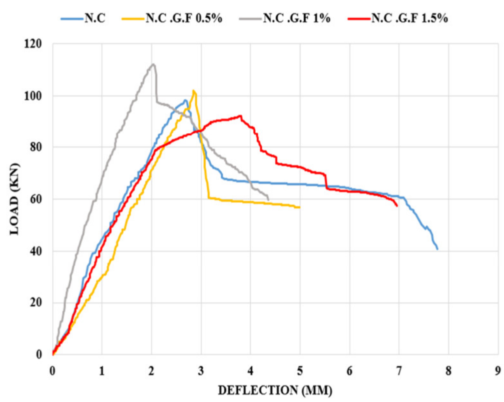

Fig. 8. Load-mid span deflection curve for normal concrete with glass fibers.

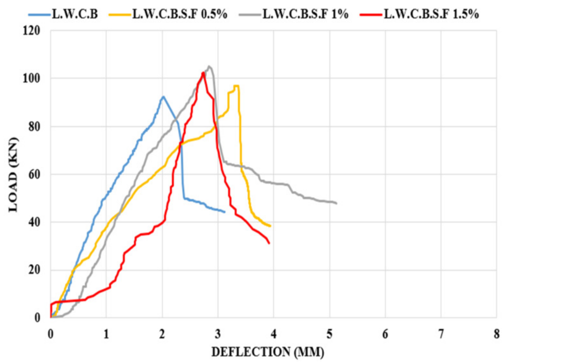

Fig. 9. Load-mid span deflection curve for lightweight concrete with steel fibers.

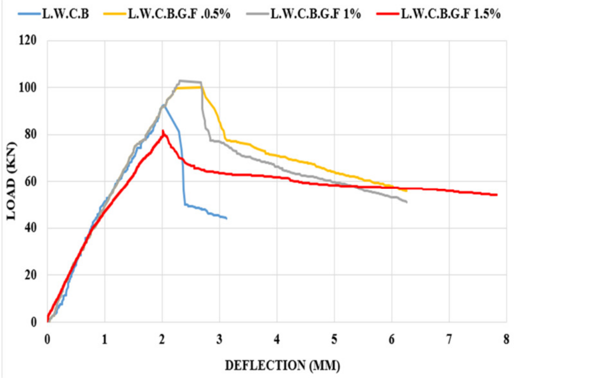

Fig. 10. Load-mid dpan deflection urve for Lightweight concrete with glass fibers.

Fig. 11. Crack patterns for normal concrete group.

Fig. 12. Crack patterns for lightweight concrete group.

3) Crack Pattern

The experimental program yielded results indicating that including fibers notably impacts forming cracks. Adding fibers in concrete with a random orientation increases its tensile resistance. It changes the bombardment failure under the influence of different types of loads to ductile failure, thus preserving the integrity of the concrete structure when the loads reach their maximum value, as shown in Figures 11 and 12 for the crack pattern for all tested beams.

VII. CONCLUSIONS

The conclusions that can be derived from the experimental findings are:

1. The addition of steel fibers at 0.5%, 1% and 1.5% rations in normal concrete increased the ultimate load by 3.5%, 13.5%, and 13.3%, respectively.
2. The addition of glass fibers in normal concrete increased the ultimate load for 0.5% and 1% ratios by 3.7% and 14.05% respectively but decreased the ultimate load by 6.21% for the 1.5% ratio.
3. For lightweight concrete with steel fibers of 0.5%, 1% and 1.5% ratio, ultimate load was increased by 4.8%, 13.5% and 10.6%, respectively.
4. For lightweight concrete with glass fibers of 0.5% and 1% ratios the ultimate load increased by 8% and 11.04%, respectively, and for 1.5% ratio was decreased by 11.9%.

5. The utilized steel fibers in this study have a high modulus of elasticity and exhibit excellent bonding with the concrete mixture. This helps the concrete's ability to withstand compressive and tensile stresses before cracking and slows the spread of capillary cracks.
6. Adding fibers in high proportions reduces the bond between the concrete components and creates voids that weaken the concrete's durability. Adding fibers at a rate of 1.5% decreases the shear strength.
7. In all specimens, the type of failure is the same as shear failure, even with a change in the percentage of added fibers. Adding fibers reduces the width and seals cracks, improving structural resistance. Reducing steel reinforcement requirements improves concrete strength and tensile strength.

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