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Research Article

Study of the Effect of Fibre Orientation on Artificially Directed Steel Fibre-Reinforced Concrete

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The fibre utilization efficiency of directionally distributed fibre-reinforced concrete is better than that of randomly distributed fibre. However, controlling the fibre direction is difficult, which limits its applications. In this paper, a method in which fibres were artificially directed was used to simulate the feasibility of orienting fibres during 3D concrete printing. Based on artificially directed steel fibre-reinforced concrete specimens, the orientation characteristics of directional fibre-reinforced concrete specimens were studied. The differences between the gravity and the boundary effects in ordinary fibre-reinforced concrete and artificially directed fibre-reinforced concrete were compared. The average orientation coefficient in randomly distributed fibre-reinforced concrete was 0.59, whereas this value in directionally distributed fibre-reinforced concrete was over 0.9. This result demonstrated the feasibility of manually orienting the fibres in steel fibre-reinforced concrete in layer-by-layer casting.

1. Introduction

The primary shortcomings of cement mixtures, paste, and concrete are low tensile strength, low ultimate elongation, and high brittleness. However, fibre has a high tensile strength and a large elongation. Incorporating fibres into concrete increases the tensile, bending, and impact strengths of the concrete as well as its elongation and toughness. Three types of fibres are used in fibre-reinforced concrete, each with different properties: steel fibre, inorganic fibre, and organic fibre. Among them, steel fibre-reinforced concrete is the most studied and widely used material; it is also the best developed fibre-reinforced concrete [1, 2]. The development of fibre-reinforced concrete started in the early 20th century. From 1907 to 1908, Некрасоъ, an expert from the Russian Empire, incorporated steel fibres into concrete, thus heralding the development of steel fibre-reinforced concrete. In 1910, Porter in the United States published the first paper on short steel fibre-reinforced concrete; he proposed distributing the short fibre evenly throughout the concrete to reinforce it. The material structure Porter proposed was generally the same as the steel fibre-reinforced concrete used today. In 1911, Graham in the United States preliminarily and experimentally demonstrated the superior mechanical properties of steel fibre-reinforced concrete and concluded that incorporating steel fibres can improve the strength and volume stability of concrete. In 1940s, scholars and engineers in Britain, the United States, France, Germany, and other countries applied and were awarded a series of patents on methodologies for improving concrete performance by incorporating steel fibres, thus enhancing the manufacturing process of the steel fibre and improving the shape of the steel fibre to enhance its bonding with the concrete matrix. During the Second World War, Japanese scholars and engineers also studied steel fibre-reinforced concrete and used it in explosion-proof structures [3] for military purposes.

In the early 1960s, research on the applications of fibre-reinforced concrete in engineering was widely conducted. In 1963, Romualdi and Baston in the United States published a series of reports on the mechanism of steel fibres for enhancing crack resistance [4]. The authors helped elucidate the theory behind the reinforcement effects and mechanism of steel fibres and introduced the famous "fibre-spacing theory," which states that the cracking resistance capacity of steel fibre-reinforced concrete is determined by the average spacing of steel fibres affecting the tensile stress. Romualdi

and Baston's work attracted extensive attention and laid a theoretical foundation for the research and development of steel fibre-reinforced concrete. Afterwards, Krenchel reported the relationship between one-dimensional, two-dimensional, and three-dimensional fibre spacings and the fibre content by accounting for fibre orientation. Based on Krenchel's work, Kobayashi Isuke from Japan further developed the fibre-spacing theory. The author treated the fibre-reinforced cement-based material as a particle-type composite material and proposed a formula for calculating the tensile strength of steel fibre-reinforced concrete [1, 3]. While the "fibre-spacing theory" was being developed, Swamy and Mangat from England proposed the "composite mechanism" theory [5, 6]. In this theory, fibre-reinforced concrete was treated as a fibre-reinforced system whose mechanical properties were evaluated using the proportioning principle. Since then, research on steel fibres has been highly productive.

Since its conception, the tensile strength of fibre-reinforced concrete has been increased by approximately 100–150%. However, steel fibre-reinforced concrete is expensive, and the steel fibre reinforcement was not fully utilized due to uncertainty in the fibre orientations. It is also difficult to use fibre-reinforced concrete in construction. For example, if it is used to construct bridges or roads, there is a risk of tires being pierced by exposed steel fibres. In recent years, a 3D concrete printing construction technology has been developed. However, the cracking problem associated with 3D printed concrete has not been effectively resolved. Some researchers proposed the use of directional fibre 3D printing technology and applied for patents for this technology. The method is to "spray" fibres into different concrete layers to "link" them and remedy the defect of each layer, so the directional fibres are required. By creating directional placement during the layered printing process, the application of directional fibre concrete becomes feasible [7, 8]. Researchers have long recognized that the reinforcement effect of directionally distributed fibre-reinforced concrete is better than that of randomly distributed fibres [9–11]. Additionally, various theories have shown that the performance of directionally distributed steel fibre-reinforced concrete is significantly improved over that of ordinary steel fibre-reinforced concrete. However, due to its difficult casting, the performance of directionally distributed steel fibre-reinforced concrete has not been fully utilized, and its application has been limited. Although scholars in many countries have conducted research on fibre orientation in directional fibre concrete, applying it to practical engineering is difficult because the traditional concrete construction casting technique involves pouring a concrete mixture into moulds and then solidifying it by vibration. In this process, the fibre's orientation cannot be ensured [12–15]. Additionally, for structures with well-defined loading positions, adapting the construction process to use directionally distributed fibre-reinforced concrete will allow builders to take full advantage of the reinforcement capacity of steel fibres. With the full utilization of the bearing capacity of the material, the performance in a certain direction will substantially improve, thus decreasing construction costs and energy consumption.

2. Preparation of Specimens

2.1. Test Materials. For the tests, a concrete mixture was designed based on GB/T 50080-2016 "Standard for Test Method of Performance on Ordinary Fresh Concrete" [16] and JGJ 55-2011 "Specification for Mix Proportion Design of Ordinary Concrete" [17]. The appropriate materials were selected, and a concrete mixture proportion that met the testing requirements was employed.

2.1.1. Cement. Ordinary Portland cement was used. In steel fibre-reinforced concrete, the most frequently used cement is 42.5R and 52.5R ordinary Portland cement. Cement in steel fibre-reinforced concrete is a type of the cementing material that is mixed with water to form a cement slurry that has a high cohesive force. After the concrete is hydration hardened, the sand, stone, and steel fibre are bound together to form steel fibre-reinforced concrete. In this study, 42.5R cement was used.

2.1.2. Fine Aggregate. Ordinary river sand was used which was zone III fine sand with a fineness modulus of 1.73. The weight of the fine aggregate after being sieved was 499 g. The measuring error was 0.2% (Figure 1).

2.1.3. Coarse Aggregate. Ordinary gravel with sizes of 5–20 mm and a continuous grain size distribution was used. The grades met the requirements. The weight of the aggregate used in the test was 4480 g after being sieved. The measuring error was 0.44% (Figure 2).

2.1.4. Additive. An SH-II-type naphthalene high-efficiency water reducer was used. A water reducer was used in this study to improve the viscosity of the benchmark concrete and its slump without increasing the amount of cement and water employed. With the same cement and slump, the water reducer can reduce 15–25% water usage; with the same slump and strength, it can reduce 10–15% water usage; with the same cement and water-cement ratio, it can increase the slump 1.0–1.5 times. Sodium sulfate content is 11.2%, pH value is 8.0, and chloride ion content is 0.07%. After several trials with multiple mixtures, the effect of this water reducer was found to be significant and had high sensitivity. Therefore, the amount of the water reducer used should be precisely controlled. Once the ideal amount of the water reducer was determined for benchmark concrete, the same amount was used for all the specimens in subsequent tests.

2.1.5. Steel Fibre. A milling-type fibre produced was used with the following dimensions: a length of 32.0 ± 2.0 mm, a width of 2.6 ± 1.2 mm, a thickness of 0.4 ± 0.05 mm, and a length-diameter ratio of 35–45. The steel fibre had a tensile strength ≥ 700 MPa. The steel fibre used in this test (Figure 3) was significantly different from the steel wire fibre used in traditional steel fibre-reinforced concrete. The cross section and longitudinal section of this steel fibre possessed zig-zag-shaped sides and a large surface area. Both ends of the fibre

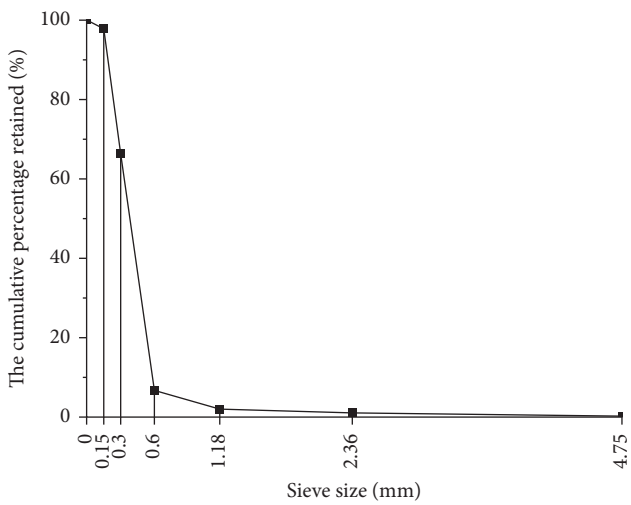


Figure 1: Fine aggregate sieving curve.

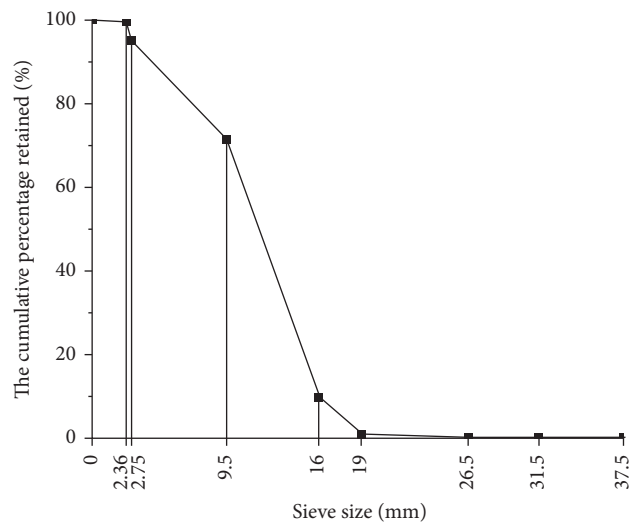


Figure 2: Coarse aggregate sieving curve.

had anchoring tails. The outer arc was smooth, but the inner arc was rough, so its bonding strength with the concrete matrix was doubled, which prevented the formation and development of microcracks within the concrete.

2.2. Mixing Ratio of the Benchmark Concrete. Although the design methodology of the concrete mixture proportions is described in detail in the codes [17, 18], the mixing ratio determined by this numerical calculation is usually inappropriate for practical construction because the properties of the raw materials can differ substantially. After repeated trial-and-error experimentation, the concrete specimens were prepared in suitable mixture proportions that met the specified requirements and the expected strength [19]. The mixture of the tested concrete was as follows.

2.2.1. Water-Cement Ratio. The maximum content of steel fibres in this test was 144 kg/m^3. The compressive strength of the steel fibre-reinforced concrete primarily depended on the strength of the cement and its bond to the aggregate when the steel fibre content was low. The compressive strength of concrete was not obviously improved by the incorporation of the steel fibre. Therefore, the water-cement ratio of the benchmark concrete was determined according to the method in [17].

The test was conducted using Grade C50 concrete [20]. The water-cement ratio was equal to 0.40.

2.2.2. Water Usage. After the water-cement ratio of the concrete was determined, the appropriate slump and the maximum particle size of the gravel were determined according to [17]. Then, the amount of water to use was determined.

To accommodate the directional placement of the fibre, the concrete should have a large slump to ensure good viscosity and to reduce the vibration casting time. At the same time, the fine aggregates used in the experiment were fine sand, so the water usage per cubic metre of the specimen can be increased by 5–10 kg. At last, 220 kg/m^3 of water was used in these specimens.

2.2.3. Sand Ratio (the Ratio of Fine Aggregates to All Aggregates). Because the particle size of sand was much smaller than that of stone, changing the sand ratio affected the total surface area of the aggregate, thus altering the workability of the concrete mixture. Many factors affected the sand ratio, whose ideal quantity could be determined by testing or based on previous experience. The ratio could also be determined based on the material specifications, the steel fibre volume ratio, the water-cement ratio, and the workability of the mixed compounds. In this study, the sand ratio of the benchmark concrete specimens was initially determined to be 31%, according to the method in [17].

2.2.4. The Amount of Coarse and Fine Aggregates. We used a mass calculating method to determine the amount of coarse and fine aggregates to use, which was 2500 kg/m^3.

2.2.5. Water Reducer. Trial-and-error casting was conducted using the initially determined mixture proportions as discussed above. Using the workability of the concrete as the main index, the amount of the water reducer to be added was determined as 1.5 kg/m^3.

It is presented in Figures 4 and 5 that the concrete with the determined mixture proportions has good workability and acceptable slump.

The standard test specimens were prepared and cured in accordance with the relevant provisions of the "Standard for Test Method of Mechanical Properties on Ordinary Concrete" GB/T50081 [20]. The compressive strength of the cubic specimens was tested after 3 days, 7 days, and 28 days.

The strength tested after 28 days, that is, of the final determined mixture, was 49.2 MPa, which met the expected strength requirements with good workability. The strength of the concrete increased rapidly initially before gradually slowing in the late period, which agrees with the theoretical predictions.

(a) (b)

Figure 3: Milling-type steel fibre. (a) Steel fibre appearance. (b) Steel fibre cross section.

Figure 4: Photograph of the workability of the concrete mixture.

Figure 5: Photograph of the concrete mixture's slump.

2.3. Preparation of Directionally Distributed Steel Fibre-Reinforced Concrete. The directionally distributed steel fibre-reinforced concrete was prepared by casting layer-by-layer and directionally placing the steel fibre [21–23] to simulate the possibility of directionally placing the fibres between layers during 3D printing. First, cement was evenly mixed with sand, gravel, and water reducer. Then, water was added into the mixture three times until the mixture was completely mixed. Then, the mixture was poured into an oiled mould layer-by-layer. The 100 mm cubic test pattern was divided into five layers along the height. Each layer had a height of 20 mm. The steel fibre needed for each cube specimen was weighed and was equally divided into four batches. A layer of concrete was poured, and then, one batch of the steel fibre was directionally placed (Figure 6). The even distribution of the steel fibre across the cross section was confirmed. The spacing between the coarse aggregate and fibre spacing should not be too small.

Figure 6: The directionally distributed steel fibre.

After completing the casting, the moulds were only manually shaked to drive out bubbles in the concrete because vibration with machine will disrupt fibre's direction. After 24 hours, the mould was disassembled. The specimen was cured for 27 days in accordance with the standard experimental method. Then, the mechanical properties were tested and measured.

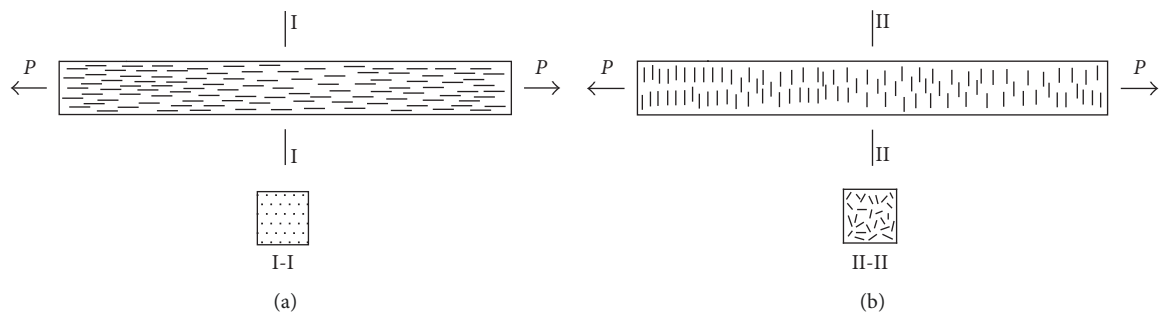


Figure 7: Different fibre orientations in components subjected to uniform tensile loading. (a) Fibres oriented parallel to the tensile direction. (b) Fibres oriented perpendicular to the tensile direction.

Note that the casting process discussed herein is different from the process for casting conventional, cubic concrete specimens. The method detailed in this report resembles the process of casting self-compacting concrete and the 3D concrete printing process. This detail should be considered when conducting mechanical tests on later stages of concrete.

3. Testing the Fibre Orientation Effect on Distributed SFRC

The orientation and distribution of steel fibres in concrete have an important effect on the mechanical properties of steel fibre-reinforced concrete. Therefore, researchers have focused on methods to determine the fibre morphology in steel fibre-reinforced concrete. Because the factors that affect the fibre morphology are complex [9, 21–25], descriptions of the fibre profile and a calculation method for determining its mechanical properties in steel fibre-reinforced concrete are still under investigation.

For directionally distributed steel fibre-reinforced concrete, the direction and distribution uniformity of the fibres are even more important. In the following contents, the authors introduced the study on the placement (orientation) and distribution of the steel fibres in a concrete matrix by measuring the specimens after casting and vibration compacting.

3.1. Fibre Orientation Pattern. In Figure 7, different orientations of fibres in steel fibre-reinforced concrete subjected to uniform, uniaxial tensile loading are shown. In Figure 7(a), the orientation of the steel fibre in the direction of tensile stress is displayed, and in Figure 7(b), the orientation of the steel fibre is shown to be perpendicular to the tensile direction. It is apparent that fibres oriented as shown in Figure 7(a) have the best reinforcement effect, while fibres oriented as shown in Figure 7(b) do not reinforce the tensile strength. If the fibres are randomly distributed in three dimensions, then the strength of their reinforcement should be between these two extremes.

Regarding the mechanical properties of concrete, if the steel fibre can be oriented along the direction of the main tensile stress, then the steel fibre has the best reinforcement effect on the concrete. However, even with artificial orientation, it is difficult to achieve this ideal state because the distribution of steel fibres in concrete components is affected by several factors, including the shape and size of the components, the volume fraction of the steel fibres, the concrete casting method, the mixing and vibration times, the equipment used, the concrete mixture proportions, and the composition of raw materials. These factors all affect the distribution and orientation of the steel fibre to various extents. In steel fibre-reinforced concrete, the mould size and vibration duration are the two most important factors that affect the distribution and orientation of the steel fibre and are mainly characterized by the gravity and boundary effects [26].

3.1.1. The Gravity Effect. When the steel fibre is artificially placed in freshly cast concrete layer-by-layer, the fibres should, in theory, all have the same direction. However, during the vibration solidification, the steel fibres move continuously to the lower part of the components because of gravity and the vibration. Some fibres move downwards under the force of gravity, which is the gravity effect (shown in Figure 8(a)). The gravitational effect causes the fibres to become densely distributed in the lower section of the mixture. Additionally, the vibration of the shaking table changes some of the orientations of the artificially placed fibres in concrete that was cast layer-by-layer.

3.1.2. The Boundary Effect. Because the mould limits the orientations of the fibre, the fibre near the mould tends to become parallel to the surface of the mould during the vibrating process. This confining effect is called the boundary effect (Figure 8(b)). In the artificially directed steel fibre-reinforced concrete that was cast layer-by-layer, the boundary effect mainly affects the steel fibre close to the mould surface that was perpendicular to the fibre direction.

However, in 3D printing processes, the steel fibre can settle slightly due to its own weight because the components cannot be vibration solidified. Because there is no boundary mould to constrain it, the concrete printed on the upper layers may compress the concrete on the lower layers, thus causing the oriented steel fibre to "flow" outwards. This pushes the steel fibre within a certain width of that layer to move horizontally. The pushing effect is more pronounced on the two sides than in the centre of the piece. Therefore, the boundary effect is characterized by the movement of steel

(a) (b)

Figure 8: Effects on steel fibre distribution and orientation. (a) Demonstration of the gravity effect. (b) Demonstration of the boundary effect.

fibres to the mould edge and is again caused by gravity, despite its name. These effects are fundamentally different from the gravity and boundary effects observed in conventional fibre-reinforced concrete.

Although the gravity and boundary effects in the directional steel fibre-reinforced concrete appear to adversely affect its performance, they can improve the performance if utilized appropriately. Because the steel fibre is placed close and parallel to the surface, it can improve the resistance of the component surface to cracking. Several reports have discussed how to improve the steel fibre reinforcement by utilizing the gravity and boundary effects while artificially placing the fibre.

3.2. Fibre Orientation Coefficient. The orientation coefficient is used to quantitatively characterize the placement of fibres in the concrete [27]. When the direction of the fibre is widely distributed in the concrete, the orientation coefficient is expressed as the ratio of the sum of the lengths of the fibres projected in one direction (usually the main tensile stress direction) to the sum of the lengths of all the fibres and is represented by the symbol η_0.

If all the fibres are parallel to the specified direction, then η_0 is equal to 1; if all the fibres are perpendicular to the specified direction, then η_0 is equal to 0. The value of η_0 changes between 0 and 1.

When the steel fibres are randomly placed in three-dimensional space, the orientation factor is expressed as follows.

The first expression is shown in Figure 9(a). For a fibre of length L, we assume that the probability distribution of the angle between the fibre and the horizontal axis (θ) is equal to that of the angle between the fibre and the vertical axis (φ). Then, its orientation in any direction (X-direction) η_0 can be obtained using

$$\eta_0 = \frac{\int_0^{\pi/2}\int_0^{\pi/2} \cos\theta \cos\varphi \, d\theta \, d\varphi}{(\pi/2)^2} = 0.405. \quad (1)$$

The second expression is based on the assumption that the number of fibres in any unit area is the same as that on the hemispherical surface shown in Figure 9(b). Then, the orientation coefficient η_0 in any direction (X-direction) can be expressed using

$$\eta_0 = \int_0^{\pi/2} \cos\theta \sin\theta \, d\theta = 0.5. \quad (2)$$

The above theoretical results are valid only when the three-dimensional steel fibre-reinforced concrete components are of large size, the concrete is fully mixed, the fibres are evenly distributed and uniformly oriented, and the fibres are located far away from the boundary wall. Fibres that are randomly distributed in three dimensions constitute the most common distribution profile in steel fibre-reinforced concrete. The steel fibres are generally assumed to be in this state when the mechanical properties are studied. In these cases, as discussed above, the orientation factor is usually set to 0.405, but sometimes, it is more reasonable to use a value of 0.5.

If the steel fibre is randomly oriented in two dimensions, then the orientation coefficient η_0 can be calculated using

$$\eta_0 = \frac{\int_0^{\pi/2} \cos\theta \, d\theta}{\pi/2} = 0.637. \quad (3)$$

This value can be used when large-plane thin-plate components are fully mixed and the steel fibres placed away from the vertical edge of the middle surface of the sheet are randomly, quasi two-dimensionally distributed. In these cases, the boundary and gravity effects in the plane can be neglected. The orientations of the fibres in the plane can be assumed to be equally distributed. The distribution model of the fibre orientations is given in Figure 10.

In 3D printing, the fibre directions are distributed similarly to the model shown in Figure 10. However, as discussed above, due to the flow pattern of the fibre caused by the gravitational effect, the orientation coefficient discussed above may change.

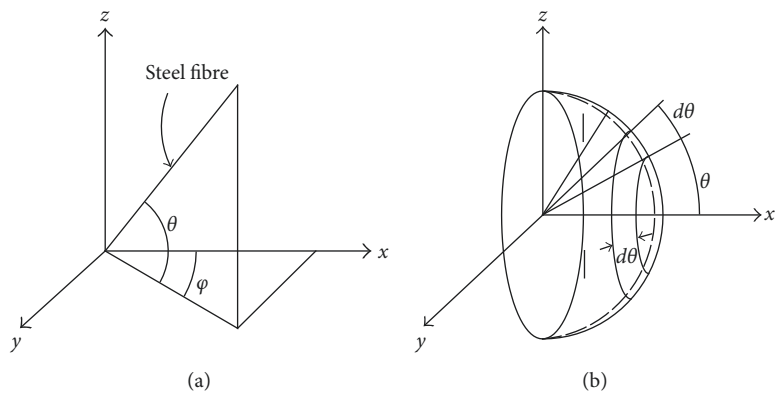


Figure 9: Model of the steel fibre orientation. (a) Model of randomly placed steel fibres in three-dimensional coordinate system. (b) Model of randomly placed steel fibres in spherical coordinate system.

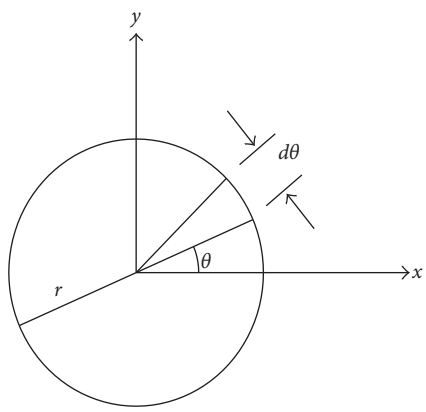


Figure 10: Orientation model of short fibres randomly distributed in a plane.

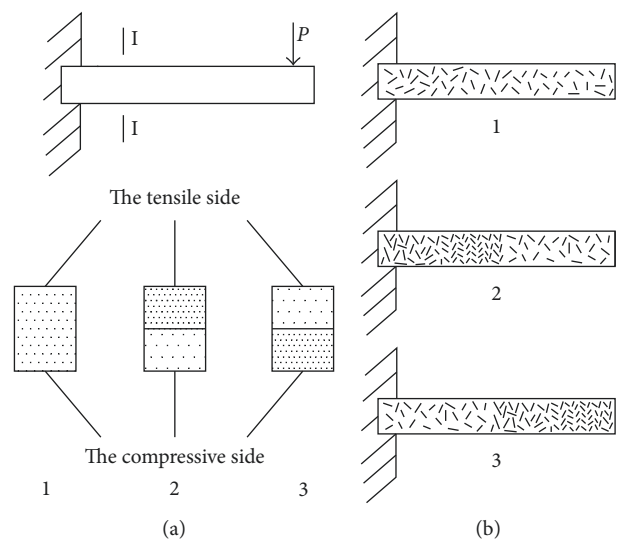


Figure 11: Different distribution patterns of steel fibre in concrete cantilever beams. (a) Different fibre distributions in I cross section. (b) Different longitudinal fibre distributions.

3.3. The Uniformity of Fibre Distribution. A steel fibre-reinforced cantilever beam is shown in Figure 11. In Figure 11(a), three different distribution patterns of steel fibres can be observed in the cross section of the fixed end that is subjected to the largest bending force. The number of steel fibres is the same. In Figure 11(b), three different distributions of the steel fibres are shown. It is apparent that the reinforcement effect of the fibres is significantly affected by the distribution pattern. In the cantilever beam, the reinforcement is strongest on the cross sections and longitudinal sections in the second case. However, if the beam ends have even tensile loads, then the longitudinal section of the first case has the best distribution because any section with the smallest number of placed steel fibres is the weakest and will fail first. Therefore, it is desirable to have evenly distributed fibres. Uneven distributions decrease the fibre volume ratio, compromising the reinforcement effect of the fibre [26, 27].

Therefore, although the fibre orientation can improve the load-bearing capacity of the reinforced components, the nonuniform distribution of these fibres will eliminate this benefit. As shown in Figure 12(a), the cross section without fibre reinforcement is always the weakest. Although the fibres are placed parallel to the stretch direction, the reinforcing effect is almost nonexistent. The ideal fibre placement can be observed in Figure 12(b).

In this study, in the casting process, the artificially directed steel fibre-reinforced concrete specimens created the pattern shown by 3 in Figure 11(a) because of the gravity effect. The nonuniform distribution of the fibres in the longitudinal distribution, as shown in Figure 11(b), did not affect the cubic specimens in the test but may have affected the beam specimen.

Seven specimens were subjected to the orientation coefficient tests discussed above to test the uniformity of the fibre distribution. Each specimen was divided into upper and low parts, and the number of steel fibres in each was statistically surveyed and compared (Table 1).

The experimental results (Table 1) show that the gravity effect exists in steel fibre-reinforced concrete. Of the three specimens with randomly distributed steel fibres, 42.5% of the fibres are in the upper part of the cross section in the Number 1b specimen. This specimen has the most severe nonuniform fibre distribution. The gravity effect in directional

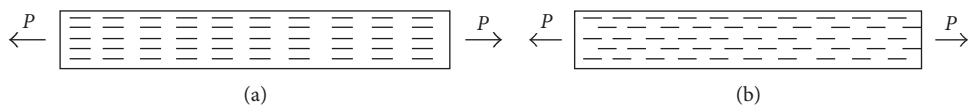


Figure 12: Nonuniform and uniform distribution of fibres of the same orientation in components subjected to tensile loading. (a) The directed fibre distribution in a faulty transverse cross section. (b) The directed fibre distribution in a nonfaulty transverse cross section.

Table 1: The uniformity of the steel fibre distribution.

Orientation of the steel fibre	The number of fibres			Proportion (%)	
	Top	Bottom	Total	Top	Bottom
Randomly distributed (1a)	37	38	85	43.5	56.5
Randomly distributed (1b)	31	42	73	42.5	57.5
Randomly distributed (1c)	33	35	68	48.5	51.5
Directionally distributed (2a)	36	69	115	31.3	68.7
Directionally distributed (2b)	36	74	109	33.0	67.0
Directionally distributed (2c)	43	83	126	34.1	65.9
Directionally distributed (2d)	46	71	118	39.0	61.0

steel fibre-reinforced concrete is more pronounced than that in ordinary steel fibre-reinforced concrete. In beam specimen Number 2a, which has the most severe nonuniform steel fibre distribution, 31.3% of the fibres are in the upper part of the cross section, meaning that less than one-third of the fibres remain in the upper part. This is crucial context for the following tests, which will allow a quantifiable evaluation of the negative influences of the gravity effect through mechanical testing.

3.4. Results of Fibre Orientation. Currently, there are three methods to determine the orientation coefficient of steel fibres in steel fibre-reinforced concrete [11, 28–30].

The first method uses experimental measurements. After the components are destroyed, the orientation coefficient of the steel fibre is determined based on the actual number of fibres. This method is destructive; although it cannot be applied to design, its concept is simple. The data obtained are reliable, and the calculation is simple. Overall, this is a good analytical method.

The second method uses a theoretical analysis. As described in Section 3.2, this method is based on the assumption that the fibre is uniformly distributed and oriented. The value of η_0 is calculated using a probability analysis. This method is simple and easy to use in design. However, its application is limited by its theoretical basis.

The third approach uses a combination of theoretical and experimental methodology [30, 31]. Using X-ray imaging, the actual morphology of the steel fibre embedded in the concrete is recorded. The fibre image is analyzed based on the three-dimensional morphology and a probabilistic theory [32, 33]. The distribution and orientation of the steel fibre in the concrete are simultaneously determined. This method is very intuitive, does not damage the components, and can pierce through the concrete to detect the actual distribution of the fibres. This technique provides real information about the fibre, thus facilitating design work. However, this method requires X-ray imaging equipment; therefore, it has not been widely utilized.

In this study, the first method was used to calculate the fibre orientation coefficient in the directed steel fibre-reinforced concrete specimen. Using this method, the reliability of the results was ensured in the subsequent tests.

Seven specimens were prepared measuring $100 \times 100 \times 400$ mm (three of which were randomly distributed steel fibre-reinforced concrete beams). The steel fibre content was 1.6% by volume. The steel fibres were manually placed in the specimens that were cast in moulds layer-by-layer and left for one day to allow the specimens to solidify fully. Then, the specimens were cured in a standard curing box for two days. After the specimen strength reached a certain level, it was broken open, and the angle between the direction of the steel fibre in the cross section and longitudinal direction of the specimen was measured. When conducting the statistical analysis, angle values from two different sections of the same beam were used.

After the randomly distributed steel fibre-reinforced beam was broken, several fibres parallel to the cross section became loose. This portion of the fibres was included in the statistical analysis to avoid their influence. It is impossible to manually determine the orientation angle of every fibre. Therefore, we divided the angles between the fibre and the beam's longitudinal direction into four zones: 0°–20°, 21°–45°, 46°–70°, and 71°–90°. We surveyed the number of steel fibres in each section and then calculated the orientation coefficient of the steel fibres using

$$\eta_0 = \frac{\sum_{i=1}^{n} l \times \cos\theta_i}{n \times l} = \frac{1}{n}\sum_{i=1}^{n} \cos\theta_i, \tag{4}$$

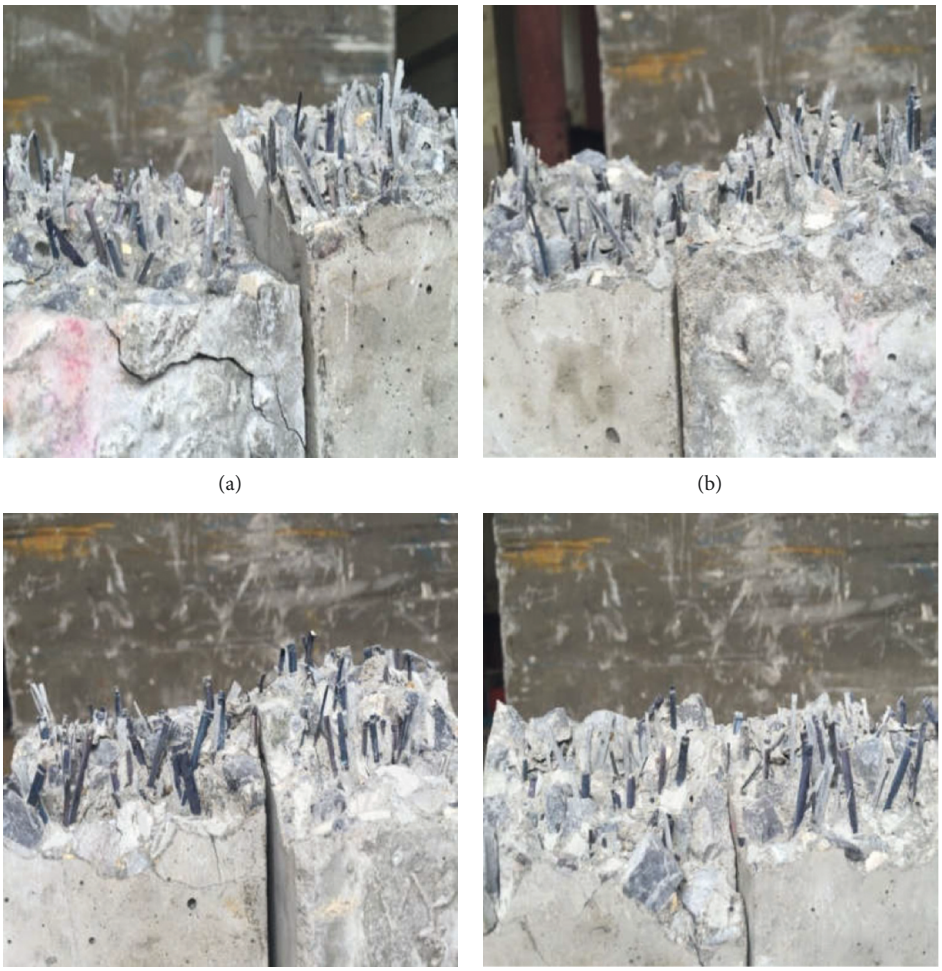
where θ is the angle of a single fibre, l is the length of the steel fibre (mm), and n is the number of steel fibres.

When the fibre angle was between 0° and 20°, θ was chosen to be 10°. When the fibre angle was between 21° and 45°, θ was chosen to be 30°. When the fibre angle was between 46° and 70°, θ was chosen to be 60°. When the fibre angle was between 71° and 90°, θ was chosen to be 80°.

In Figures 13 and 14, cross sections of the test beam used for the statistical analysis are shown. The angles of the fibre statistical result are shown in Table 2.

(a) (b) (c)

Figure 13: Cross section of a randomly distributed steel fibre-reinforced concrete beam. (a) Number 1a. (b) Number 1b. (c) Number 1c.



(a) (b)

(c) (d)

Figure 14: Cross section of a directionally distributed steel fibre-reinforced concrete beam. (a) Number 2a. (b) Number 2b. (c) Number 2c. (d) Number 2d.

The results (Table 2) show that the average orientation coefficient of the three randomly distributed steel fibre-reinforced concrete beams is 0.59, which is slightly higher than the theoretical value of 0.5. The coefficients of the four directionally distributed steel fibre-reinforced concrete beams are above 0.9. The average value is 0.925, demonstrating

Table 2: The angle statistics of the steel fibres.

Orientation of steel fibres	Number of fibres with different angles					Orientation coefficient
	0°–20°	21°–45°	46°–70°	71°–90°	Total	
Randomly distributed (1a)	36	8	17	24	85	0.51
Randomly distributed (1b)	26	13	13	21	73	0.64
Randomly distributed (1c)	28	7	11	22	68	0.63
Directionally distributed (2a)	104	3	5	3	115	0.94
Directionally distributed (2b)	100	2	4	3	109	0.94
Directionally distributed (2c)	107	5	8	6	126	0.91
Directionally distributed (2d)	99	5	11	3	118	0.91

the feasibility of studying the basic mechanical properties of directionally distributed steel fibre-reinforced concrete specimens by artificially placing fibres in concrete specimens cast in moulds layer-by-layer. This work ensures the success of subsequent mechanical performance tests.

4. Conclusions

(1) The effect of the directionally distributed fibre on improving the special stress state in fibre-reinforced concrete is obvious. However, the reasonable usage volume of the fibre and the stress of the fibres are subjected to determine its applications.

(2) By analyzing and controlling the fibre placement and orientation coefficients, the fibre orientation in the concrete can meet expectations. This information provides a foundation for manufacturing directionally distributed steel fibre-reinforced concrete in mechanized constructions.

(3) The gravitational effect causes the fibres to become densely distributed in the lower section of the mixture. The vibration of the shaking table changes some of the orientations of the artificially placed fibres in concrete that was cast layer-by-layer. In the artificially directed steel fibre-reinforced concrete that was cast layer-by-layer, the boundary effect mainly affects the steel fibre close to the mould surface that was perpendicular to the fibre direction.

(4) The steel fibres in ordinary, randomly distributed and directionally distributed fibre-reinforced concrete are all subject to gravitational effects. In artificially directed steel fibre-reinforced concrete, the influence of the boundary effect is not obvious.

(5) The influence of the gravity effect is more pronounced in artificially directed systems than in ordinary fibre-reinforced concrete. The ratio of steel fibres distributed in the top of the specimen to the bottom reaches as high as 3 : 7. This problem should be approached by enhancing the concrete casting technology.

(6) The average orientation coefficient of randomly distributed steel fibre-reinforced concrete beams is 0.59, and the average coefficient is 0.925 in directionally distributed steel fibre-reinforced concrete beams. This result demonstrates that fibre orientation has substantial effects on directionally distributed steel fibre-reinforced concrete that was manually cast layer-by-layer. The layered orientation moulding processes should be improved with a special construction method.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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