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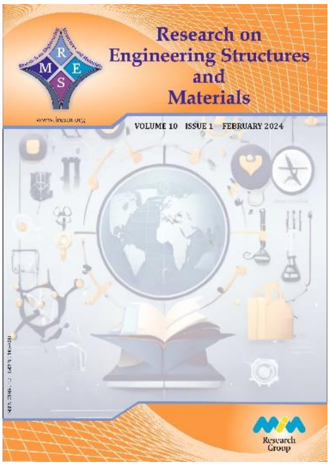

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Research Article

Flexural behavior of printed concrete wide beams with dispersed fibers reinforced

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Abstract

Thanks to the highlighted advantages of the construction method, including digitalization and automation, sustainable materials, and environmental protection, 3D concrete printing technology has been a hot topic for a few decades. This construction method was initially used in small and non-structural applications and is now being adopted for large-scale structures. This transition requires a lot of research on the structural behavior of structures. Therefore, the study focuses on the behavior of wide beams, which is the primary element in the structure system. Nine wide beams with different glass/steel fiber amounts were printed, and 3-point loading tests were conducted. The failure mode, flexural strength, deflection, and ductility were reported in this study. In this study, the girder web was designed in the style of truss beams, and glass/steel fibers were used. The fibers, including glass and steel fiber, will enhance the beams' flexural strength and ductility. The results showed that (1) The adhesion force between the printed layers ensures the overall working of the wide beams; (2) The failure patterns of glass fiber beams were brittle; glass fibers show insignificant improvement in compressive strength; the flexural capacity was significantly enhanced, and the optimal steel fiber amount is 1.0%. (3) The failure patterns of steel fiber beams were ductile; steel fibers showed light improvement in compressive strength. The steel fiber significantly impacted the flexural strength. The optimum amount of steel fibers was determined to be ranged from 1.0% to 1.5%.

1. Introduction

Digitalization and automation have enabled a rapid increase in productivity in many producing industries over the last few decades. The seamless data flow from digital planning into fully automated construction would mark qualitatively this new level of technology, often referred to as Construction Industry 4.0. Moreover, sustainability in building construction is essential for future projects, making 3D concrete printing construction a standout advantage over traditional construction practices. The justification for sustainability becomes highly appreciated when comparing 3D concrete printing technology with conventional construction techniques, mainly due to the absence of formwork, reduced labor requirement, and protected environment thanks to decreased waste production and the use of green materials. For example, the Dubai project (the United Arab Emirates National Committee) has reported labor cost reductions of 50 to 80% and a decrease in construction waste of 30 to 60% [1], [2].

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However, the limitations and challenges of 3D printing concrete technology must be researched and solved in the future. There is a lack of knowledge regarding the effects of different environmental factors when printing on sites. Higher capital investment is required to create and develop digital models, which requires skilled personnel and is especially limited in design. Additionally, there is a lack of understanding about the behavior of 3D concrete printed structures under different loading conditions. This knowledge gap stems from the initial use of this process in small non-structural applications and its subsequent adoption for large-scale structures. Therefore, research on the structural behaviors of printed components [3] or whole systems has been limited. By examining the progress of the development stages for concrete printing technology in the construction field, as shown in Fig. 1, we can reflect on past advancements and anticipate future ones.

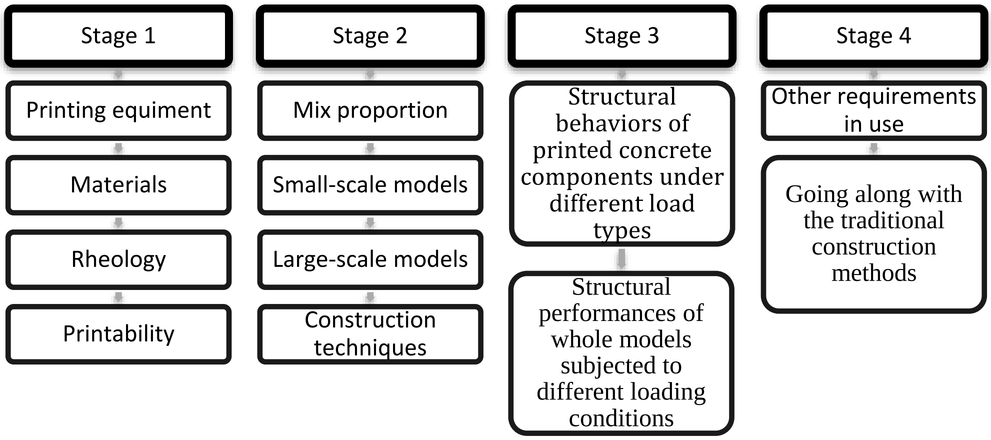


Fig. 1. Development stages of application concrete printing technology in the construction field

Stages 1 and 2 have been researched and recently published by many authors worldwide. Extensive literature reviews have been conducted [4]–[6] [7]. Based on a considerable number of publications, concrete printers and mixed proportions have been recommended and successfully applied in both academic and industrial zones [1], [8]–[12]. However, one of the disadvantages of concrete printing technology is rebars, which will reinforce concrete structures. To overcome this obstacle, multi-nozzle or reinforced concrete with random fibers such as polypropylene, glass, steel, and palm fiber have been explored [13]–[18] [19] [20][21]. Both small and larger-scaled models have been constructed using revealed construction techniques [12][22][8]. Although these achievements have significantly enhanced the development of 3D concrete printing technology in construction projects, the structural performances of the printed buildings need to be tested for safety.

Researchers have recently dealt with Stage 3 to devote to the structural performance of structures built with 3D concrete printing technology. This stage is initial, with some studies focusing on the structural behaviors of components such as panels [3], walls[23], and printed concrete specimens [24][25]. The results obtained from this research will contribute to the success of Stage 3 and become an essential part of Stage 4 in the future.

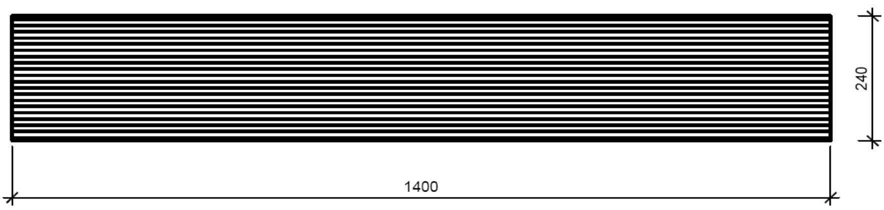
The beam is one of the essential structural parts in the structural system of the works, especially the frame structure. The beam is the part that supports the floor, supports the wall, and connects the columns to form a frame system. Choosing wide beams instead of traditional beams is increasingly popular because of two simultaneous goals: reducing the height of buildings and increasing the aesthetics of the space used. Thus, to meet the requirements of workability and the development of the trend of using wide beams in works, the study of the working of this type of beam is an indispensable and objective requirement.

Because of the absence of reinforcement inside beams, the fibers, including glass and steel fiber, will enhance the flexural strength and ductility of the printed wide beams in this study. The use of fiber to reinforce components has widened over the decades. Glass and steel fibers have become popular thanks to the economic advantage they offer combined with other advantages. Glass is a type of thermoset polymer composite that improves the mechanical properties of the components such as stiffness, strength or corrosion assistance. Many investigations have used short glass fibers [26], [27]. The results show that short glass fibers in the matrix can be excellent secondary reinforcements (micro-fillers). Steel fiber reinforced concrete also has extensive applications. Many investigations found that adding steel fibers influences the concrete components' flexural strength and ductility [28], [29].

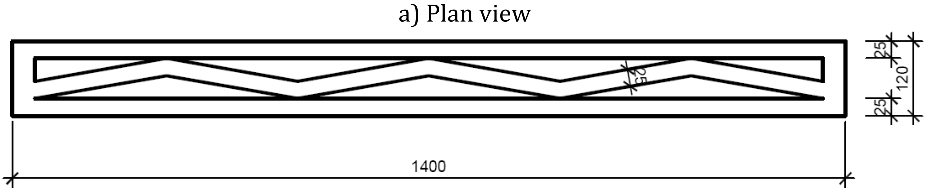
From the authors' perspective, research on the flexural behavior of wide beams, including failure modes, moment resistance, and deflection of printed beams, has been carried out and analyzed. Therefore, the flexural behavior of the fiber concrete wide beams, which are printed instead of traditionally fabricated, is studied. The results contribute to Stage 3 mentioned above, including (1) the understanding of the structural behavior of the fiber concrete wide beams, including failure modes, flexural strength, load–deflection relationship, and ductility will be revealed; (2) the 3D concrete printing technology can precisely fabricate structure sections with complex geometries directly from computer-aided design (CAD) files; (3) the combination of the type of wide beam section and technology will suggest a new concept/ new idea to designers. At last, applying 3D concrete printing technology to the construction field can be considered a reference and orientation from this research.

2. Details of Wide Beams

The beams' dimension length, width, and height are 1450 mm, 240 mm, and 120 mm, respectively. The thickness of the perimeter and the girder web is 25 (mm). Details of the printed concrete wide beams are shown in Fig. 2.



a) Plan view



b) Front view

Fig. 2. Details of the printed wide beam

3. Materials and Mix Proportions

In this research, ordinary Portland cement (O.P.C.) by Chiffon PC40 was used to form the binder component, thanks to successfully applied cement-based materials by many researchers as well [30]–[35]. Commercially available manufactured natural sand with a nominal maximum aggregate size of 1.5mm was used. Crushed sand with a nominal maximum aggregate size of 2.5mm was used. Glass fibers (G.F.) and steel fibers (S.F.) were used to mix the proportions, the main properties of G.F. and S.F. fibbers, as listed in Table 1. The mix proportions were designed based on the procedure presented in Fig. 4 and listed in Table 2.

Table 1. Properties of fibers

Properties	G.F.	S.F.
Tensile strength (MPa)	900	2200
Modulus (GPa)	72	200
Diameter (mm)	0.0012	0.22
Length (mm)	12	13
Density (kg/m3)	2600	7750

To adjust the workability of the fresh concrete Superplasticizer, Visconcrete 3000-200M was used. Materials used for mixing concrete in this research are presented in Fig. 3.

Fig. 3. Materials used for mixing concrete

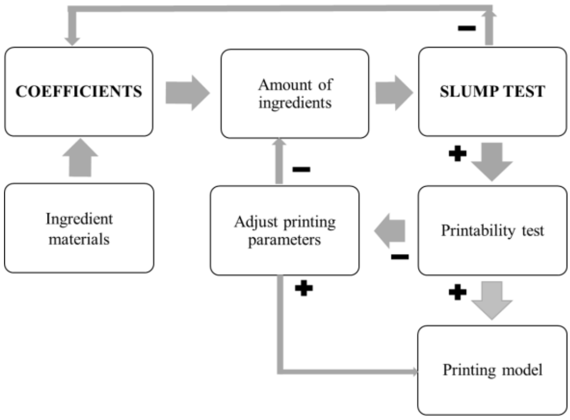


Fig. 4. Mix proportion design process [36]

Table 2. Mix proportions

Beam label	Water	Natural sand	Crushed sand	Glass Fiber (%)	Steel Fiber (%)	S.P. (%)
CB-00	0.31	0.5	0.5	-	-	0.4
GB-0.5				0.5	-	
GB-1.0				1.0	-	
GB-1.5				1.5	-	
GB-2.0				2.0	-	
SB-0.5				-	0.5	
SB-1.0				-	1.0	
SB-1.5				-	1.5	
SB-2.0				-	2.0	

(Note: Values are a ratio of weight to cement.)

4. Printing Process

The process starts with a 3D CAD model of the object, which was saved in ".STL" format. Then, Simplify3D software was used to slice layers of the model and save it as a ".Gcode" file. Finally, 3D concrete printers controlled by Mach3 software printed all nine beams. **Hata! Başvuru kaynağı bulunamadı.** illustrates this process presented here above.

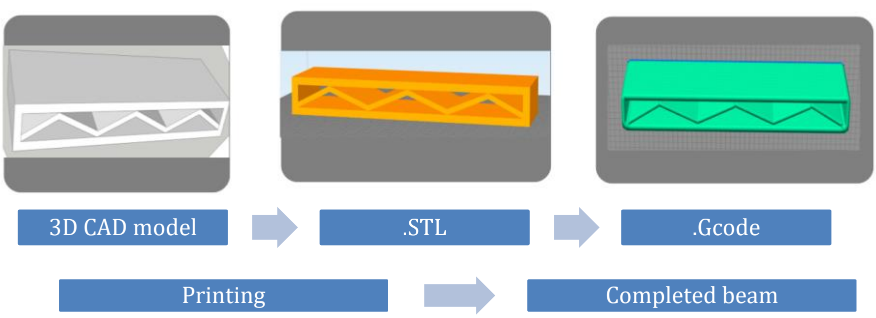


Fig. 5. Steps of the printing process

Printing was carried out in parts according to the design. The printing process is guaranteed according to the steps presented in Figure 5**Hata! Başvuru kaynağı bulunamadı.**. The circular nozzle with an 18 mm diameter was employed to print all beams. The height of each printing layer is 10mm, and the width of filaments ranges from 22mm to 25mm. A total of nine wide beams were printed, as shown in Fig. 6.

a) WB00 and Glass Fiber beams (GB01 to GB04) (from inside to outside)

b) Steel Fiber beams (SB01 to SB04) (from inside to outside)

Fig. 6. Wide beams printed

The extrudability of the dispersed fiber concrete was affected by the ratios of fiber to cement. The extrudability intends to degrade since the fiber ratios increase. There was no jamming during the printing process, but the appearance and quality of the layers printed were affected, as shown in Fig. 6.

5. Experimental Program

5.1 Bending Test Setup

A 3-point bending test was set up for the experimental beams with a nominal length of 1350 mm. Each specimen was supported on roller assemblies to locate the exact supporting point. The linear variable differential transformers (L.V.D.T.) were used to record the deflection based on the applied load. L.V.D.T. was fixed at the mid-section of the beam specimen - under the loading point. The test setup and instrumentations for tested specimens are illustrated in Fig. 7. The procedure for carrying out the test and the loading are certified to comply with T.C.V.N. 9347:2012 [37].

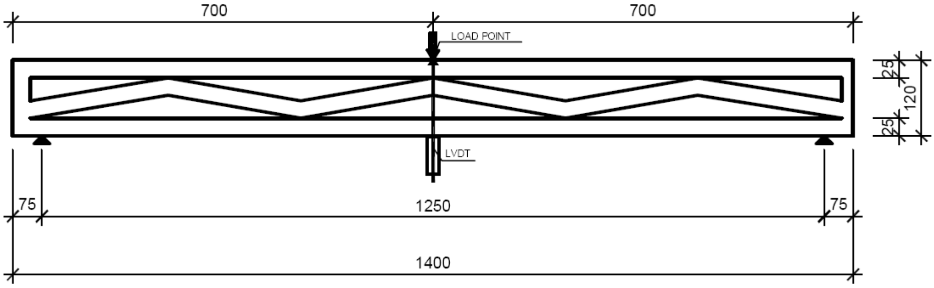


Fig. 7. Flexural test setup

5.2 Compression Test

After the concrete samples printed with 10x10x10 cubes were cast, they were cured in guaranteed humidity conditions. The glass fiber beams were cured according to Requirements for natural moist curing [37]. The beams with steel fibers were cured using a film-forming agent on the concrete surface, and spraying was carried out according to the film-forming agent manufacturer's instructions or covering the beam surface with water-proof materials such as nylon and canvas. Herein, the steel fiber beams were covered with nylon. Then, the procedure for carrying out the test and the loading is certified to comply with TCVN 3118-1993 [38], as shown in Fig. 8.

Fig. 8. Compression test of concrete cube

6. Experimental Results

6.1 Failure Modes

The CB00 beam was a control beam without fiber reinforcement, resulting in brittle failure, as shown in Fig. 9. The results of the failure pattern of glass fiber beams, as shown in Fig. 10, show that sudden failure of concrete printed beams is characteristic of brittle failure form. The presence of dispersed glass fibers did not show a significant increase in the plasticity of concrete. However, the failure mode of the beam GB-2.0 indicates a more spread crack development in the tensile zone of concrete than the others. As captured, all the glass fiber beams were broken after reaching the ultimate load without warning (deformation) due to brittle failure.

(a) Initial state (b) Final state

Fig. 9. The failure mode of CB00

GB-0.5

GB-1.0

GB-1.5

GB-2.0

Fig. 10. The failure mode of Glass fiber beams

SB-0.5

SB-1.0

SB-1.5

SB-2.0

Fig. 11. The failure mode of Steel fiber beams

The results of the failure pattern of steel fiber beams, as shown in Fig. 11, show that sudden failure of SB-0.5 and SB1.0 concrete printed beams is characteristic of brittle failure form due to beams with small steel fiber amounts. The presence of steel fibers smaller than 1% did not show a significant increase in the flexibility of concrete. Beams SB-1.5 and SB-2.0 showed the failure combined with shear failure. A long crack appeared in the middle of the beams and around the support; the beams ended with flexural and shear damage. The failure modes of SB-1.5 and SB-2.0 can be explained by the fact that concrete at the compression areas reached the compressive strength, but the amount of steel fibers was relatively high, so the moment resistance was higher than the shear strength. It resulted in shear cracks at the support areas, as shown in Fig. 12.

SB-1.5 SB-2.0

Fig. 12. The shear cracks of steel fiber beams

Thanks to the steel fibers that acted as reinforcements compared to traditional beams, none of the steel fiber beams broke after reaching the ultimate load. Another conclusion drawn from these figures and observations of the beam surface after fracture is that there is no delamination between the printed layers. It shows that the adhesion force between the printed layers ensures the overall working of the structure. Moreover, observing the beam surface after failure also indicates the solidity of the printed layers, as shown in Fig. 13.

Fig. 13. The surface fracture of the printed beams

6.2 Load-Bearing Capacity

Based on the results of force measurement, displacement meter, and compression tests, the compressive strength of concrete cubes and the bearing capacity of the beams are calculated, as shown in Table 3. Table 3 and Fig. 14 show that the compressive strengths of the glass fiber concrete cubes (G.B.-) are smaller than those of the control sample (CB00). The optimal amount of glass fiber is 1.0%, but the glass fiber amount did not show significant improvement in compressive strength.

Table 3. Load bearing capacity

Beam label	Concrete compression strength Rn (Mpa)	Ultimate load (kN)	Deflection (mm)
CB00	37.9	4.4	-
GB-0.5	33.4	7.2	-
GB-1.0	37.7	7.6	-
GB-1.5	36.7	6.1	-
GB-2.0	31.3	5.7	-
SB-0.5	39.5	6.3	27.5
SB-1.0	38.9	6.5	48.0
SB-1.5	37.8	6.8	50.4
SB-2.0	35.8	8.7	53.9

The reason is that it is impossible to achieve a consistent distribution of concrete ingredients in the presence of glass fibers. These results corroborate those of other authors [39]. When glass fibers are introduced to reinforced concrete composites, they act as a connecting agent. Distributing stress from glass fibers to the substrate only offers a resistance of samples to crack initiation in terms of interface shear resistance.

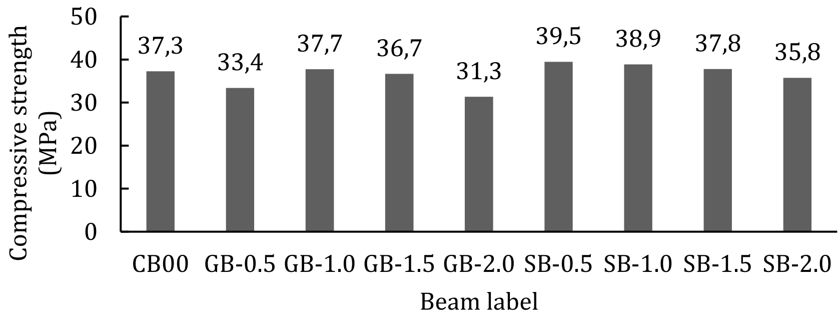


Fig. 14. Effect of fiber on the average compressive strength of concrete

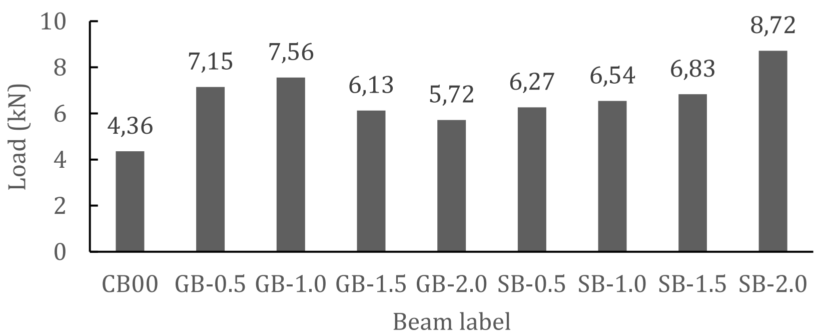


Fig. 15. The flexural capacity of wide beams

Concrete reinforcement using steel fiber changes the concrete's properties, allowing it to endure fracture and enhance its mechanical properties. Compared to the control sample, the compressive strengths of steel fiber concrete cubes are mostly higher, except for SB-2.0. However, the increase in fiber amount decreases compressive strength. These results also corroborate those of other authors [40], [41].

Table 3 and Fig. 15 show that the 1.0% glass fiber reinforced concrete achieved the highest load bearing of 7.56 kN compared to the control sample, which reached 4.36 kN, higher than 73%. The variation in load bearing of glass fiber beams with the increase in glass fiber reinforcement can be similar to that of compressive strength. The flexural capacity with 0.5% glass fiber reinforcement achieved 7.15 kN, and 1.0% achieved the highest flexural capacity of 7.56 kN. Further increase in glass fiber reinforcement dropped the flexural capacity to 6.13 kN and 5.72 kN for 1.5% and 2.0% glass fibers, respectively. However, the flexural capacity achieved by 1.5% and 2.0% glass fiber reinforcement in concrete was higher than the control sample, 41% and 31%, respectively. This is a result of the glass fibers' ability to resist cracking. Considering the influence of glass fiber amount on the flexural capacity and the compressive strength of concrete reinforced with glass fiber, the optimal fiber amount is 1.0%.

Table 3 and Fig. 15 show that the 2.0% steel fiber reinforced concrete achieved the highest load bearing of 8.72 kN compared to the control sample, which completed 4.36 kN. The increase in flexural capacity of steel fiber beams with the rise in steel fiber reinforcement can be seen in contrast to compressive strength. The load bearing of the steel fiber beams increases from 6.27 kN to 8.72 kN, corresponding to the amount of steel fibers from 0.5% to 2.0%. The ultimate load values of the steel fiber beams are much higher than that of the control beam, specifically, 44%, 50%, 57%, and 100% higher corresponding to beam SB-0.5, SB-1.0, SB-1.5, and SB-2.0.

6.3 Deflection and Ductility of The Steel Fiber Wide Beams

The reason is that the beams without fiber (CB00) and the glass fiber beams (G.B.-) were ruptured with minimal recorded deflection. Therefore, the deflection and ductility of the steel fiber-wide beams are presented and analysed in this section. With the load–deflection relationship, it can be seen that steel fiber significantly improves the stiffness and ductility of the printed wide beams. The ductility ratio is called in this study to evaluate the deformation ability of beams under bending. It is expressed in Eq. 1 [42].

$$\mu = \frac{\Delta_u}{\Delta_y} \quad (1)$$

Δy is the yield deflection, and Δu is the deflection when the load falls to 80% of the ultimate load.

K is the bending stiffness defined in Eq. 2 [42].

$$K = \frac{P_{\Delta_y}}{\Delta_y} \quad (2)$$

where P_{Δ_y} is the value of the load at the yield deflection.

Table 4. Ductility ratio and bending stiffness.

Beam label	Δ_y (mm)	Δ_u (mm)	P_{Δ_y}	μ	K (kN/mm)
SB-0.5	6.81	25.5	6.27	3.74	0.92
SB-1.0	6.29	38.7	6.54	6.16	1.04
SB-1.5	6.49	42.8	6.83	6.60	1.05
SB-2.0	8.01	53.9	8.72	6.74	1.09

From the results shown in Table 4, it can be summarized that the bending stiffness increases as the steel-fiber ratio increases. However, the steel fiber amount increases four times while the bending stiffness of the beam SB-2.0 is higher than that of the beam SB-0.5 by only 15.6%. In contrast, the ductility ratios reflect the influence of the steel fiber amount. The ductility ratio is improved 1.8 times since the steel fiber amount increases four times. It can be more clearly seen in the comparison of the load–deflection curves in Fig. 16.

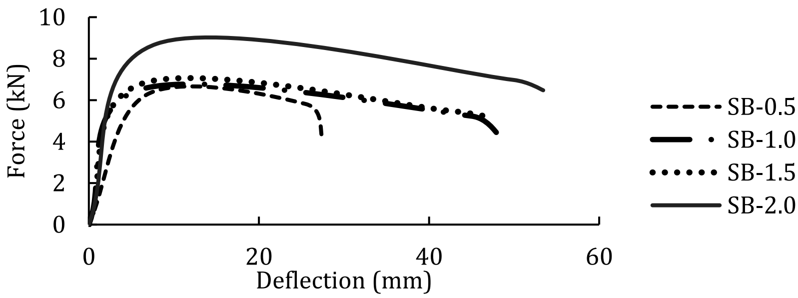


Fig. 16. Load–deflection curves

When reinforced with steel fibers, as the fiber amount in the concrete gradually increases, it dramatically helps effectively restrict the formation, propagation, and widening of cracks. This results in an increase in both flexural strength and ductility. Thanks to the effective bridging action of steel fibers across the cracks, the ductile behavior of the concrete beam was significantly improved. Therefore, this brittle nature of concrete beams, observed with glass fiber beams, is converted into ductile. It results in resist cracking and crack propagation of the printed wide beams. Considering the influence of steel fiber amount on the flexural strength, bending stiffness, ductility, and compressive strength of concrete reinforced with steel fiber, the optimal steel fiber amount ranges from 1.0% to 1.5%.

7. Conclusions

Based on the analysis of the 3-point bending test of nine printed wide beams with dispersed glass and steel fibers reinforced, the results obtained from the study of theory combined with experiment, some conclusions are drawn as follows:

- The girder web of wide beams designed in the style of truss beams was precisely fabricated directly from design files by a printer.
- The extrudability intends to degrade, and the appearance quality of the printed layers was affected since the fiber ratios increased.
- The failure pattern and cracked surfaces of all printed wide beams indicate that the adhesion force between the printed layers ensures the overall working of the structure.
- The failure patterns of glass fiber beams were brittle due to flexural damage.
- Glass fibers did not show significant improvement in compressive strength. The flexural capacity, on the other hand, was significantly enhanced. The increase in flexural strength ranged from 31% to 73%.
- Considering the influence of glass fiber amount on the flexural capacity and the compressive strength of concrete reinforced with glass fiber, the optimal fiber amount is 1.0%.

- The failure patterns of steel fiber beams were ductile due to flexural damage with fiber amounts smaller than 1.5% and flexural combined with shear damage with fiber amounts higher than 1.5%.
- Steel fibers showed slight improvement in compressive strength. However, with the increase in fiber amount, the compressive strength decreases.
- The addition of steel fiber in concrete significantly impacted the flexural strength due to the improvement in the ductility behaviour of concrete. The increase in flexural strength ranged from 44% to 100%.
- Increasing steel fiber contents significantly improved the bending stiffness and ductility of the steel fiber concrete beam. The ductility ratio and bending stiffness are improved 1.8 and 1.2 times, respectively, since the steel fiber amount increases four times.
- The optimum amount of steel fibers ranged from 1.0% to 1.5%, at which the flexural strength and ductility were achieved at a slight reduction of compressive strength.

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