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Impact Loading of Circular Slabs Using Curvilinear Shear Reinforcement Under Different Support Conditions

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Abstract

The impact resistance and punching behavior of circular reinforced concrete slabs are critical for structures subjected to localized dynamic loading. This study experimentally investigates the failure mechanisms and punching capacity of circular slabs incorporating W-bent shear reinforcement and steel fibre reinforced concrete (SFRC) under repeated drop-weight impact loading. Circular slabs with diameters of 450 mm, 600 mm, and 750 mm were tested under simply supported and fixed boundary conditions to evaluate the influence of slab geometry, support restraint, and fibre reinforcement on impact performance. The experimental observations revealed that slab failure was governed by a combination of radial and circumferential cracking, flexural tensile stress development, and localized punching shear beneath the impact zone. Conventional concrete slabs exhibited brittle behavior characterized by wide radial cracks and pronounced punching cone formation. SFRC slabs demonstrated delayed crack initiation, distributed crack propagation, and reduced fragmentation due to the fibre bridging mechanism. The incorporation of W-bent shear reinforcement further enhanced the shear transfer capacity and restricted the propagation of inclined punching cracks. An impact energy balance approach was adopted to evaluate the energy absorption capacity of the slabs between the initial cracking and final failure stages. The results showed that increasing slab diameter, the presence of steel fibres, and fixed boundary conditions significantly improved the energy dissipation capacity and crack resistance ratio of the slabs. Based on the experimental findings, an energy-based analytical model was proposed to predict the punching capacity of circular slabs, incorporating the effects of energy dissipation, crack resistance, slab diameter, and boundary conditions. The proposed model demonstrated good agreement with the experimental trends. The results confirm that the combined use of steel fibres and W-bent shear reinforcement significantly enhances the impact resistance and punching capacity of circular slabs, making them suitable for structures exposed to severe dynamic or impact loading conditions.

Introduction

Reinforced concrete (RC) slabs employed in industrial floors, bridge decks, airport pavements, and protective infrastructure are frequently subjected to accidental low-velocity impacts, where localized punching and brittle shear failure govern structural safety. Experimental evidence has shown that conventional RC slabs experience sharp increases in peak impact force accompanied by significant mid-span displacement when subjected to drop-weight loading. For example, Anbu and Kothandapani [1] reported that impact-enhanced slab configurations could improve peak impact resistance by approximately 15–25% while reducing central deflection by nearly 18% compared with control specimens. Similarly, Kumar et al. [2] observed through drop-weight tests (using impact energies in the range of 2–4 kJ) that steel fibre reinforced slabs absorbed up to 30–40% more impact energy than conventional RC slabs, particularly under fixed support conditions. These findings confirm that while material modification improves global toughness, localized punching shear failure remains a dominant vulnerability under concentrated impact.

Considerable research has therefore focused on advanced cementitious composites and fibre systems to enhance impact resistance. Murali et al. [3] demonstrated that the incorporation of graphene oxide, steel

wire mesh, and fibres in preplaced aggregate concrete increased the number of blows to failure by more than 2.5 times compared with plain concrete, highlighting strong synergistic crack-bridging effects. In ultra-high-performance fibre reinforced concrete (UHPFRC), Murali et al. [4] reported impact energy dissipation improvements exceeding 60%, primarily attributed to fibre pull-out and dense matrix characteristics. Numerical investigations by Jin et al. [5] further indicated that increasing impact velocity from 2 m/s to 6 m/s significantly elevated peak impact force in GFRP-reinforced concrete columns, with dynamic amplification strongly dependent on axial load ratio. Repeated impact studies on steel fibre-reinforced UHPC by Shao et al. [6] showed that increasing fibre length from 6 mm to 13 mm improved cumulative impact life by nearly 35%, while the inclusion of crumb rubber enhanced damage tolerance. Chen et al. [7] reported that reinforced geopolymer concrete slabs exhibited up to 20% higher impact resistance than ordinary Portland cement slabs, demonstrating the benefits of alternative binders. A comprehensive review by Esaker et al. [8] concluded that fibre reinforcement is highly effective in improving impact toughness but is less efficient in preventing punching-type shear failures under localized impact.

Several studies have examined hybrid and durability-oriented concrete systems. Gunasekaran et al. [9] found that green high-performance fibre reinforced concrete maintained more than 85% of its original impact strength after freeze–thaw exposure in NaCl solution. The influence of fibre geometry has been widely documented; Murali et al. [10] showed that hooked and crimped fibres increased impact numbers by approximately 1.8–2.2 times relative to plain concrete. Nili and Afrouhsabet [11] reported that the combined use of 10% silica fume and 1% steel fibres significantly enhanced both compressive strength and impact resistance. Earlier work by Marar et al. [12] established a strong correlation between compression toughness and impact energy in high-strength fibre reinforced concrete. More recent investigations into layered geopolymer fibrous concrete [13] demonstrated substantial improvements in repeated drop-weight performance, while Pan et al. [14] showed that GFRP mesh-reinforced ECC runway panels exhibited superior impact fatigue life due to distributed tensile resistance. Two-stage fibrous concrete systems were also reported to improve reliability against repeated impacts [15], and Manohar et al. [16] demonstrated that composite fender systems could effectively dissipate vessel impact energy through multi-layered steel–concrete interaction.

Advancements in nano-modified and recycled systems have further improved impact behaviour. Murali et al. [17] observed that prepacked expanded clay aggregates fibrous concrete incorporating carbon nanotubes and glass fibre mesh increased absorbed impact energy by nearly 50% compared with conventional fibrous concrete. Treated recycled aggregate concrete evaluated using Weibull statistics showed reliable impact performance with reduced variability [18]. Long et al. [19] reported that graphene oxide improved both mechanical performance and sustainability of cement composites. Multi-layered prepacked fibrous composites [20] demonstrated enhanced post-impact integrity, while Wang et al. [21] showed that steel wire mesh under medium-velocity impact exhibited progressive failure governed by mesh spacing and strain-rate effects. Recent studies using blended binders and recycled materials confirmed significant gains in fracture toughness and impact strength [22–24], and advanced finite element simulations have highlighted the importance of accurate damage modelling in predicting impact failure of composite panels [25].

Despite these material-level advancements, relatively few studies have addressed structural shear reinforcement strategies in slab systems subjected to impact. Functionally graded RC slabs tested by Mastali et al. [26] showed improved resistance under drop-weight and projectile impacts, while Murali et al. [27] reported enhanced impact properties in graded fibrous composites incorporating alkali-activated slag and carbon nanotubes. Hybrid fibre systems combining carbon nanofibres and PVA fibres [28] and polyolefin fibre reinforcement with optimized geometry [29] further improved impact toughness. Hybrid fibrous geopolymer composites also demonstrated notable gains in absorbed energy under drop-weight loading [30]. However, the overwhelming majority of these studies focus on flexural toughness enhancement, whereas the mechanics of impact-induced punching shear, especially the evolution of the shear cone, remains insufficiently explored.

More critically, the role of inclined discrete shear reinforcement, such as W-bent bars, in altering punching behaviour under impact has received almost no systematic investigation. Circular slabs exhibit radial stress flow and non-uniform shear distribution that differ fundamentally from rectangular slab

behaviour commonly reported in the literature. Under localized impact, the formation, inclination, and propagation of the shear cone govern the ultimate capacity and failure mode. The potential of W-bent shear reinforcement to intercept diagonal cracks, enhance confinement, and improve energy dissipation through inclined steel engagement has not yet been quantified. Furthermore, the interaction between strain-rate effects, shear cone evolution, and energy absorption in circular RC slabs remains largely unresolved.

Accordingly, the present study investigates the impact-induced shear cone evolution and energy dissipation mechanism in circular RC slabs incorporating W-bent shear reinforcement through an integrated experimental and finite element approach. The objectives are to: (i) characterize failure modes and crack propagation under drop-weight impact, (ii) quantify the influence of W-bent geometry on peak impact force and absorbed energy, (iii) examine modifications in shear cone characteristics, and (iv) develop a rational analytical model for impact punching capacity. The findings are expected to advance the understanding of shear-resistant reinforcement mechanisms and support the development of performance-based design strategies for impact-resistant concrete slab systems.

Experimental Program

Material, Specimen design and Reinforcement detailing

The circular slab specimens were reinforced using a concentric curvilinear reinforcement system combined with W-bent shear reinforcement to enhance shear resistance and crack control around the central opening under low-velocity impact loading. Three slab diameters of 450 mm, 600 mm, and 750 mm were considered with a constant slab thickness of 100 mm (Fig.1). The reinforcement consisted of multiple concentric circular rings (S1–S9) arranged to ensure uniform stress distribution and to mitigate stress concentration effects. The 450 mm slab contained five reinforcement rings, while the 600 mm and 750 mm slabs incorporated seven and nine rings, respectively, each consisting of eight reinforcing bars placed along the circular path.

In addition, W-bent curvilinear shear reinforcement was embedded within the slab thickness. The reinforcement bars were fabricated in a repetitive zig-zag configuration with an average segment spacing of 107 mm, an inclination angle of approximately 71° , and a vertical depth of about 70 mm (Fig.2). This configuration enables the inclined segments to effectively intercept diagonal shear cracks and enhance the mechanical interlock between the steel reinforcement and the concrete matrix, thereby improving impact resistance and crack control.

The experimental program included twelve slab specimens, categorized based on support conditions and concrete type. Both simply supported (SS) and fixed support (FS) boundary conditions were considered, and each support configuration included conventional concrete (CC) and steel fiber reinforced concrete (SFRC) slabs with diameters of 450 mm, 600 mm, and 750 mm (Table 1).

The SFRC mixture incorporated 1% hooked-end steel fibers (Fig. 3) with a length of 60 mm, diameter of 0.5 mm, and an aspect ratio of 120, providing a tensile strength exceeding 1100 MPa and a modulus of elasticity of approximately 200 GPa. The concrete mix proportion consisted of 205 kg/m³ water, 342 kg/m³ cement, 685 kg/m³ sand, and 1218 kg/m³ gravel, with the addition of 3.42 kg/m³ steel fibers for the SFRC mixture. The compressive strength of the conventional concrete was 27.41 MPa, whereas the SFRC achieved 33.22 MPa, indicating enhanced mechanical performance due to fiber reinforcement (Table 2 and 3).

The combined use of concentric reinforcement rings, W-bent shear reinforcement, and steel fiber reinforcement formed an effective structural system capable of improving shear resistance, limiting crack propagation, and enhancing the impact performance of circular slabs.

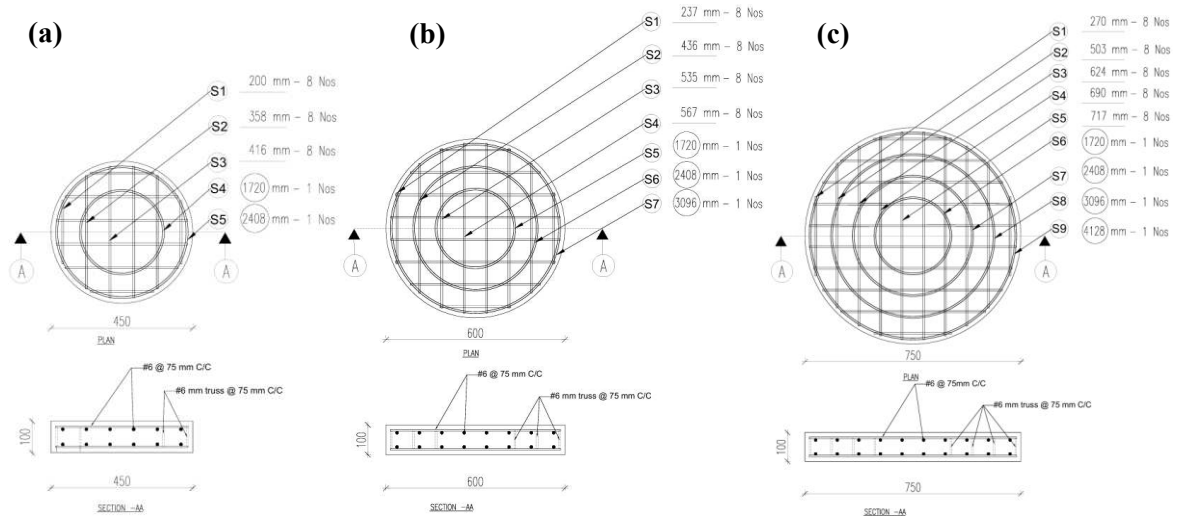


Fig.1. W-Bent curvilinear shear reinforcement in circular slab: (a) 450mm, (b) 600mm and (c) 750mm

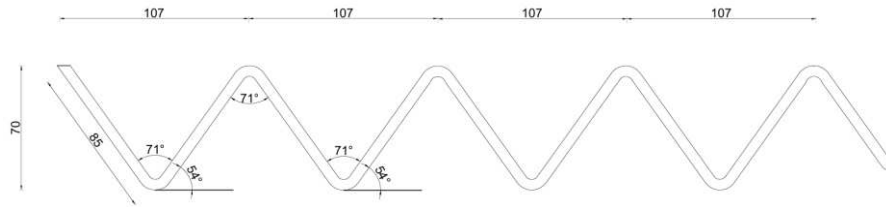


Fig.2. W-Bent curvilinear shear reinforcement detail

Table 1
Dimensions

Support Type	Concrete Type	Specimen ID	Dimensions	
			Diameter (mm)	Depth (mm)
Simply Supported (SS)	Conventional (CC)	SS-CC-450	450	100 (Typical)
		SS-CC-600	600	
		SS-CC-750	750	
	SFRC	SS-SFRC-450	450	
		SS- SFRC - 600	600	
		SS- SFRC - 750	750	
Fixed Support (FS)	Conventional (CC)	FS-CC-450	450	
		FS-CC-600	600	
		FS-CC-750	750	
	SFRC	FS- SFRC - 450	450	
		FS- SFRC - 600	600	
		FS-SF-750	750	

Table 2
Steel fiber properties

Property	Value
Fiber type	Hooked-end steel fiber
Fiber length (l_f)	60 mm
Fiber diameter (d_f)	0.5 mm
Aspect ratio (l_f/d_f)	120
Tensile strength	≥ 1100 MPa
Modulus of elasticity	~ 200 GPa
Density	7850 kg/m ³

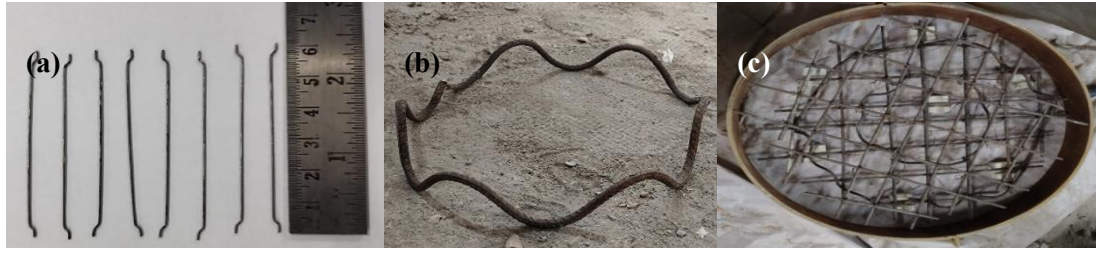


Fig.3. (a) Steel fiber, (b) Curvilinear w-bent shear reinforcement and (c) Reinforcement arrangement

Table 3

Mix proportion and properties

Material	Fiber Vol. (V _f %)	Water (kg/m ³)	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Steel fiber (kg/m ³)	f _{cu} (MPa)	f _c (MPa)	E _c (MPa)
Conventional Concrete (CC)	0.00%	205	342	685	1218	0	27.41	21.64	2.89×10 ⁴
Steel Fiber Reinforced Concrete (SFRC)	1.00%	205	342	685	1218	3.42	33.22	26.78	3.12×10 ⁴

Impact test setup

The low-velocity impact tests were conducted using a vertical drop-weight impact testing apparatus, as illustrated in Fig. 4(a). The experimental setup consisted of a rigid steel frame equipped with a pulley-guided drop mechanism that allows the controlled release of a spherical steel impactor from a predetermined height. The slab specimen was placed horizontally on a rigid support platform positioned directly below the drop path of the impactor to ensure accurate impact loading at the designated location.

The circular slab specimen was mounted on a specially fabricated support frame to simulate the required boundary conditions. Depending on the test configuration, the slabs were subjected to simply supported or fixed support conditions. The specimen was centrally aligned with the drop axis to ensure consistent impact loading. The drop-weight impactor used in the experiment was a solid steel ball weighing 2.5 kg, as shown in Fig. 4(b). The spherical geometry of the impactor ensures uniform contact during impact and reduces stress concentration effects caused by irregular contact surfaces [1,2].

During the test, the steel ball was raised to a specified drop height (h) using the pulley system and then released freely to strike the slab specimen under the action of gravity. The velocity of the impactor immediately before contact with the slab surface can be determined using the principle of conservation of energy or free-fall kinematics. The impact velocity (v) can be calculated as:

$$v = \sqrt{2gh}$$

where, v = impact velocity (m/s), g = gravitational acceleration (9.81 m/s²), h = drop height (m)

The impact energy (E) transferred to the slab at the moment of contact is expressed as:

$$E = mgh$$

where, m = mass of the impactor (kg), g = gravitational acceleration (9.81 m/s²), h = drop height (m)

This drop-weight testing arrangement enables the evaluation of impact resistance, energy absorption capacity, and damage characteristics of circular slab specimens subjected to low-velocity impact loading. The controlled release mechanism ensures repeatability of the tests, while the spherical steel impactor provides consistent contact conditions for reliable assessment of the structural response of the slabs.

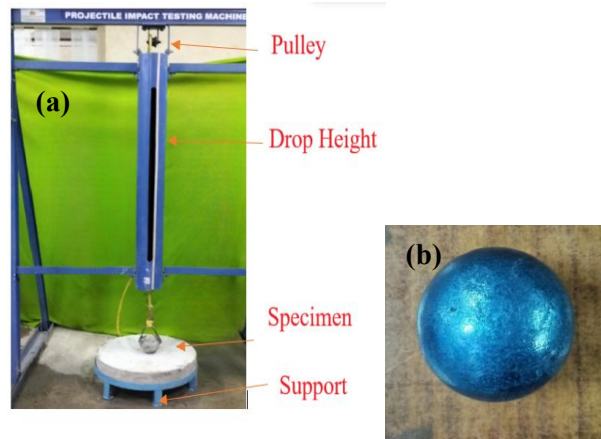


Fig.4. Test setup: (a) Projectile impact testing setup and (b) 2.25 kg impactor

Experimental Results and Discussion

Failure Modes

Simply Supported Conditions

The crack patterns observed in Figs. 5–7 illustrate the progressive failure mechanism of the simply supported circular slabs subjected to concentrated impact loading. The damage morphology provides clear insight into the crack initiation process, propagation pattern, punching shear behavior, and the influence of W-bent shear reinforcement in both conventional concrete (CC) and steel fiber reinforced concrete (SFRC) slabs [1,2].

Crack Initiation and Early Damage Development

Crack initiation in the tested slabs predominantly occurred at the point of impact where the stress concentration was highest. Immediately after impact, localized crushing and micro-cracking developed in the top surface around the loading zone due to the high compressive stress and stress wave reflection. In the SS-CC specimens (Figs. 5(a), 6(c), and 7(e)), the initial cracks formed rapidly and propagated outward from the impact point along the radial directions. These cracks were associated with the tensile stresses generated in the lower region of the slab due to bending and stress wave dispersion.

In contrast, the SS-SFRC specimens (Figs. 5(b), 6(d), and 7(f)) exhibited delayed crack initiation and reduced crack width due to the bridging action of randomly distributed steel fibers. The fibers enhanced the tensile resistance of the concrete matrix and effectively controlled micro-crack growth during the early stages of impact loading. Consequently, crack propagation occurred in a more distributed and controlled manner compared to conventional concrete slabs.

Radial and Circumferential Crack Formation

Two dominant crack patterns were observed in the circular slabs: radial cracks and circumferential cracks. Radial cracks initiated at the impact point and propagated towards the slab boundary along the direction of maximum tensile stress. These cracks are primarily attributed to flexural tensile stresses generated by the localized bending of the slab. The radial crack pattern is clearly visible in all specimens, particularly in the SS-CC-600 and SS-CC-450 slabs where long, continuous cracks extend from the center toward the supports.

Circumferential cracks developed around the impact zone as a result of shear stress redistribution and tensile hoop stresses generated by the radial expansion of the slab under impact loading. These cracks formed concentric rings surrounding the damaged region. In conventional concrete slabs, circumferential cracking was less pronounced and often merged with radial cracks, leading to unstable crack propagation. However, in SS-SFRC specimens, the presence of steel fibers promoted the formation of multiple fine circumferential cracks instead of a few dominant fractures. This behavior indicates improved stress redistribution and crack arrest capability.

Punching Cone Formation

The impact loading produced a localized punching shear mechanism characterized by the formation of a truncated cone-shaped failure surface beneath the impact point. This punching cone developed due to the combination of compressive stresses at the top surface and shear stresses along inclined planes within the slab thickness. The failure surface typically propagated at an angle ranging between 25° and 35° relative to the slab plane, forming a distinct conical fracture zone.

In the SS-CC slabs, the punching cone was clearly visible on the rear surface, where a large fragmented region formed around the impact location. The fracture surface was relatively brittle, indicating limited energy absorption capacity of conventional concrete. The cone boundary was irregular and accompanied by extensive radial cracking extending to the slab edges.

For the SS-SFRC slabs, the punching cone was more confined and less fragmented. Steel fibers enhanced the post-cracking resistance of the concrete matrix, preventing sudden separation of the cone and maintaining structural integrity around the impact region. The fiber bridging mechanism reduced spalling and restricted the propagation of the shear failure surface, resulting in a more ductile punching response.

Effect of W-Bent Shear Reinforcement

The incorporation of W-bent shear reinforcement significantly influenced the crack propagation and overall impact resistance of the circular slabs. The W-shaped reinforcement provided effective anchorage within the concrete matrix and improved the shear transfer mechanism across potential failure planes.

In the conventional concrete slabs with W-bent reinforcement, the reinforcement acted as an internal shear resisting element, intercepting the inclined cracking planes associated with punching failure. As a result, the propagation of the punching cone was partially restrained, and the slab exhibited a wider distribution of radial cracks instead of a single dominant failure surface.

The effectiveness of the W-bent reinforcement was further enhanced in the SFRC slabs. The combined action of steel fibers and W-bent reinforcement produced a synergistic strengthening effect. While the fibers controlled micro-crack development and improved tensile capacity, the W-bent reinforcement provided additional resistance against shear-induced separation. This dual reinforcement mechanism resulted in reduced crack width, limited crack propagation, and improved energy dissipation capacity under impact loading.

Furthermore, the crack density observed in SS-SFRC specimens indicates that the reinforcement system promoted distributed cracking rather than localized brittle failure. Such behavior is desirable in impact-resistant structures because it enhances ductility and prevents sudden catastrophic collapse.

Failure Characteristics

The experimental observations demonstrate that the failure mechanism of simply supported circular slabs under impact loading is governed by the interaction of flexural cracking, radial tensile stress, circumferential stress redistribution, and punching shear action. Conventional concrete slabs exhibited brittle failure characterized by large radial cracks and extensive punching damage. In contrast, slabs reinforced with steel fibers and W-bent shear reinforcement displayed controlled cracking, reduced fragmentation, and improved structural integrity.

These results confirm that the integration of W-bent shear reinforcement and steel fiber reinforcement significantly enhances the impact resistance and crack control capability of circular concrete slabs, making them suitable for applications requiring high resistance to localized dynamic loading.

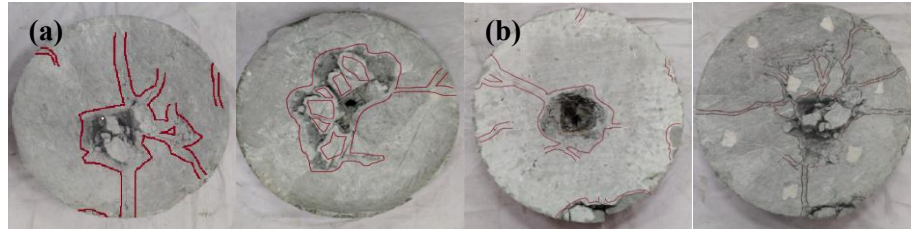


Fig.5.Front and back of: (a) SS-CC-450 (b) SS-SFRC-450

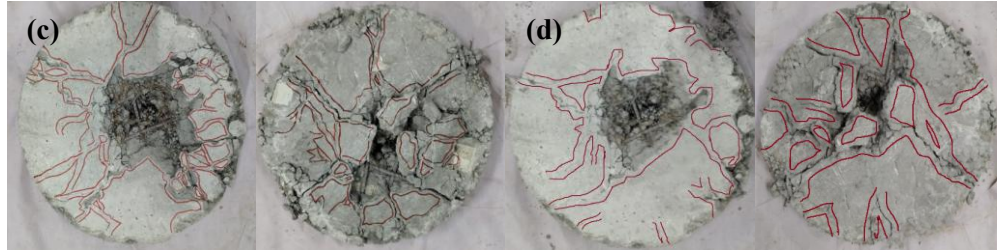


Fig.6.Front and back of: (c) SS-CC-600 (d) SS-SFRC-600

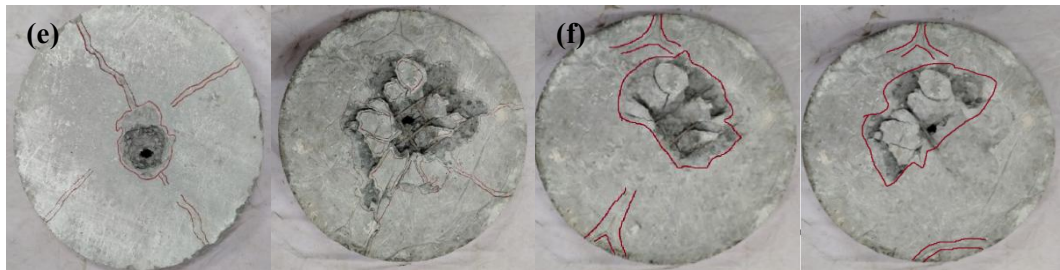


Fig.7.Front and back of: (e) SS-CC-700 (f) SS-SFRC-700

Fixed Supported Conditions

Based on the damage morphology presented in Figs. 8–10, the following analysis details the failure mechanisms of fixed-supported circular slabs under concentrated loading, highlighting the transition from conventional concrete (CC) to steel fiber reinforced concrete (SFRC) [1,2].

Crack Initiation and Early Damage Development

Crack initiation in the tested fixed-supported slabs predominantly occurred at the center of the span, where tensile stresses were highest under the concentrated load. In the FS-CC specimens (Figs. 8(a), 9(c), and 10(e)), cracks initiated rapidly once the tensile capacity of the concrete was reached. These initial cracks propagated outward from the loading point toward the fixed boundaries, driven by the high stress concentration at the center. The brittle nature of the conventional matrix resulted in wide, distinct cracks that appeared almost immediately following the elastic limit.

In contrast, the FS-SFRC specimens (Figs. 8(b), 9(d), and 10(f)) demonstrated a delayed crack initiation process. The randomly oriented steel fibers provided an internal bridging mechanism that intercepted micro-cracks at their inception. This fiber-bridging action effectively enhanced the first-crack strength of the slabs, leading to a more controlled development of damage. Consequently, the early stages of loading in SFRC specimens were characterized by a larger number of hairline cracks rather than the singular, dominant fractures observed in the CC slabs.

Radial and Circumferential Crack Formation

The failure patterns in these circular slabs are defined by the interaction of radial and circumferential cracking. Radial cracks initiated at the center and extended toward the fixed supports along the lines of maximum principal stress. In the FS-CC slabs, these radial cracks are long and continuous, effectively dividing the slab into triangular segments or "wedges". This pattern is indicative of a primary flexural failure mode where the slab's rotation is restrained at the perimeter.

Circumferential cracks formed around the loading zone as the slab underwent localized deformation. In the FS-CC specimens, these cracks were relatively sparse and often merged into the radial cracks, contributing to a sudden loss of structural integrity. However, the FS-SFRC specimens displayed a significantly more complex network of circumferential cracking. The fibers promoted stress redistribution, allowing the concrete to develop multiple concentric crack rings. This transformation from a few wide radial cracks to a dense mesh of radial and circumferential cracks signifies superior energy dissipation and a more redundant load-carrying mechanism in the fiber-reinforced specimens.

Punching Cone Formation

The concentrated loading induced a localized punching shear mechanism, resulting in the formation of a truncated cone-shaped failure surface. In the FS-CC slabs, the punching cone is clearly defined by sharp, brittle fracture planes. The failure was characterized by a sudden separation of the conical plug from the surrounding slab, with significant fragmentation visible on the rear surfaces. The steep angle of these fracture planes indicates a lack of internal shear resistance beyond the aggregate interlock of the concrete matrix.

For the FS-SFRC slabs, the punching cone was far more confined and integrated. The steel fibers acted as "miniature shear stirrups" across the diagonal tension cracks forming the cone. This action effectively increased the shear friction and prevented the sudden "punch-through" observed in conventional concrete. The resulting failure surface in SFRC was tougher and more tortuous, requiring significantly higher energy to complete the separation, which preserved the overall structural integrity of the slab even at high deformation levels.

Effect of W-Bent Shear Reinforcement

The presence of W-bent shear reinforcement significantly altered the internal stress distribution and crack propagation paths. This reinforcement system provided a mechanical link between the top and bottom layers of the slab, intercepting the inclined shear cracks that lead to punching failure.

In the CC specimens, the W-bent reinforcement acted as a primary defense against brittle shear failure, forcing the cracks to propagate over a wider area and reducing the severity of the punching cone fragmentation. When combined with steel fibers in the FS-SFRC specimens, a synergistic reinforcement effect was observed. The steel fibers controlled the width of micro-cracks, while the W-bent bars provided macroscopic shear resistance. This dual-reinforcement strategy resulted in the highest crack density and the most ductile failure mode seen in Fig. 10(f). The W-bent reinforcement effectively anchored the compression zone to the tension zone, ensuring that the slab maintained its load-bearing capacity through extensive plastic deformation.

Failure Characteristics

The experimental observations confirm that the failure of fixed-supported circular slabs is a complex interaction of flexural radial cracking and localized punching shear. Conventional concrete slabs (FS-CC) exhibited a brittle, localized failure characterized by wide radial cracks and distinct punching cones. Conversely, the integration of steel fibers and W-bent shear reinforcement (FS-SFRC) transformed the failure into a pseudo-ductile process. The resulting damage morphology, marked by distributed cracking, reduced spalling, and a robust punching zone, demonstrates the high impact and shear resistance provided by the combined reinforcement system under international structural standards.



Fig.8. Front and back of: (a) FS-CC-450 (b) FS-SFRC-450

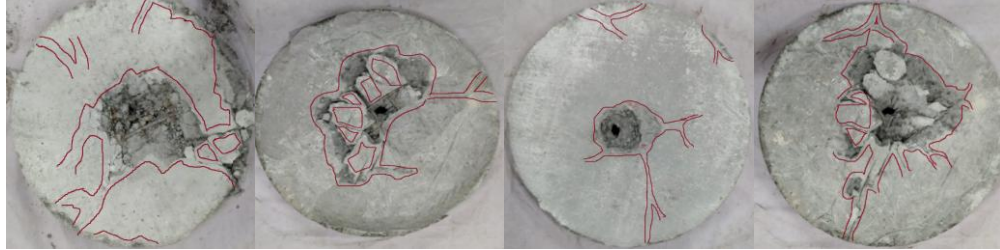


Fig.9. Front and back of: (c) FS-CC-600 (d) FS-SFRC-600

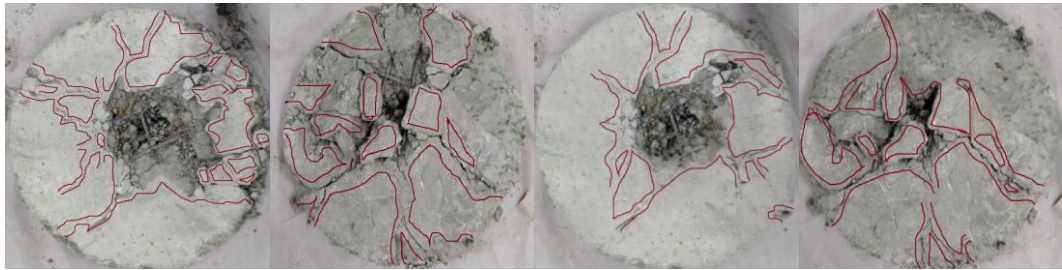


Fig.10. Front and back of: (e) FS-CC-700 (f) FS-SFRC-700

Development of Analytical Model

Impact energy balance

The impact resistance of circular slabs can be effectively interpreted through an energy balance approach, in which the kinetic energy imparted by the falling mass is progressively dissipated through crack formation, plastic deformation, and internal friction within the concrete matrix. The experimental results obtained from the conventional concrete (CC) and steel fibre reinforced concrete (SFRC) slabs demonstrate the evolution of energy absorption capacity between the initial cracking stage and the final failure stage.

For repeated impact loading, the cumulative impact energy absorbed by the slab up to a specific damage stage is obtained by multiplying the energy per blow by the number of blows (Table 4) sustained by the specimen:

The impact energy (E) transferred to the slab at the moment of contact is expressed as:

$$E = Nmgh$$

where, N = impact count, m = mass of the impactor (2.25 kg), g = gravitational acceleration (9.81 m/s²), h = drop height (2 m)

Table 4
Impact counts

Diameter (mm)	Conventional Concrete (CC)				Steel Fibre Reinforced Concrete (SFRC)			
	Simply Supported		Fixed Support		Simply Supported		Fixed Support	
	Initial Crack Count (IC)	Final Crack Count (FC)	Initial Crack Count (IC)	Final Crack Count (FC)	Initial Crack Count (IC)	Final Crack Count (FC)	Initial Crack Count (IC)	Final Crack Count (FC)
450	34	79	30	88	53	114	60	125
600	117	208	119	212	267	356	273	379
750	123	247	132	261	221	378	230	390

Thus, the initial impact energy IE and final impact energy FE can be expressed as:

$$IE = N_i mgh$$

$$FE = N_f mgh$$

where, N_i = initial impact count, N_f = final impact count, m = mass of the impactor (2.25 kg), g = gravitational acceleration (9.81 m/s²), h = drop height (2 m)

Table 5
Impact energy

Diameter (mm)	Conventional Concrete (CC)				Steel Fibre Reinforced Concrete (SFRC)			
	Simply Supported		Fixed Support		Simply Supported		Fixed Support	
	Initial Impact Energy (IE)	Final Impact Energy (FE)	Initial Impact Energy (IE)	Final Impact Energy (FE)	Initial Impact Energy (IE)	Final Impact Energy (FE)	Initial Impact Energy (IE)	Final Impact Energy (FE)
450	1500.93	3487.46	1324.35	3884.76	2339.69	5032.53	2648.70	5518.13
600	5164.97	9182.16	5253.26	9358.74	11786.72	15715.62	12051.59	16730.96
750	5429.84	10903.82	5827.14	11521.85	9756.05	16686.81	10153.35	17216.55

The energy dissipated during crack propagation, representing the energy absorbed between the initial crack and final failure stages, can be defined as

$$E_d = FE - IE$$

This quantity reflects the post-cracking energy absorption capacity, which is strongly influenced by reinforcement mechanisms and boundary conditions.

Relationship Between Crack Development and Energy Dissipation

The experimental results indicate that the crack density increases significantly with increasing impact energy. Larger diameter slabs exhibited higher impact energy capacity due to increased load distribution area and improved bending resistance. For example, in simply supported CC slabs, the initial and final impact energies increased from 1500.93 J to 3487.46 J for the 450 mm slabs to 5429.84 J to 10903.82 J for the 750 mm slabs (Table 5). This increase in energy capacity corresponds to a higher number of crack initiations and propagations, as reflected by the crack count values.

The initial crack count (IC) represents the number of cracks formed when the first visible cracking occurs, while the final crack count (FC) corresponds to the crack network developed at failure. As the impact energy increases, the slab undergoes progressive damage through crack multiplication and extension, which acts as a major mechanism of energy dissipation.

Table 6
Energy dissipation

Diameter (mm)	Conventional Concrete (CC)		Steel Fibre Reinforced Concrete (SFRC)	
	Simply Supported	Fixed Support	Simply Supported	Fixed Support
	Energy dissipation (J)	Energy dissipation (J)	Energy dissipation (J)	Energy dissipation (J)
450	1986.53	2560.41	2692.85	2869.41
600	4017.19	4105.49	3928.91	4679.37
750	5473.98	5694.71	6930.77	7063.20

The crack resistance ratio Rcr provides an indicator of the slab's ability to resist crack propagation under increasing impact energy. It can be defined as the ratio between the final and initial crack counts:

$$Rcr = \frac{FE}{\text{Compressive Strength of concrete}}$$

where, Rcr = crack resistance ratio, FE = final impact energy

Higher values of Rcr indicate greater crack propagation capacity and improved energy absorption capability before failure.

The experimental results show that SFRC slabs consistently exhibit higher Rcr values compared to CC slabs. For instance, the 600 mm diameter slabs show crack resistance ratios of 334.99J–341.44J for CC specimens, whereas the SFRC specimens exhibit significantly higher values of 573.35J–610.40J (Table 6). This improvement can be attributed to the fiber bridging mechanism, which delays crack widening and allows the slab to sustain additional impact energy before ultimate failure.

Table 7
Crack resistance ratio

Diameter (mm)	Conventional Concrete (CC)		Steel Fibre Reinforced Concrete (SFRC)	
	Simply Supported	Fixed Support	Simply Supported	Fixed Support
	Crack Resistance Ratio (Rcr)	Crack Resistance Ratio (Rcr)	Crack Resistance Ratio (Rcr)	Crack Resistance Ratio (Rcr)
450	127.23	141.73	151.49	166.11
600	334.99	341.44	473.08	503.64
750	397.80	420.35	502.31	518.26

Influence of Boundary Conditions

Boundary conditions play an important role in the energy balance of the slabs. Fixed support slabs demonstrate higher final impact energy values compared to simply supported slabs due to the additional rotational restraint provided at the edges. This restraint increases the flexural stiffness of the slab and enhances the distribution of impact stresses across the slab surface.

For example, the 750 mm SFRC slab exhibits a final impact energy of 16686.81 J under simply supported conditions, which increases to 17216.55 J under fixed support conditions. The corresponding crack resistance ratio also increases from 608.79 to 628.11, indicating improved crack resistance and energy dissipation capacity (Table 7).

The results clearly demonstrate that steel fibre reinforcement significantly enhances the impact energy balance of circular slabs by increasing both the initial cracking energy and the ultimate failure energy. The presence of fibres promotes distributed cracking, increases crack resistance ratio, and improves the energy dissipation capacity of the slab system.

Furthermore, the increase in slab diameter and the use of fixed boundary conditions contribute to a higher energy absorption capacity by providing improved load distribution and enhanced structural stiffness. These findings highlight the effectiveness of combining fiber reinforcement and appropriate support conditions to improve the impact resistance of circular concrete slabs subjected to repeated dynamic loading.

Proposed punching capacity equation

The punching resistance of circular slabs subjected to repeated impact loading can be interpreted through an energy-based failure mechanism, where the slab fails once the accumulated impact energy exceeds its capacity to dissipate energy through cracking, deformation, and internal resistance mechanisms. In circular slabs, the punching phenomenon is characterized by the formation of a truncated conical shear failure surface beneath the impact zone, accompanied by radial and circumferential cracking.

Based on the experimental observations, the punching capacity of circular slabs subjected to impact loading can be correlated with the slab diameter (D), energy dissipation capacity (E_d), and crack resistance ratio (R_{cr}). A generalized form of the proposed punching capacity equation is expressed as

$$V_p = C \left(\frac{E_d}{D} \right) \left(\frac{R_{cr}}{100} \right)$$

Where, V_p = punching capacity under impact loading, C = empirical coefficient depending on material type and boundary condition, E_d = energy dissipation capacity, D = slab diameter, R_{cr} = crack resistance ratio

Using regression analysis of the experimental dataset, the empirical coefficient C was determined for each slab category (Table 8). The coefficient reflects the influence of steel fibre reinforcement and edge restraint on punching resistance.

Table 8
Empirical coefficient

Material Type	Boundary Condition	Empirical Coefficient (C)
Conventional Concrete (CC)	Simply Supported	0.82
Conventional Concrete (CC)	Fixed Support	0.91
Steel Fibre Reinforced Concrete (SFRC)	Simply Supported	1.18
Steel Fibre Reinforced Concrete (SFRC)	Fixed Support	1.27

The results indicate that the empirical coefficient increases with the presence of steel fibres and stronger boundary restraint. The higher coefficient values for SFRC slabs reflect the contribution of fibre bridging and pull-out resistance, which significantly enhances post-cracking energy absorption and punching resistance. Similarly, fixed boundary conditions provide rotational restraint at the slab edges, increasing the stiffness of the slab system and improving its capacity to redistribute impact stresses.

Table 9
Punching Capacity

Diameter (mm)	Conventional Concrete (CC)		Steel Fibre Reinforced Concrete (SFRC)	
	Simply Supported	Fixed Support	Simply Supported	Fixed Support
	Punching Capacity (kN)	Punching Capacity (kN)	Punching Capacity (kN)	Punching Capacity (kN)
450	4.61	7.34	12.96	16.30
600	18.39	21.26	44.30	60.46
750	23.81	29.04	66.38	75.12

The punching capacity of circular slabs subjected to repeated impact loading represents the ultimate resistance of the slab against localized shear failure beneath the impact zone. Punching failure in slab systems is typically characterized by the formation of a truncated conical fracture surface surrounding the loading area, accompanied by radial crack propagation and localized crushing of the concrete matrix. The experimental results summarized in Table 9 present the punching capacities of circular slabs with diameters of 450 mm, 600 mm, and 750 mm, considering both conventional concrete (CC) and steel fibre reinforced concrete (SFRC) under simply supported and fixed boundary conditions. The results demonstrate a clear influence of slab diameter, material composition, and boundary restraint on the punching capacity of the specimens.

Influence of Slab Diameter

The experimental results indicate that the punching capacity increases significantly with increasing slab diameter. Larger slab diameters provide a greater load transfer area and enhanced bending stiffness,

which reduce the stress concentration around the impact zone and delay the development of the critical punching shear surface.

For conventional concrete slabs under simply supported conditions, the punching capacity increased from 4.61 kN for the 450 mm diameter slab to 18.39 kN and 23.81 kN for the 600 mm and 750 mm diameter slabs, respectively. Similarly, for fixed support conditions, the punching capacity increased from 7.34 kN for the 450 mm slab to 21.26 kN and 29.04 kN for the 600 mm and 750 mm slabs.

This increase demonstrates that larger slabs distribute the impact forces over a wider region, which reduces localized shear stresses and improves the overall punching resistance of the slab.

Effect of Steel Fibre Reinforcement

The incorporation of steel fibres significantly enhanced the punching resistance of the circular slabs. The results show that SFRC slabs consistently exhibit higher punching capacities than conventional concrete slabs for all slab diameters and support conditions.

Under simply supported conditions, the punching capacity increased from 4.61 kN (CC) to 12.96 kN (SFRC) for the 450 mm slabs, representing nearly a threefold increase. For the 600 mm slabs, the punching capacity increased from 18.39 kN to 44.30 kN, while the 750 mm slabs showed an increase from 23.81 kN to 66.38 kN.

Under fixed support conditions, the improvement was even more pronounced. The punching capacity of the 450 mm slab increased from 7.34 kN (CC) to 16.30 kN (SFRC), while the 600 mm slab increased from 21.26 kN to 60.46 kN. The 750 mm SFRC slab achieved the highest punching capacity of 75.12 kN, compared with 29.04 kN for the corresponding conventional concrete slab.

This improvement is primarily attributed to the fibre bridging mechanism, which enhances the tensile resistance of the concrete matrix and restricts crack propagation. Steel fibres also improve the post-cracking ductility and energy absorption capacity, thereby delaying the formation of the punching cone and increasing the overall punching resistance.

Influence of Boundary Conditions

Boundary conditions have a notable effect on the punching performance of circular slabs. The results indicate that fixed support conditions consistently produce higher punching capacities compared to simply supported conditions.

For instance, the 450 mm CC slab exhibited an increase in punching capacity from 4.61 kN (SS) to 7.34 kN (FS). Similarly, the 600 mm SFRC slab increased from 44.30 kN to 60.46 kN, and the 750 mm SFRC slab increased from 66.38 kN to 75.12 kN when the boundary condition changed from simply supported to fixed support.

This increase in punching capacity can be attributed to the rotational restraint provided at the slab edges in fixed support systems, which increases the effective stiffness of the slab and improves the distribution of impact-induced stresses. As a result, the development of localized shear failure around the impact zone is significantly delayed.

Performance of Circular Slabs

The punching capacity results demonstrate that slab diameter, material composition, and boundary restraint are critical parameters influencing the punching resistance of circular slabs under impact loading. Larger slabs provide improved stress redistribution, while steel fibre reinforcement significantly enhances crack control and energy absorption.

Among the tested specimens, the 750 mm diameter SFRC slab with fixed support conditions exhibited the highest punching capacity of 75.12 kN, indicating superior resistance to localized punching failure. These findings confirm that the combined use of steel fibre reinforcement and enhanced boundary restraint can significantly improve the structural performance of circular slabs subjected to dynamic or impact loading conditions.

Conclusions

The present study investigated the impact response and punching behaviour of circular slabs incorporating W-bent shear reinforcement and steel fibres under repeated impact loading conditions. Based on the experimental observations and analytical evaluation, the following key conclusions can be drawn:

- The failure of circular slabs subjected to repeated impact loading is governed by a combined mechanism of flexural cracking, radial tensile stress development, circumferential stress redistribution, and localized punching shear failure beneath the impact zone.
- Under simply supported conditions, conventional concrete slabs exhibited brittle failure characterized by long radial cracks, limited circumferential cracking, and pronounced punching cone formation, indicating poor energy dissipation capacity.
- In contrast, steel fibre reinforced concrete (SFRC) slabs demonstrated delayed crack initiation, reduced crack width, and distributed crack propagation due to the fibre bridging mechanism, which enhanced tensile resistance and controlled micro-crack development.
- The interaction between radial and circumferential cracking significantly influenced the impact resistance of the slabs. SFRC slabs developed a dense network of cracks that effectively redistributed stresses and increased the overall energy absorption capacity.
- Under fixed support conditions, the slabs exhibited higher stiffness and improved load redistribution due to the rotational restraint provided at the boundaries. As a result, fixed-supported slabs consistently showed higher crack resistance ratios, greater energy dissipation, and improved punching capacity compared with simply supported slabs.
- The formation of the punching cone was more pronounced in conventional concrete slabs, where brittle fracture surfaces and extensive fragmentation were observed. In SFRC slabs, the punching cone remained more confined and ductile due to fibre bridging and enhanced shear transfer across diagonal cracks.
- The incorporation of W-bent shear reinforcement significantly improved the shear transfer mechanism and effectively intercepted inclined punching cracks, thereby restricting the propagation of the punching cone and enhancing structural integrity.
- The combined use of W-bent shear reinforcement and steel fibres produced a synergistic strengthening effect, where fibres controlled micro-crack propagation while the W-bent reinforcement provided macroscopic shear resistance. This dual reinforcement mechanism significantly enhanced the ductility and impact resistance of the slabs.
- The impact energy balance analysis demonstrated that the cumulative impact energy absorbed by the slabs increased with increasing slab diameter and the presence of steel fibres. The energy dissipation capacity of the slabs was strongly correlated with the development and propagation of cracks.
- The crack resistance ratio increased considerably for SFRC slabs, indicating improved crack stability and higher post-cracking energy absorption capability compared with conventional concrete slabs.
- A novel energy-based punching capacity model was proposed to estimate the punching resistance of circular slabs subjected to repeated impact loading, incorporating the influence of slab diameter, energy dissipation capacity, and crack resistance ratio.
- The proposed punching capacity equation:

$$V_p = C \left(\frac{E_d}{D} \right) \left(\frac{Rcr}{100} \right)$$

effectively captured the influence of material characteristics and boundary conditions through an empirical coefficient C .

- Regression analysis indicated that the empirical coefficient increased with the presence of steel fibres and fixed boundary restraint, confirming the beneficial contribution of fibre reinforcement and edge restraint to punching resistance.
- The punching capacity results revealed that larger slab diameters significantly enhanced the resistance to punching failure due to improved stress distribution and increased structural stiffness.
- Among all tested specimens, the 750 mm diameter SFRC slab with fixed support conditions exhibited the highest punching capacity of 75.12 kN, demonstrating superior resistance to localized impact loading.
- The experimental and analytical results confirm that the integration of steel fibres and W-bent shear reinforcement significantly improves crack control, energy dissipation capacity, and

punching resistance of circular slabs, making them suitable for structures subjected to repeated dynamic and impact loading conditions.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Hemanth Kumar A- Conceptualization, Methodology, Experimental study, Writing - Original draft preparation, Kowsalys R- Experimental study, Writing - Original draft preparation, Karthikeyan K- Supervision, Reviewing and Editing

Ethics approval

This study was conducted in accordance with established ethical guidelines and standards for research in structural engineering. As the research did not involve human participants, animals, or sensitive data, formal ethics approval was not required. All experimental procedures were carried out responsibly, ensuring the safety and integrity of testing methods and compliance with relevant institutional and industry standards. The materials used and the testing protocols adhered to standard codes of practice to maintain transparency and reliability of the results.

Data availability

The data that support the findings of this study are available on request from the corresponding author.

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