



Article

Plastic Hinge Length Mechanism of Steel-Fiber-Reinforced Concrete Slab under Repeated Loading

Pradeep Sivanantham ¹, Beulah Gnana Ananthi Gurupatham ², Krishanu Roy ^{3,*} , Karthikeyan Rajendiran ¹ and Deepak Pugazhendi ¹

¹ Department of Civil Engineering SRMIST, Chennai 603203, India; pradeeps@srmist.edu.in (P.S.); karthikeyan9000@gmail.com (K.R.); deepakpugazhendi@gmail.com (D.P.)

² Division of Structural Engineering, College of Engineering Guindy Campus, Anna University, Chennai 600025, India; beulah28@annauniv.edu

³ School of Engineering, The University of Waikato, Hamilton 3216, New Zealand

* Correspondence: krishanu.roy@waikato.ac.nz

Abstract: The plastic hinge is the most critical damaging part of a structural element, where the highest inelastic rotation would occur. In particular, flexural members develop maximum bending abilities at that point. The current paper experimentally investigates the influence of steel fiber reinforcement at the plastic hinge length of the concrete slab under repeated loading, something which has not been reported by any researcher. Mechanical properties such as compressive strength and tensile strength of M20-grade concrete that are used for casting specimens are tested through the compressive strength test and the split tensile strength test. Six different parameters are considered in the slab while carrying out this study. First, the conventional concrete slab and then the steel-fiber-reinforced slab were cast. The plastic hinge length of the slab was calculated through different empirical expressions taken from methods by Baker, Sawyer, Corley, Mattock, Paulay, Priestley and Park. Finally, the steel fiber was added as per methods detailed by Paulay, Priestley and Park in the plastic hinge length mechanism in the concrete slab at 70 mm and 150 mm separately. The results arrived through experimental investigation by applying repeated loads to the slab, indicating that steel fibers used at critical sections of plastic hinge length provide similar strength, displacement, and performance as that of the conventional RCC slab and fully steel-fiber-reinforced concrete slabs. Steel fiber at a plastic hinge length of slab has a better advantage over a conventional slab.

Keywords: SFRC (steel-fiber-reinforced concrete); conventional RCC slab; plastic hinge length; repeated loading and composite material



Citation: Sivanantham, P.; Gurupatham, B.G.A.; Roy, K.; Rajendiran, K.; Pugazhendi, D. Plastic Hinge Length Mechanism of Steel-Fiber-Reinforced Concrete Slab under Repeated Loading. *J. Compos. Sci.* **2022**, *6*, 164. <https://doi.org/10.3390/jcs6060164>

Academic Editor: Francesco Tornabene

Received: 28 April 2022

Accepted: 31 May 2022

Published: 2 June 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The maximum bending moment occurs at the plastic hinge length, which is considered to be the most critically damaged location of the RCC member and will experience more inelastic deflection in the member. In recent years, researchers have become more interested in the length of plastic hinges. The experimental study of plastic hinge length examines the load-carrying capacity and its deformation capability. When the RCC member is subjected to load, the deformation is inelastic, and these inelastic zones result in places where the bending moment is greater. As the applied load is raised further, the zones rotate till the final hinge is formed, and this results in the collapse of the structural member [1].

The plastic hinge length can be obtained by various formulas devised by scientists such as Sawyer, Baker, Priestley, Park, etc. These formulas can be used to find the required plastic hinge for the slab, which is a factor of the concrete grade and reinforcement detailing. It is also a factor of support distance, contra flexure distance, and the geometry of the member [2,3]. Nazari-poor et al. [4] have studied the acoustic emission damage detection by performing three-point bend tests and demonstrating the accumulation of flexural damage for composite panels of different sizes and fiber volume content. Paulay et al. [5]

studied over one thousand specimens representing various types of reinforced concrete (RC) members (beams, columns, and walls). This was then used to develop expressions for the deformations of RC members at yielding or failure under cyclic loading in terms of member geometric and mechanical properties. The yield and ultimate curvature expressions based on the plane-section assumption agree on averages within the test results, but with a large scatter. The same was found to be true for models based on curvatures and the concept of ultimate drift or chord-rotation capacity [5].

The previous study by Paulay et al. [4] was created for analytical purposes, and the analysis was created to study the behavior of RCC members subjected to various loadings and plastic hinge lengths. The properties of steel-fiber-reinforced concrete (SFRCs) are determined by the amount and percentage of fibers introduced into the concrete. The length of the plastic hinge zone is an important design parameter that should be provided with intense confinement to increase the ductility of the member to survive extreme events such as earthquakes. The behavior of plastic hinges is extremely complicated due to the high nonlinearity of the materials, interaction, relative movement between the constituent materials, and strain localization. As a result, the majority of researchers [6,7] used experimental testing to investigate the problem. The plastic hinge zone's performance is crucial for flexural members since it regulates the load-bearing and deformation capabilities of the member. A computational model is developed and validated using existing experimental data, such as load-deflection response, rotational capacity, and reinforcement stress and strain distributions detailed by Qin et al. [8].

The length of the rebar yielding zone is thought to represent the upper bound of the three physical inelastic deformation zones, with its value never exceeding more than twice the effective depth of the cross-section in any of the conditions investigated by Zhao et al. [9]. The diameter of the rebar under tension has a reduced impact on the plastic hinge length and flexural capacity of the member due to its impact on bond strength. The true plastic hinge zone is much smaller than the yielding zone of the member, which comprises the majority of the plastic rotation. None of the existing empirical models for forecasting plastic hinge length have taken all of these crucial aspects into account [9]. A constitutive model has been developed for material non-linear analysis of steel-fiber-reinforced concrete slabs supported on the soil. The energy absorption capacity provided by fiber reinforcement is taken into account in the material constitutive relationship. The plasticity theory is used to explain the elastoplastic behavior of concrete [10].

The RCC member would fail immediately without providing a prior warning when this plastic hinge is formed. For these reasons, understanding the behavior of plastic hinge length formations is critical in RCC construction. Steel fibers have been used as replacements for conventional RCC structures as they have good tensile strength and delay the brittle failure of the concrete. The goal is to contribute to the development of design guidelines that can accurately predict the punching resistance of SFRC flat slabs. Past investigation data show that SFRC has better performance than conventional concrete. To have better performance [11–14], the steel fibers are used at 1.5% of the volume of the concrete.

Holschemacher et al. [15] tested 28 steel-fiber-reinforced concrete (SFRC) slabs under flexure to see the effect length of steel fiber percentage on the energy absorption capacity of concrete slabs with varying concrete strengths. According to the findings from the tests, longer fibers with a greater fiber content were found to absorb more energy. The findings are contrasted with a theoretical prediction based on fiber distribution randomness. The theoretical technique yielded a larger energy absorption than the experimental method. Within the range of fiber volumetric percentages employed in the study, a design technique based on permissible deflection is provided for SFRC slabs [15].

Fiber concrete is a technology that has been studied for several decades, mostly to prevent cracking in specific reinforced concrete constructions. Fiber concrete has recently been examined for use in various applications, such as the total replacement of steel-reinforcing rebar. The behavior of a fiber concrete slab was investigated using a validated

numerical model [16–18]. The findings demonstrated that fiber concrete slabs without rebar reinforcement met the limit states required by the different dwellings (spans ranging from 4–5 m). The effect mechanisms of SFRC's strength parameters and slab's structural parameters are clarified using both finite element and theoretical analysis and a technique are devised [16–18]. Service stress limits in SFRC slabs were achieved at higher demands than in RC slabs. When service stress limitations in SFRC slabs were achieved, crack widths were substantially less than conventional crack width limits, indicating that designing for crack widths may be an effective way of addressing serviceability in SFRC slabs [16–18].

Paramasivam et al. [19] conducted 50 tests on reinforced concrete slab specimens; both repaired and unrepaired slabs were examined under static and cyclic stress conditions. The specimens had a rectangular cross-section of 300×80 mm and were tested in flexure on a span of 600 mm with a line load at mid-span. Four different kinds of specimen were tested. The performance of statically loaded to failure specimens was tracked, whereas the deterioration of flexural rigidity of cyclically loaded specimens was examined after a preset number of cycles at various stress levels [19]. Steel-fiber-reinforced concrete (SFRC) is used to improve the flexural and cyclic responses of reinforced concrete bridge deck slabs. First, cyclic loads were applied to one plain concrete slab and two SFRC slabs reinforced with mill-cut steel fibers and corrugated steel fibers, respectively. Load-deflection responses, cyclic deformation behaviors, strain and fracture development are all examined. The results show that employing SFRC in deck slabs improves cyclic deformation performance, reduces residual strain in the slab section, and improves crack behavior by decreasing residual fracture width and improving cracking stiffness [20,21].

Experimental and numerical analyses were used to investigate the impact of fiber clustering on the fatigue behavior of steel-fiber-reinforced concrete (SFRC) beams with reinforcements. Furthermore, to better understand the underlying mechanism, the fiber distribution in the cross-section of concrete was experimentally investigated. The results showed that when the fiber volume percentage grew, the fatigue life of the beam increased [22]. To forecast the shear strength of steel-fiber-reinforced concrete beams, a mechanics-based mathematical model that considers the effect to resist shear was suggested (without transverse reinforcement). The suggested model's efficacy was tested using a wide number of datasets, and it was discovered that it had good correlations with experimental results, with mean, standard deviation, and coefficient of variation of 0.94%, 0.22%, and 22.99%, respectively. In addition, each effect to resist shear contribution was recommended [23].

Although the importance of fiber distribution to the characteristics of SFRC members was highlighted in the literature listed above, the underlying mechanism of fiber distribution to the fatigue performance of SFRC, as well as the behavior of the beam and slab under static and repetitive loading, was not. Even though there have been some studies on identifying plastic hinges, the contribution of steel fibers to plastic hinge length has had little attention. There has been no research on the impacts of fiber distribution at the slab's plastic hinge length under repeated stress.

In this paper, the concrete was tested experimentally with various SFRC parameters at various plastic hinge lengths. Using five different slabs of varying parameters, the behavior of steel fiber at the plastic hinge length under repetitive loads was investigated. The mechanical properties of the RCC slab were determined for standard concrete and SFRC. The properties of the steel fiber slab at plastic hinge length were determined under repeated loading becomes the novelty of this work. In the future, the plastic hinge length concept along with different strengthening techniques may be applied to beams and slabs under different types of loading.

The plastic hinge will form at the yielding zone of any structural member, which is the location of the highest bending moment. The most crucial damaged region of the structural element is the plastic hinge zone, where the more inelastic rotation would occur in the structural element. The shape of the bending moment diagram (BMD), the support distance, the contra flexure distance, and the geometry of the member all influence the plastic hinge.

The BMD considers the concrete's durability and the amount of steel required. The plastic hinge length of the RCC member has been calculated using a variety of empirical formulae. Table 1 contains a collection of formulas for determining the length of a plastic hinge.

Table 1. Empirical formula to calculate plastic hinge length.

Description	Empirical Formula
Baker (1956)	$k(z/d)^{1/4} d$
Herbert and Sawyer (1964)	$0.25 d + 0.075 z$
Corley (1966)	$0.5 d + 0.2 \sqrt{d} (z/d)$
Priestley and Park (1987)	$0.08 z + 6 d_b$
Paulay and Priestley (1992)	$0.08 z + 0.022 d_b f_y$

The empirical formulas of Corley, Herbert and Baker provide the same results. The empirical formula provides a high value for plastic hinge length and a factor of the diameter of the rebar. Figure 1 shows the plastic hinge length formed due to the application of load 'w'.

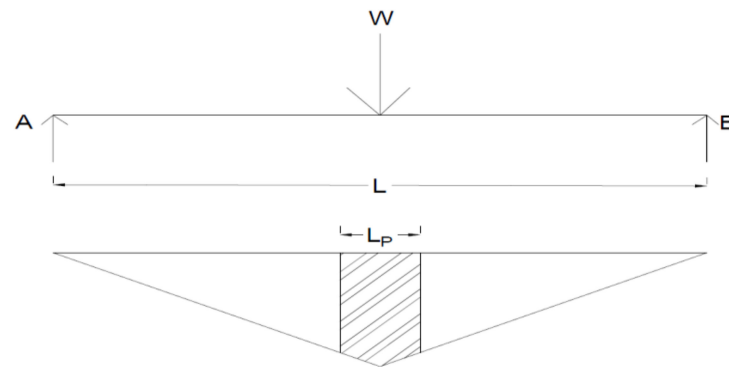


Figure 1. Plastic hinge length (L_p).

2. Materials

Table 2 shows the M20 grade mix design used in the experimental studies. The steel fibers until utilized in the casting had a hook end of 30 mm and a diameter of 0.5, and they were cast in M20 concrete. Steel fiber accounts for 1.5% of the weight of concrete in the specimen. The steel fiber parameters used in this study are listed in Table 3.

Table 2. M20 grade mix design as per IS 10262-2009.

Component	Quantity	Quantity (kg/m ³)
Cement		438.7
F.A		757.28
C.A		1071.11
Steel Fiber		36.96
W/C		197

Table 3. Properties of steel fibers.

Description	Properties
Shape	Straight
L(length)	30 mm
Dia	0.5 mm
L/Dia	1/60

Figure 2 depicts the picture of the steel fibers, of which the weight is about 1.5% of the concrete.



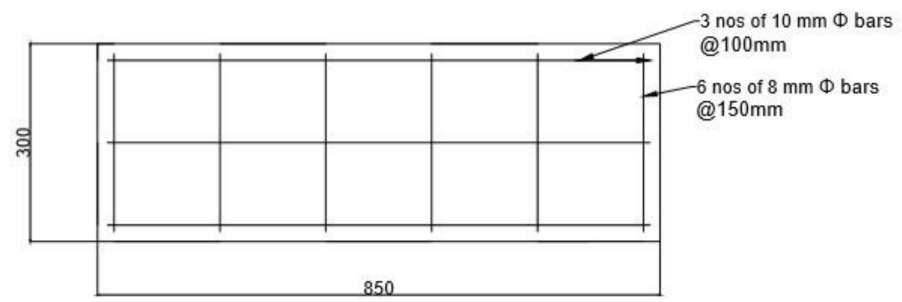
Figure 2. Steel fibers (30 mm length and 0.5 mm diameter).

Slab Specifications

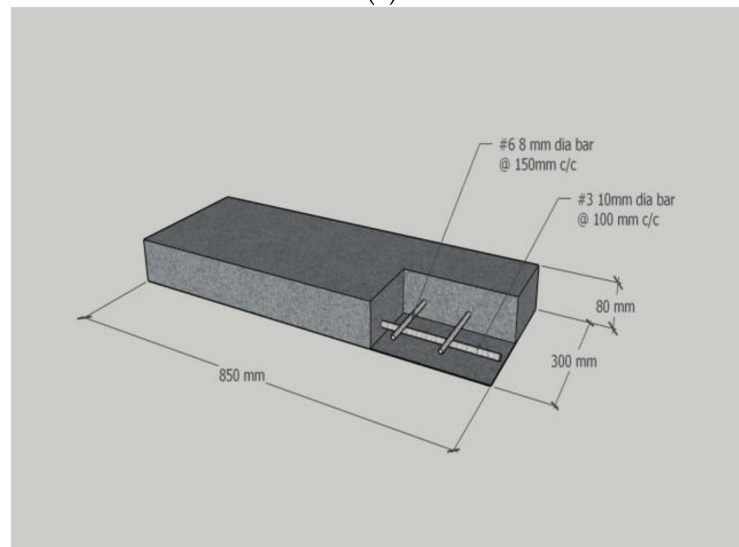
The slabs cast for the experimentation have the dimensions 850 mm × 300 mm × 80 mm as per the Indian standard IS456-2000. Five distinct slabs are cast, each with their own sets of criteria, such as minimum reinforcement and plastic hinge length. Mattock's ($0.5d + 0.05z$) and Priestly and Park's ($0.08z + 6db$) empirical formulas are used to compute the plastic hinge length of slabs. The minimum reinforcement considered for the slab is a 10 mm diameter bar of three numbers as longitudinal reinforcement at 100 mm c/c and an 8 mm diameter bar of 6 numbers as transverse reinforcement with 150 mm c/c based on the requirement and laboratory condition as per the design. Figure 3a,b represent the conventional RCC concrete slab with minimum reinforcement and Figure 3c shows the steel-fiber-reinforced concrete slab. Figure 3d shows the combination of RCC concrete slab and steel-fiber-reinforced concrete slab of 1.5% of the weight of the concrete. Consecutively, the steel-fiber-reinforced concrete with 1.5% weight of the concrete at 150 mm and 70 mm plastic hinge length are shown in Figure 3e,f, respectively. The complete specifications and details of slabs are mentioned in Table 4, along with plastic hinge length.

Table 4. Dimensions and specifications of slabs.

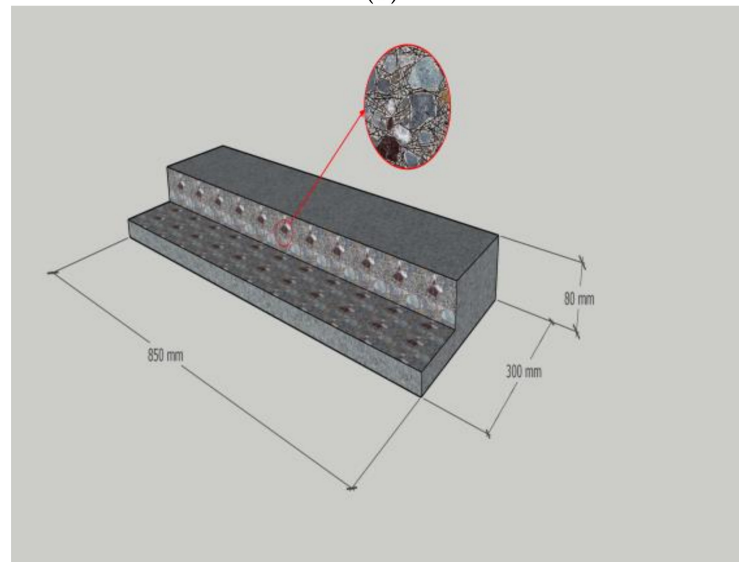
Sl.No	Description	Dimension (mm)	Plastic Hinge Length (mm)	Reinforcement Details
1	RCC Slab	850 × 300 × 80	-	Longitudinal-3 no's 10 mm diameter bar at 100 mm c/c Transverse-6 no's 8 mm diameter bar at 150 mm c/c
2	SFRC Slab	850 × 300 × 80	-	-
3	SFRC Slab + Min Reinforcement	850 × 300 × 80	-	Longitudinal-3 no's 10 mm diameter bar at 100 mm c/c Transverse-6 no's 8 mm diameter bar at 150 mm c/c
4	SFRC + L _p @150 mm	850 × 300 × 80	150	-
5	SFRC + L _p @70 mm	850 × 300 × 80	70	-



(a)

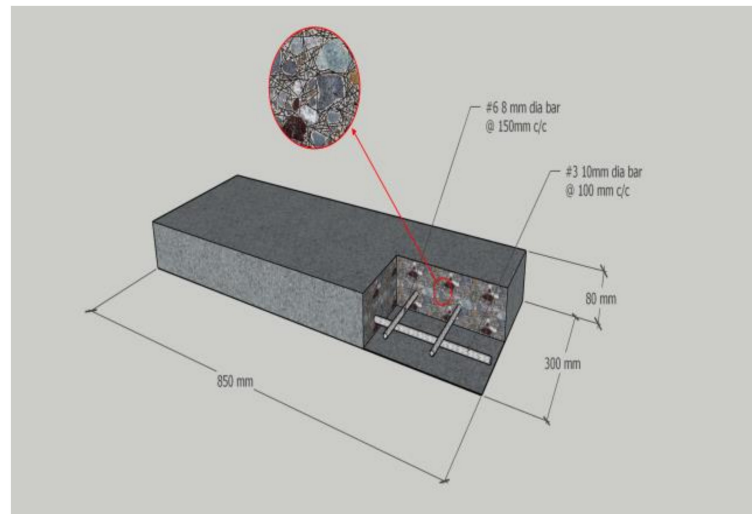


(b)

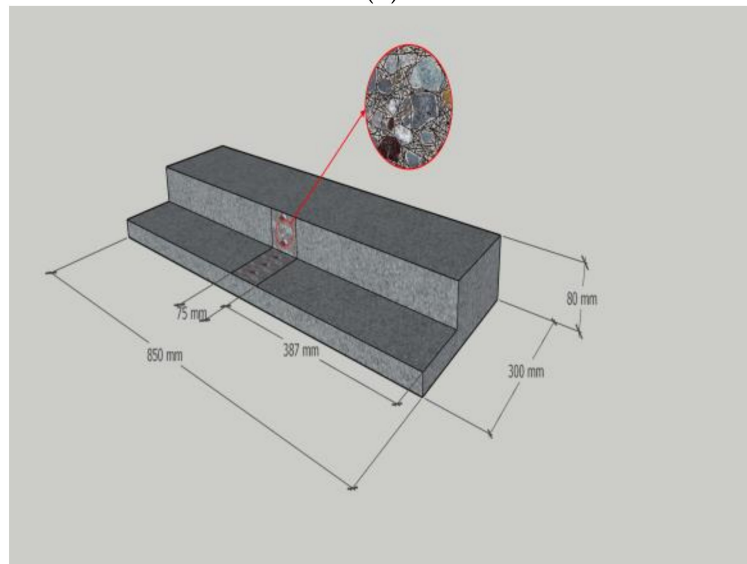


(c)

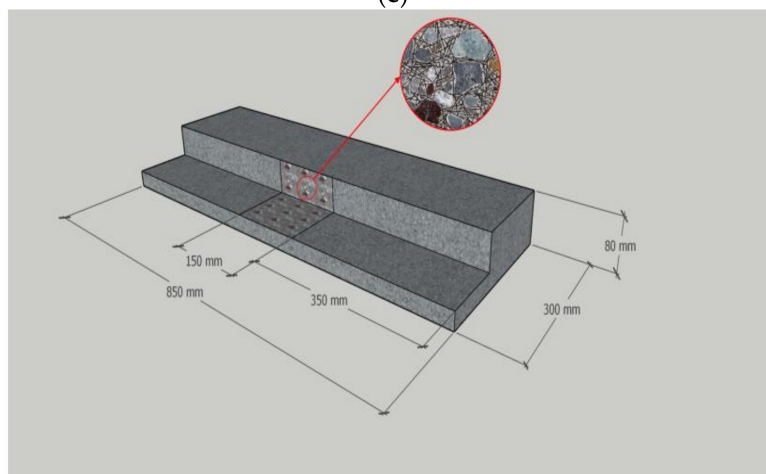
Figure 3. Cont.



(d)



(e)



(f)

Figure 3. Schematic representation of different types of slabs. (a) Reinforcement details of slab; (b) RCC Slab; (c) SFRC Slab; (d) SFRC Slab + Min Reinforcement; (e) SFRC + L_p @150 mm; (f) SFRC + L_p @70 mm.

3. Experimental Test Procedure and Results

3.1. Test Specimens

Before casting the slabs, the compressive strength of concrete, split tensile strength and flexure strength of concrete are investigated as per codal standards to finalize the concrete used for casting the specimens. Ten cubes of size 150 mm × 150 mm × 150 mm were cast, out of which 5 cubes are made of conventional concrete of grade M20. Meanwhile, the 5 remaining same-sized cubes were cast with steel-fiber-reinforced concrete of 1.5% by weight of concrete. Cylinders of size 100 mm × 200 mm of 10 numbers are cast to determine the tensile strength of concrete through a split tensile strength test. In total, 5 cylinders are made of conventional concrete and the remaining 5 are made of steel-fiber-reinforced concrete. In total, 6 flexure beams of size 500 mm × 150 mm × 150 mm were cast, out of which 3 beams are made of conventional concrete and 3 beams are made of SFRC to determine the flexural strength of concrete.

Testing slabs of different configurations based on the parameters of the study are cast. The size of all the 6 specimens of slabs remain the same as 850 mm × 300 mm × 80 mm, but the change in parameters is carried out through reinforcement detailing. Minimum reinforcement is provided in the first conventional concrete slab. Meanwhile, the second specimen was completely replaced with steel-fiber-reinforced concrete, and the third specimen was a combination of both the cases mentioned above. The last 2 specimens are dosed with steel fibers placed at the plastic hinge length of 70 mm and 150 mm, and the remaining portion of the slab is completely made of plain cement concrete. Figure 4a,b show the cube specimens and cylinder specimens to be tested after 28 days of curing. Figure 4c, shows the flexure beam specimen (RCC beam and SFRC beam) and Figure 4d–h, shows the 5 slab specimens (RCC slab, SFRC slab, SFRC + min rein, SFRC + 150 mm, SFRC + 70 mm) to be tested.

3.2. Experimental Setup

A hydraulic jack is connected with a load cell of 200 kN capacity fixed to the self-straining testing frame, and the slab is fixed on all the sides. The repeated loading is applied to the top of the slab at the center, as shown in Figure 5a,b. A mechanical dial gauge is fixed below the loading area of the slab to measure the deflection of the slab under repeated loading.

3.3. Repeated Loading

Figure 6 shows the repeated loading processes for slab specimens. Plastic hinge lengths were calculated to be 70 mm and 150 mm, respectively, based on the theoretical study. The slab loads applied are always kept between load levels of 0 kN to 100 kN. For all cyclic loading stages, the force-controlled mode with rates of 10 kN was used. Upon loading 10 cycles at the maximum of 10 kN per cycle were applied on the slab.

3.4. Result and Discussion

The compressive strength, split tensile strength and flexural strength of both RCC and SFRC are determined by a compression testing machine. The average strength of the specimen for both concrete types tested is presented in Figure 7a–c. The concrete strength is high in all aspects when the steel fiber reinforcement was used as mentioned in Table 5.

After carrying out the compressive strength test in the testing machine for cast cubes, which are cured in a concrete tank for 28 days, the strength of concrete after crushing was found to be 22 N/mm², 21 N/mm², and 22 N/mm² for all three cubes, respectively. Therefore, the target strength of the M20 grade is achieved and the same is used for casting the concrete beams and slabs. Cylinders with 1.5% steel fiber amount of concrete are cast and cured for 7, 14, and 28 days. The same has been tested for split tensile strength. For all the three curing periods, SFRC specimens outperformed plain cement concrete specimens in terms of strength. 28 days cured, SFRC concrete cylinders achieved around 4 N/mm² when compared with plain cement concrete cylinder's strength of 2.7 N/mm²,

as mentioned in Figure 7a. A flexure beam with 1.5% steel fiber amount by weight of concrete was cast and cured for 7, 14, and 28 days.

The same has been tested for flexural strength, as mentioned in Figure 7c. For all the three curing periods, SFRC specimens outperformed plain cement concrete specimens in terms of strength. After curing for 28 days, SFRC concrete beams achieved around 3.92 N/mm^2 when compared with plain cement concrete flexural strength of 2.86 N/mm^2 .



(a)



(b)



(c)



(d)



(e)



(f)



(g)

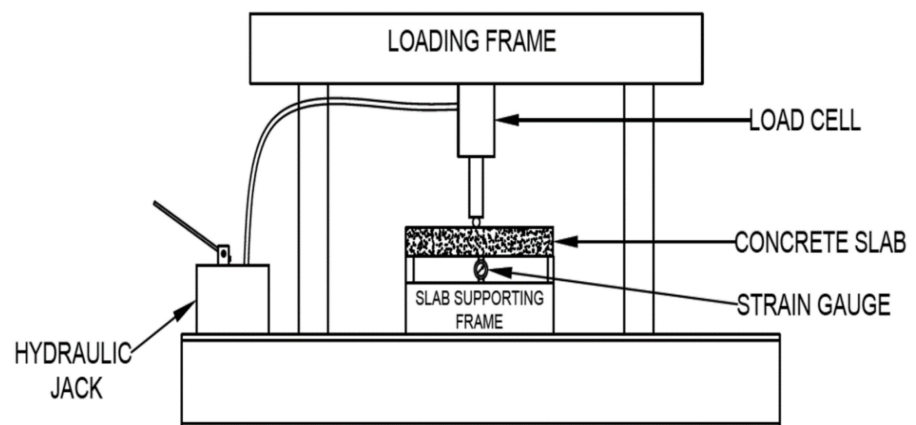


(h)

Figure 4. Test specimens (a,b) the cube specimens and cylinder specimens; (c) flexure beam specimen; (d) RCC slab specimen; (e) SFRC slab specimen; (f) SFRC + min rein specimen; (g) SFRC + 150 mm specimen; (h) SFRC + 70 mm specimen.



(a)



(b)

Figure 5. (a) Experimental setup for repeated loading; (b) schematic representation of loading Frame.

The modulus of elasticity was calculated by applying uniaxial compression to the cylinder specimen and measuring the deformations with a dial gauge set between the 200 mm gauge length, as illustrated in Figure 7d. The tests were carried out using a compressometer in accordance with the IS 516-1959. The cylinder specimens were put on a compression testing machine, and a uniform load was applied until the cylinder reached its failure. The target load and deflection were taken into consideration.

The deflection values are calculated as a strain based on length change. The strain is calculated by dividing the dial gauge readings by the gauge length, and the stress is calculated by dividing the load applied by the area of the cylinder's cross-section. The deformation of various loads was recorded and the findings were plotted graphically against the tension to determine the Young's modulus of concrete of both the conventional and SFRC specimen as shown in Figure 7e,f. Later, the modulus of elasticity of conventional concrete and of steel-fiber-reinforced concrete (SFRC) was derived as 25.47 N/mm² and 29.025 N/mm², as mentioned in Table 6.

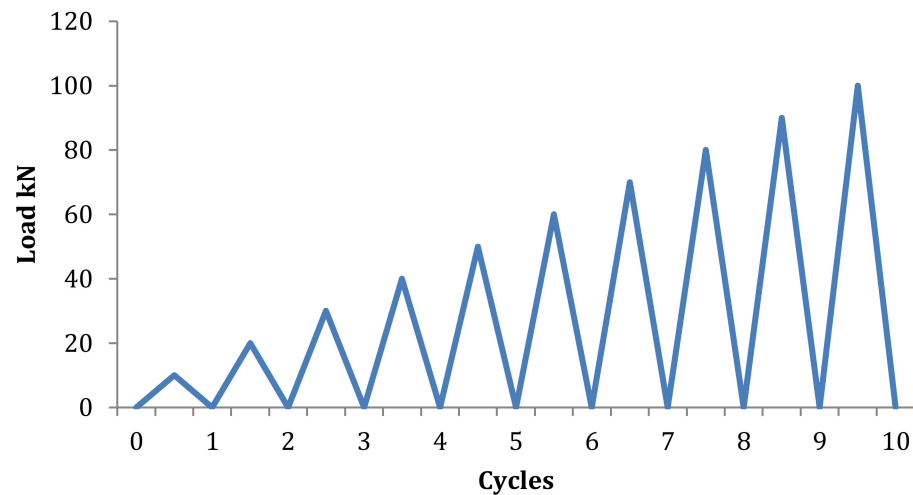


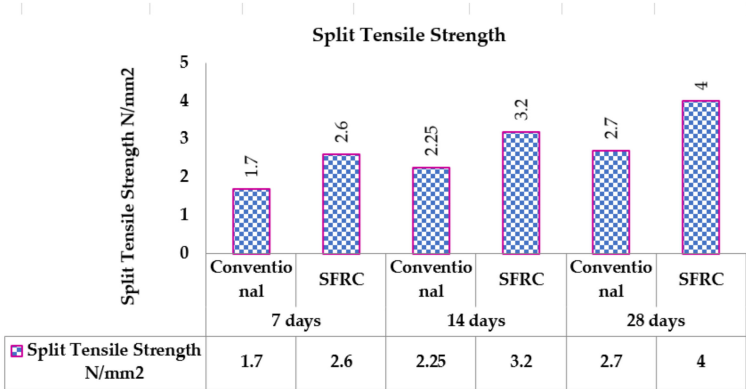
Figure 6. Repeated loading procedures.

The five slabs were subjected to repeated loading, and the experimental setup is presented in Figure 5b. The deformation of the slabs was measured by a digital dial gauge. The repeated load was applied on all the types of slabs and the obtained results are tabulated in Table 5. A maximum load of 96 kN was achieved by a steel-fiber-reinforced slab with a minimum reinforcement and the deflection observed in the dial was 5.78 mm. Meanwhile, an SFRC slab with a steel fiber amount of 1.5% at 150 mm plastic hinge length achieves an 80 kN maximum load with a deflection of 7.29 mm. A minimum of 40 kN was achieved at a 70 mm plastic hinge length as given in Table 7.

Table 5 shows the test results of the five different slab specimens subjected to repeated loading. The RCC slab has less deflection compared with the other slab; however, the maximum load at the failure for RCC is less compared with the SFRC slab and SFRC Slab + Min Reinforcement and SFRC + L_p @150 mm. Hence, the load-carrying capacity for the SFRC slab, SFRC Slab + Min Reinforcement, and SFRC + L_p @150 mm is greater compared with the RCC slab. This shows that the performance of the SFRC slab, SFRC Slab + Min Reinforcement and SFRC + L_p @150 mm is better than the RCC slab.

Figure 8a depicts the load versus deflection for a repeatedly loaded RCC slab. Figure 8b shows the load versus deflection for the SFRC slab under repeated loading (half cycle), which has less deflection than the RCC slab because steel fibers increase the strength of the concrete slab. The load versus deflection curve for the SFRC + minimum reinforced slab subjected to repeated loading (half cycle) is shown in Figure 8c, and it outperforms the RCC slab. Figure 8d depicts the load versus deflection curve for an SFRC + L_p 150 mm slab subjected to repeated loading (half cycle), demonstrating improved performance as steel fibers are added to the plastic hinge length. Figure 8e depicts the load versus deflection curve for an SFRC + L_p 70 mm slab subjected to repeated loading (half cycle), which performs satisfactorily but has more deflection than an SFRC + L_p 150 mm slab.

From the load–displacement curve, it is very clear that up to 60 kN, a conventional RCC slab behaves well, and the curves show the even distribution of load. After that, there is an uneven scattering of load due to the strength-losing character of the slab. Once the steel fibers are added to the slab, the curves are evenly scattered due to the improvement in the ductility of the slab. Steel fibers at 150 mm plastic hinge length and steel fibers amounting for overall slab behavior are almost identical, which comes to around 5.78 and 7.29 mm with a maximum load of 96 kN and 80 kN.



(a)



(b)

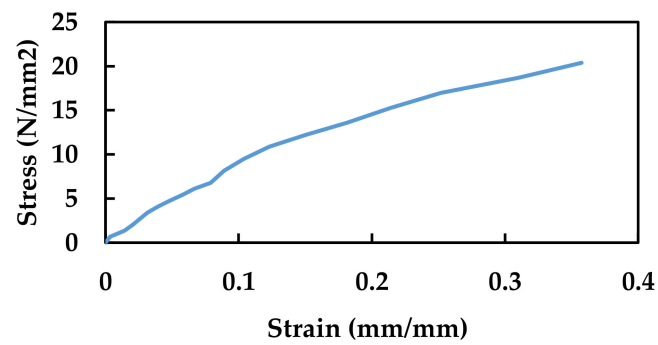


(c)

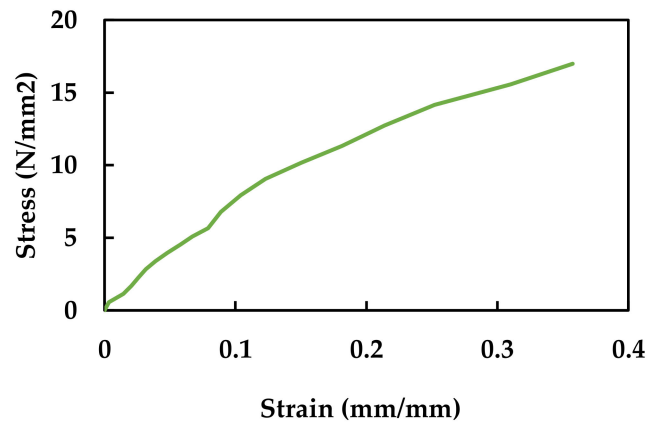
Figure 7. Cont.



(d)



(e)



(f)

Figure 7. (a) Split tensile strength; (b) split tensile strength testing machine; (c) flexural strength test; (d) compression test of cylinder specimens with compressometer; (e) stress–strain behavior of conventional concrete; (f) stress–strain behavior of SFRC.

Table 5. Mechanical properties of concrete.

Sl.No	Type	Compressive Strength	Split Tensile Strength	Flexural Strength
		28 Days Curing		
1	Conventional Concrete	22 N/mm ²	2.7 N/mm ²	2.86 N/mm ²
2	Steel-Fiber-Reinforced concrete (SFRC)	26 N/mm ²	4 N/mm ²	3.92 N/mm ²

Table 6. Modulus of elasticity of specimens.

Sl.No	Specimen	Modulus of Elasticity
1	Conventional Concrete	25.47 N/mm ²
2	Steel-Fiber-Reinforced concrete (SFRC)	29.025 N/mm ²

Table 7. Test load deflection of the slab under cyclic loading.

Slab Specimen	Description	Max Load (kN)	Deflection of the Slab (mm)
1	RCC Slab	68	2.31
2	SFRC Slab	72	4.58
3	SFRC Slab + Min Reinforcement	96	5.78
4	SFRC + L _p @150 mm	80	7.29
5	SFRC + L _p @70 mm	40	6.75

Deflection of the specimen SFRC with minimum reinforcement was decreased and the corresponding ultimate load was increased than RC Slab and SFRC slab. The addition of steel fibers increased the stiffness and ultimate load. At the initial stage of loading, the stiffness of the slabs was high. As the load increased, the stiffness of the slab was reduced, and cracks were formed. SFRC at plastic hinge length with minimum reinforcement has a higher initial crack load than SFRC at plastic hinge length without minimum reinforcement. Additionally, the deflection of SFRC at plastic hinge length with minimum reinforcement was lesser than SFRC at plastic hinge length without minimum reinforcement. Comparing SFRC at plastic hinge length with minimum reinforcement and SFRC with minimum reinforcement, deflection of SFRC at plastic hinge length with minimum reinforcement was thus equal to SFRC with minimum reinforcement. Specimens with bar reinforcement had lower deflection and higher ultimate load than specimens without reinforcement. As a result, steel-fiber-reinforced concrete increased the flexure strength of the slab under loading.

Figure 9a depicts the crack pattern on the RCC slab due to repeated loading (half cycle). Figure 9b depicts the crack pattern on the SFRC slab as a result of repeated loading (half cycle), demonstrating that cracks are minimal in comparison to the RCC slab. Figure 9c depicts the crack pattern on the SFRC + min reinforced slab as a result of repeated loading (half cycle), demonstrating that the cracks are very small in comparison to the RCC slab. Figure 9d depicts the crack pattern on the SFRC + L_p 150 mm slab as a result of repeated loading (half cycle), demonstrating that cracks are kept to the minimum because steel fibers are included in the plastic hinge length. Figure 9e depicts the crack pattern on the SFRC + L_p 70 mm slab as a result of repeated loading (half cycle), demonstrating that cracks are more prevalent than on the SFRC + L_p 150 mm slab.

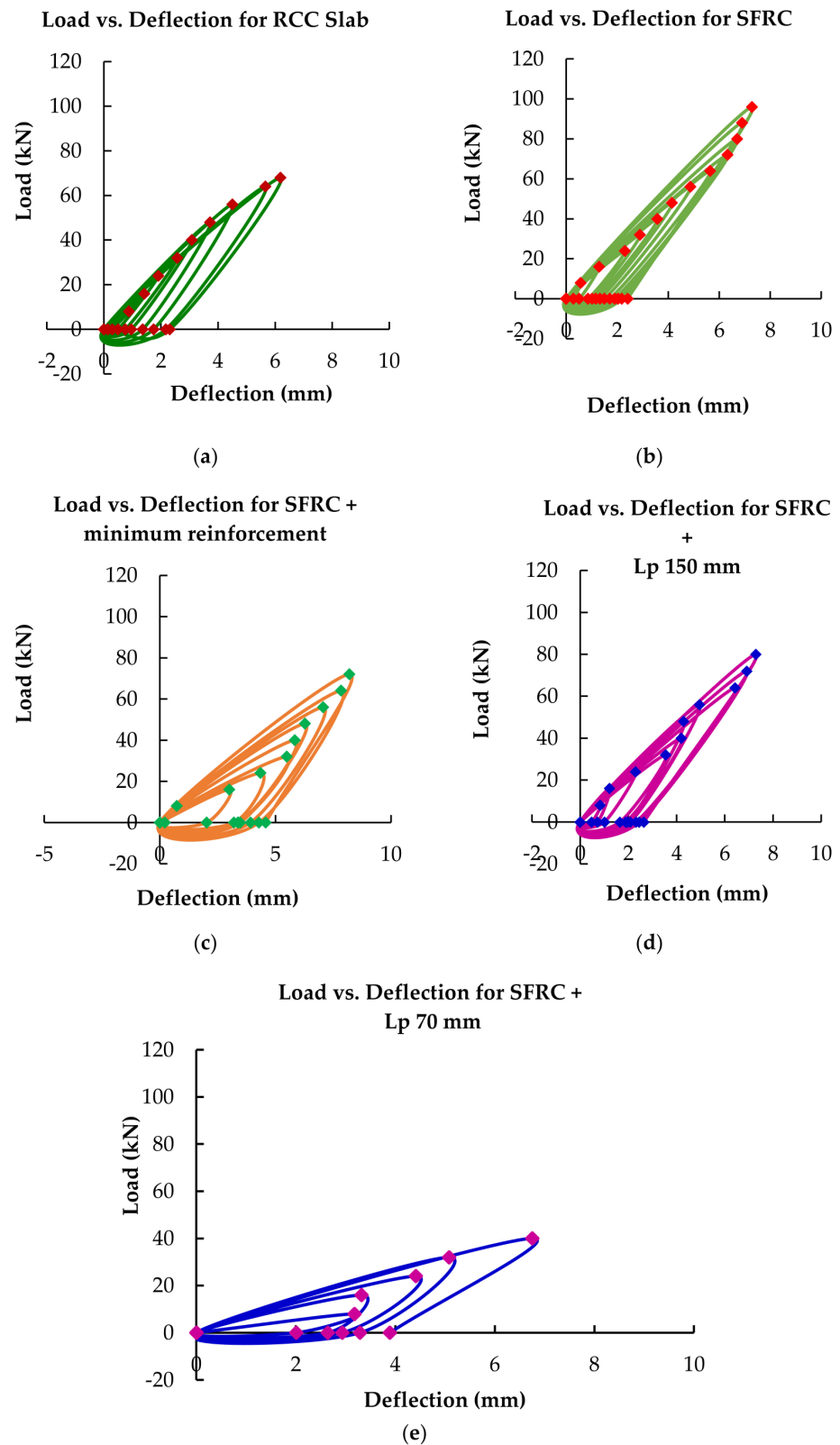


Figure 8. (a) Load versus deflection curve for RCC Slab; (b) load versus deflection curve for SFRC Slab; (c) load versus deflection curve for SFRC + Minimum reinforcement Slab; (d) load versus deflection curve for SFRC + Lp 150 mm; (e) load vs. deflection curve for SFRC + Lp 70 mm.

The conventional RCC slab developed a 2 mm diagonal crack running almost the whole length of the specimen, and the SFRC Slab at 70 mm plastic hinge length shows the wider brittle cracks of 4 mm at the middle of the slab where the maximum deflection took place. Meanwhile, the SFRC Slab with minimum reinforcement and the SFRC Slab with 150 mm plastic hinge length shows a 1 mm crack width and that crack moved away from the maximum deflection zone to another area.



(a)



(b)



(c)

Figure 9. *Cont.*



(d)



(e)

Figure 9. (a) Depiction of the crack pattern on the RCC slab due to repeated loading (Half cycle); (b) depiction of the crack pattern on the SFRC slab due to repeated loading; (c) depiction of the crack pattern on the SFRC + minimum reinforcement slab due to repeated loading; (d) depiction of the crack pattern on the SFRC + Lp 150 mm due to repeated loading; (e) depiction of the crack pattern on the SFRC + Lp 70 mm due to repeated loading.

4. Conclusions

The examination of steel fiber reinforcement at the plastic hinge length of slab is presented in this experimental investigation. The mechanical properties of five distinct slabs are studied after they are cast and subjected to repeated loading (half cycle). The conclusions obtained from this following are as follows:

1. Steel-fiber-reinforced concrete with the amount of 1.5% shows better performance in compressive as well as split-tensile strength compared with that of conventional concrete.
2. Split tensile strength of steel-fiber-reinforced concrete seems to be 1.5 times higher than that of conventional concrete due to the distribution of steel fibers in concrete, which influence the bonding and improves the ductility. The modulus of elasticity was calculated by applying uniaxial compression to the cylinder specimen showing that SFRC specimen with 1.5% steel fiber performs 1.14 times better than the conventional concrete specimen. Hence, the same was adopted for slab specimen casting. The behavior under bending is evident from the flexural strength test, where the flexure beam with steel fibers shows 1.39 times performance improvement than that of a conventional concrete beam.

3. The steel fiber reinforcement in the concrete provides higher ductility and can withstand intensive loads compared with conventional concrete when subjected to repeated loading (Half cycle). Steel-fiber-reinforced concrete at 150 mm plastic hinge length and steel fiber dosed throughout the slab span have similar types of crack pattern, and the failure occurred at the same time due to improved ductility; cracks are forming away from the maximum deflection zone due to the steel fiber at the hinge length.
4. The SFRC slab shows relatively fewer deflections compared with the RCC slab. A similar observation was noticed in the SFRC slab with the addition of minimum reinforcement because the steel fibers increase the strength of the slab. Steel fiber reinforcement at 150 mm plastic hinge length provides equal ductility, and resistance against the load is equal to that of SFRC and minimum reinforcement slab.
5. Crack formation in the steel-fiber-reinforced slab at a plastic hinge length of 150 mm shows 1 mm crack width, which moved away from the maximum stress zone. The crack pattern was similar to that of a fully steel-fiber-reinforced concrete slab.
6. Rather than using the steel fibers throughout the member, the steel fibers can be incorporated at the plastic hinge length alone. This provides a similar performance to that of a full SFRC slab. This would decrease the quantity of steel fiber and is more economical.
7. Based on the experimental results, it is evident that incorporating steel fibers into the 150 mm plastic hinge length of the slab alone will result in a more economical and efficient method of slab construction.
8. Further studies can be carried out for other structural elements with different fibers under different types of loading conditions.

Author Contributions: P.S. and K.R. (Karthikeyan Rajendiran): Conceptualized the model and established the empirical theorem, experimented. B.G.A.G. and K.R. (Krishanu Roy): Supervised the research as well as the analysis of results. K.R. (Karthikeyan Rajendiran) and D.P.: Introduced the idea of cyclic loading in this project, designed the slab, and wrote the paper. Review and submission, Collaborated in and Co-ordinated the research. B.G.A.G. and K.R. (Krishanu Roy): suggested and chose the journal for submission. B.G.A.G. and K.R. (Krishanu Roy): Participated in the manuscript revision phase. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: This manuscript has not been submitted to, nor is it under review by, another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript. The authors declare no conflict of interest.

References

1. Gopinath, A.; Nambiyanna, B.; Nakul, R.; Prabhakara, R. Parametric study on rotation and plastic hinge formation in RC beams. *J. Civ. Eng. Technol. Res.* **2014**, *2*, 393–401.
2. Ko, M.-Y.; Kim, S.-W.; Kim, J.-K. Experimental study on the plastic rotation capacity of reinforced high strength concrete beams. *Mater. Struct.* **2001**, *34*, 302–311. [[CrossRef](#)]
3. Mendis, P. Plastic hinge lengths of normal and high-strength concrete in flexure. *Adv. Struct. Eng.* **2001**, *4*, 189–195. [[CrossRef](#)]
4. Nazaripour, H.; Ashrafizadeh, H.; Schultz, R.; Runka, J.; Mertiny, P. Acoustic Emission Damage Detection during Three-Point Bend Testing of Short Glass Fiber Reinforced Composite Panels: Integrity Assessment. *J. Compos. Sci.* **2022**, *6*, 48. [[CrossRef](#)]
5. Paulay, T.; Priestley, M.J.N. *Seismic Design of Reinforced Concrete and Masonry Buildings*; John Wiley & Sons. Inc.: Hoboken, NJ, USA, 1992; pp. 135–146.
6. Mattock, A.H. Rotational Capacity of Hinging Regions in Reinforced Concrete Beams, Flexural Mechanics of Reinforced Concrete. In Proceedings of the ASCE-ACI International Symposium, Miami, FL, USA, 10–12 November 1964; pp. 143–180.

7. Pradeep, S.; Vengai, V.U.E.; Florence, D. Experimental Investigation on the Usage of Steel Fibres and Carbon Fibre Mesh at Plastic Hinge Length of Slab. *Mater. Today Proc.* **2019**, *14*, 248–256. [[CrossRef](#)]
8. Qin, S.; Gao, D.; Wang, Z.; Zhu, H. Research on the fracture behavior of steel-fiber-reinforced high-strength concrete. *Materials* **2022**, *15*, 135. [[CrossRef](#)] [[PubMed](#)]
9. Zhao, X.; Wu, Y.F.; Leung, A.Y.; Lam, H.F. Plastic hinge length in reinforced concrete flexural members. *Procedia Eng.* **2011**, *14*, 1266–1274. [[CrossRef](#)]
10. Zhao, X.M.; Wu, Y.F.; Leung, A.Y.T. Analyses of plastic hinge regions in reinforced concrete beams under monotonic loading. *Eng. Struct.* **2012**, *34*, 466–482. [[CrossRef](#)]
11. Barros, J.A.O.; Figueiras, J.A. Model for the Analysis of Steel Fiber Reinforced Concrete Slabs on Grade. *Comput. Struct.* **2001**, *79*, 97–106. Available online: www.elsevier.com/locate/compstruc (accessed on 25 April 2022).
12. Neto, B.N.M.; Barros, J.A.O.; Melo, G.S.S.A. A model for the prediction of the punching resistance of steel fibre reinforced concrete slabs centrically loaded. *Constr. Build. Mater.* **2013**, *46*, 211–223. [[CrossRef](#)]
13. Eligehausen, R.; Langer, P. *The Rotation Capacity of Plastic Hinges in Reinforced Concrete Beams and Slabs*; Institute for Building Materials University of Stuttgart: Stuttgart, Germany, 2012.
14. Michels, J.; Waldmann, D.; Maas, S.; Zürbes, A. Steel fibers as only reinforcement for flat slab construction—Experimental investigation and design. *Constr. Build. Mater.* **2012**, *26*, 145–155. [[CrossRef](#)]
15. Holschemacher, K.; Mueller, T.; Ribakov, Y. Effect of steel fibres on mechanical properties of high-strength concrete. *Mater. Des.* **2010**, *31*, 2604–2615. [[CrossRef](#)]
16. Khaloo, A.R.; Afshari, M. Flexural behaviour of small steel fibre reinforced concrete slabs. *Cem. Concr. Compos.* **2005**, *27*, 141–149. [[CrossRef](#)]
17. Nguyen, N.T.; Bui, T.T.; Bui, Q.B. Fiber reinforced concrete for slabs without steel rebar reinforcement: Assessing the feasibility for 3D-printed individual houses. *Case Stud. Constr. Mater.* **2022**, *16*, e00950. [[CrossRef](#)]
18. Xiang, D.; Liu, Y.; Gu, M.; Zou, X.; Xu, X. Flexural fatigue mechanism of steel-SFRC composite deck slabs subjected to hogging moments. *Eng. Struct.* **2022**, *256*, 114008. [[CrossRef](#)]
19. McMahon, J.A.; Birely, A.C. Service performance of steel fiber reinforced concrete (SFRC) slabs. *Eng. Struct.* **2018**, *168*, 58–68. [[CrossRef](#)]
20. Paramasivam, P.; Ong, K.C.G.; Ong, B.G.; Lee, S.L. Performance of Repaired Reinforced Concrete Slabs Under Static and Cyclic Loadings. *Cement Concr.* **1995**, *17*, 37–45. [[CrossRef](#)]
21. Xiang, D.; Liu, S.; Li, Y.; Liu, Y. Improvement of flexural and cyclic performance of bridge deck slabs by utilizing steel fiber reinforced concrete (SFRC). *Constr. Build. Mater.* **2022**, *329*, 127184. [[CrossRef](#)]
22. Gao, D.; Gu, Z.; Wei, C.; Wu, C.; Pang, Y. Effects of fiber clustering on fatigue behavior of steel fiber reinforced concrete beams. *Constr. Build. Mater.* **2021**, *301*, 124070. [[CrossRef](#)]
23. Negi, B.S.; Jain, K. Shear resistant mechanisms in steel fiber reinforced concrete beams: An analytical investigation. *Structures* **2021**, *39*, 607–619. [[CrossRef](#)]