International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 01 | Jan 2026 www.irjet.net p-ISSN: 2395-0072

Experimental Study on Low-Velocity Impact Behaviour of SFRC Slabs Reinforced with HYSD, Hybrid and GFRP Bars

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Abstract- *Impact loading at low velocity is one of the important design considerations for reinforced concrete elements under accidental and service-level dynamic actions. The paper reports an experimental study on the impact performance of steel Fibre reinforced concrete (SFRC) slabs internally reinforced with HYSD, hybrid (HYSD+GFRP), and GFRP bars in ambient temperature exposure. A total of six square slab specimens of size 500 × 500 × 50 mm were prepared using M30 grade concrete; two specimens for each type of reinforcement, with and without 0.65% steel Fibre volume fraction. All slabs were internally reinforced with a single layer of reinforcement near the tension face and tested under repeated low-velocity impact loading from a drop weight of 10 kg released from a height of 1 m. The impact performance was assessed in terms of the number of blows at which the first visible crack appeared and the total number of blows withstood prior to failure. The test results show that HYSD bar-reinforced slabs have the best impact performance, with hybrid reinforcement closely following, while GFRP-reinforced slabs have comparably poorer performance. Steel Fibres further enhance cracking resistance and also increase post-crack energy absorption amongst the types of reinforcements. Hybrid reinforcement tends to give a balanced response in terms of combining the toughness of steel and the corrosion resistance of GFRP. The test results thus demonstrate the potential of addition of Fibres and hybridization strategies to improve the impact performance of concrete slabs under low-velocity impact loading conditions.*

Key Words: **Steel Fibre Reinforced Concrete (SFRC), Glass Fibre Reinforced Polymer (GFRP), impact loading, residual strength, energy absorption, crack propagation, bond degradation, impact resistance**.

1. INTRODUCTION

Concrete slabs in civil and industrial structures are often subjected to low-velocity impact load arising from falling objects, vehicular movements, industrial accidents, and extreme events. Such loading results in highly localized damage, degradation in stiffness properties, and progressive cracking, and is not sufficiently elicited through conventional static design procedures. Hence, a large number of experiments have been conducted and numerical investigations done to understand the impact response of reinforced concrete slabs.

A few researchers have explored the influence of reinforcement detailing and slab parameters on impact performance. Yue Wang et al. (2021) and Senthil et al. (2024) found that the peak impact force and displacement and mode of failure were significantly controlled by the thickness of the slab and the location of impact, while an increase in reinforcement ratio alone allows only limited improvement because the damage mechanism is dominated by concrete. Reinforcement spacing has been experimentally and numerically studied by Tolga Yılmaz et al. (2019), who demonstrated that closer spacing of the bar effectively restricts deflection and propagation of cracks under drop-weight impact loading.

With the purpose of enhancing impact resistance, steel fibre reinforced concrete has gained significant attention. Experimental works by Tekleab and Wondimu (2022) and Vivas et al. (2020) showed that steel fibres enhance crack control, toughness, post-cracking energy absorption, and reduction of spalling and punching damage. Similarly, Reddy et al. (2024) pointed out the synergistic effect resulting from hybrid fibre systems, which exhibited high mechanical properties improvement and outstanding impact resistance when compared to plain concrete.

Over the last couple of decades, there has been interest in non-corrosive reinforcement as an alternative to traditional steel reinforcement. Experimental and numerical studies conducted by Maher A. Adam et al. (2021) and Hamid Sadraie et al. (2019) demonstrated that GFRP-reinforced slabs develop larger deflections and more dispersed cracking under impact, attributed to the lower elastic modulus of GFRP. However, adequate impact resistance may be achieved by adopting an appropriate reinforcement configuration. Further numerical studies by Liu Jin et al. (2023) have demonstrated that during impact, concrete absorbs most of the energy, while GFRP reinforcement contributes insignificantly to energy dissipation but rather to post-impact integrity.

Hybrid reinforcement systems are being presented to combine the advantages of steel and GFRP reinforcement. Tohid Mousavi and Erfan Shafei demonstrated in 2019 that

the use of hybrid FRP steel reinforcement increases impact resistance because of balancing stiffness, ductility, and energy absorption. It leads to a more uniform crack distribution with lower residual damage compared to conventional reinforcement.

Despite these, the majority of current research concentrates on steel-reinforced slabs, GFRP-reinforced slabs, or fibre-reinforced concrete separately. Very few comparative experimental tests have been conducted at ambient temperature regarding low-velocity impact performance between HYSD steel, hybrid reinforcement (HYSD + GFRP), and GFRP-reinforced SFRC slabs under identical conditions. The combined effects of reinforcement type and steel fibre addition on cracking resistance, number of blows to failure, ductility, and energy absorption capacity have also not been adequately addressed.

Therefore, the current study investigates experimentally the low-velocity impact behaviour of SFRC slabs reinforced with HYSD steel, hybrid HYSD + GFRP, and GFRP bars. The study focuses on some of the main impact response parameters such as cracking behavior, peak impact response, ductility, and energy absorption characteristics, hence providing experimental evidence for the development of impact-resistant and durable concrete slab systems.

2. MATERIALS AND MIX PROPORTIONS

The experimental program involved preparation and testing of six reinforced concrete slab specimens which included three different reinforcement systems, that were HYSD steel, hybrid (HYSD + GFRP), and GFRP reinforcements cast with the help of two concrete mixes, including normal concrete (NC) and a steel fibre reinforced concrete (SFRC). The aim was to determine the effect of the type of reinforcement and the incorporation of fibre on the effect performance of slab elements. All mixes were made using Ordinary Portland Cement (OPC) 53 grade that conformed to the IS 12269. Fine aggregates (Manufactured sand M-sand) with specific gravity of 2.65 were taken, and crushed granite coarse aggregate with a maximum nominal size of 20 mm was taken. All the aggregates qualified the grading requirements of the IS 383 and were kept dry to allow uniformity in the water-cement ratio during batching. NC and SFRC mixes were adjusted in a manner that they would gain a distinguishing compressive strength of 30 MPa (M30 grade) in 28 days and water-cement ratio remained constant at 0.43. In the case of SFRC mix, the volume fraction of crimped steel fibre was 0.65 percent, a value chosen to improve the post-cracking behaviour, toughness and be able to absorb energy during impact loading. The fibres were 67 in aspect ratio with the capability to bridge the crack and delay crack propagation effectively. Both mixes were added with a normal consistency plasticizer that met the requirements of IS 9103 to enhance workability and even distribution of fibres. The reinforcement was differentiated by the type of specimen. The single-layer constructions were built with HYSD steel bars, GFRP bars and hybrid reinforcement (HYSD + GFRP) which were installed close to the tension face. Layouts all the reinforcement layouts used 6 mm diameter bars and centre-to-centre spacing of 75 mm longitudinally and transversely. The GFRP bars were in compliance with the specifications of IS 18255: 2023, and the tensile strength of the bar was averaged to 600700 Mpa with a modulus of elasticity ranging between 40-50Gpa and also HYSD bars offered ductile behaviour and underwent a high plastic deformation before yielding. Each of the slab specimens was cast with a consistent size of 500 mm x 500 mm x 50 mm and a nominal cement cover of 15mm was made so that the reinforcement was embedded in the shallow concrete depth. Each reinforcement category had a slab cast with NC and slab with SFRC each, which allowed making a direct comparison of the impact resistance effect of the incorporation of steel fibres.

The mix proportions adopted for M30 concrete used in the study are summarized in Table 2.1.

Table 2.1: Mix Proportion

Water (l/m^3)	**Cement** (kg/m^3)	**Fine aggregate** (kg/m^3)	**Coarse aggregate** (kg/m^3)	**Dosage of Admixture** (kg/m^3)
148	345	823	1104	17.25
0.43	1.00	2.38	3.20	0.05

3. EXPERIMENTAL PROGRAM

The objective of the experimental program was to examine the behaviour of low-velocity impacts of SFRC slabs reinforced with various reinforcement systems in ambient temperature conditions. Six slab specimens with and without steel Fibre were cast and tested and included three reinforcement types including HYSD, hybrid (HYSD+GFRP) and GFRP. All the specimens were experimented at room temperature under repeated drop-weight impact loading test.

3.1 Specimen Details and Identification

All slab specimens measured 500 mm × 500 mm × 50 mm, with a single reinforcement layer placed near the tension face. The slabs were designated as shown in Table 3.1 based on reinforcement condition.

Table 3.1: Specimen I'd of Slabs

Specimen ID	Reinforcement	Fibres
H-NC	HYSD	No Fibre
H-SFRC	HYSD	0.65% Steel Fibre
HG-NC	HYSD+GFRP	No Fibre
HG-SFRC	HYSD+GFRP	0.65% Steel Fibre
G-NC	GFRP	No Fibre
G-SFRC	GFRP	0.65% Steel Fibre

3.2 IMPACT TEST SETUP

The impact behaviour was evaluated using a vertical drop-weight impact testing apparatus. A 10 kg steel impactor was repeatedly dropped from a height of 1 meter onto the centre of each slab to induce progressive damage.

- Impactor Mass: 10 kg
- Drop Height: 1.0 m
- Impact Energy (per blow): E = mgh ≈ 98 Joules
- Support System: Four-edge fixed frame with a clear span of 450 mm
- Damage Tracking: Number of blows to first visible crack and ultimate failure

A simple schematic of the impact setup is shown in Fig-3.1.

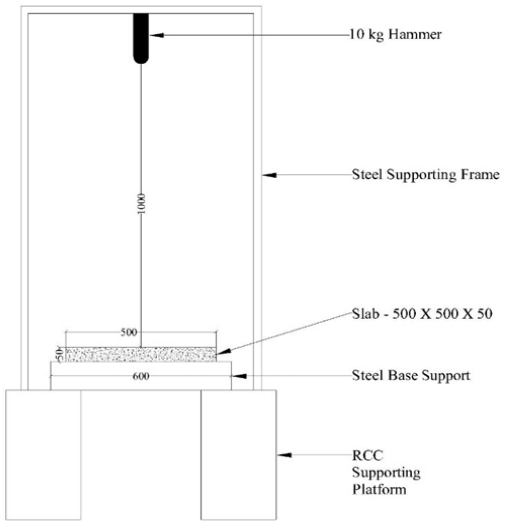

Fig-3.1: Test Setup of Drop Weight Impact Test

During each drop, the impactor was manually guided to maintain a consistent strike position. After every blow, the slab was visually inspected for surface cracks, edge failure, spalling, delamination, and penetration. Crack patterns were traced using a permanent marker to record progressive damage characteristics.

3.3 INSTRUMENTATION AND MEASUREMENTS

The damage-based and energy-based performance measures were considered to be the primary measure of impact response of the slab specimens without explicit impact load and displacement time history. The process of watching the progress of damage during the testing process used visual inspection and photographic documentation. The patterns of crack initiation, crack propagation, surface spalling and failure patterns were captured using a high-resolution digital camera following every impact blow.

The key response parameters considered in the present study were:

- Number of blows required to initiate the first visible crack
- Number of blows sustained until ultimate failure
- Total energy absorbed by the slab specimen
- Qualitative assessment of stiffness degradation based on progressive damage evolution
- Crack propagation characteristics and surface deterioration patterns

The energy absorption of each specimen was evaluated in terms of the cumulative impact energy sustained until failure. Since the mass of the drop hammer and the drop height were kept constant throughout the experimental program, the impact energy imparted per blow was assumed to be constant and was calculated using:

$$E_b = mgh$$

Where E_b is the impact energy per blow (J), m is the mass of the hammer (kg), g is the acceleration due to gravity (9.81 m/s^2), and h is the drop height (m). The total energy absorbed by a specimen, E_{total} was then computed as:

$$E_{total} = N_f \times E_b$$

Where N_F is the number of blows sustained until ultimate failure. This approach enabled a consistent and objective comparison of the impact energy dissipation capacity of different slab specimens.

The test was extended until the specimen showed loss of structural integrity, which was the development of through-thickness cracking, extreme surface crushing in the impact location, punching-type failure, or obvious rupture of reinforcement in the tension area. This methodology enabled to conduct a credible evaluation of impact resistance and prioritize to experimentally significant and practically relevant performance indicators.

4. RESULTS AND DISCUSSIONS

The performance of the SFRC slabs reinforced with various reinforcement methods was tested on the basis of the blows that are needed to cause the first visible crack and the number of blows that the structure can withstand till it becomes fractured. The findings give an idea about the

impact of type of reinforcement and steel fibre inclusion on low-velocity impact resistance.

Table 4.1 – Number of Blows to First Crack and Ultimate

Specimen ID	First Crack Blows	Final Failure Blows
H-NC	10	22
H-SFRC	16	30
HG-NC	8	20
HG-SFRC	13	26
G-NC	6	16
G-SFRC	10	21

4.1 Number of Blows to First Crack

The number of blows taken to make the first visible crack gives a measure of the initial stiffness and resistance to cracking of the slab system when subjected to repeated impact load. The findings indicate that the HYSD-reinforced slabs were the most resistant to crack initiation as the H-SFRC and H- NC needed 16 and 10 blows respectively. This is mostly related to the fact that the reinforcement is made of steel, which has a higher modulus of elasticity and a ductile nature, thus is able to inhibit the development of tensile stress in the concrete matrix.

The slabs reinforced with hybrid proved to be intermediate concerning cracking, where HG-SFRC and HG-NC first recorded a crack at 13 and 8 blows, respectively. The steel also helped in enhanced crack control of the hybrid system in comparison to GFRP-reinforced slabs entirely and the lower rigidity of GFRP led to tensile cracking earlier than HYSD systems.

GFRP-reinforced slabs demonstrated minimum resistance to crack formation, where G-NC and G-SFRC slabs crack after receiving 6 and 10 blows respectively. Linear elasticity and the lesser elasticity of GFRP bars was a factor of increased tensile strain in concrete, which favors a faster crack development.

The use of steel fibre throughout the reinforcement types enhanced the blows to first-crack, which confirmed their ability to slow down the occurrence and growth of micro-cracks.

4.2 Number of Blows to Ultimate

The damage tolerance and after crushing resistance of slab specimens to repeated impact loading are the number of blows taken to ultimate failure. Slabs that were reinforced with HYSD showed better resistance to failure with H-SFRC taking 30 blows as compared to H-NC taking 22 blows.

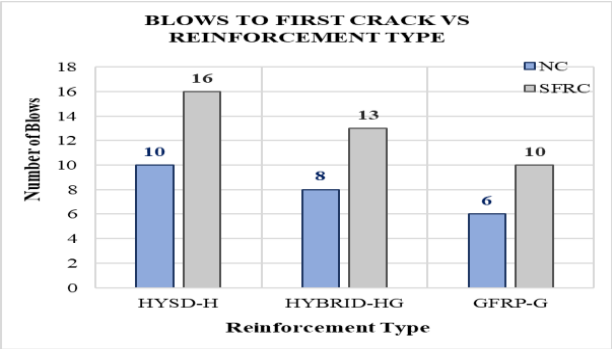

Chart-1: Number of Blows to First Crack Vs Reinforcement Type

Gradual stiffness degradation and progressive energy dissipation before failure were allowed by the capability of the steel reinforcement to go through plastic deformation. Hybrid-reinforced slabs withstood 26 and 20 blows (HG–SFRC) and (HG–NC), respectively, which suggests that they have greater damage tolerance than GFRP-reinforced slabs but are not as effective as HYSD-reinforced systems.

The reinforcement of the steel plus the GFRP allowed the redistribution of stress partially, which led to both the post-cracking behaviour and the delayed failure. Slab reinforced with GFRP was most sensitive to failures with GFRP, G-NC and G-SFRC collapsing at 16 and 21 blows, respectively.

There were no yielding characteristics and brittle rupture characteristics of GFRP bars which restricted post-cracking energy dissipation, causing swifter stiffness decay.

However, incorporation of steel fibre vastly enhanced the number of blows to failure in all the types of reinforcements because of improved crack bridging and structural integrity during multiple impacts loading.

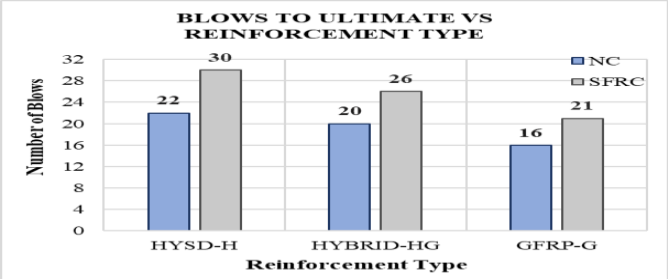

Chart-2: Number of Blows to Ultimate Vs Reinforcement Type

4.3 Total Energy Absorption

The total energy absorbed by the slab specimens was evaluated as the cumulative impact energy sustained until final failure. The results indicate that the reinforcement

system and the incorporation of steel fibres significantly influence the impact energy dissipation capacity of concrete slabs.

Among all specimens, H–SFRC exhibited the highest total energy absorption (2943 J), followed by H–NC (2158 J), demonstrating the superior damage tolerance of HYSD-reinforced slabs. The enhanced performance is attributed to the ductile yielding behaviour and higher stiffness of steel reinforcement, which enabled progressive damage accumulation under repeated impact loading. Hybrid-reinforced slabs showed intermediate energy absorption capacities, with HG–SFRC (2551 J) and HG–NC (1962 J) sustaining lower total energies compared to HYSD-reinforced slabs but significantly higher energies than GFRP-reinforced slabs. This response reflects the combined contribution of steel and GFRP reinforcement, where steel facilitated energy dissipation while GFRP maintained structural continuity. GFRP-reinforced slabs absorbed the lowest total impact energy, with G–NC and G–SFRC recording 1569 J and 2060 J, respectively. The relatively lower energy absorption is associated with the linear elastic response and brittle failure characteristics of GFRP bars, which limited post-cracking energy dissipation. However, the inclusion of steel fibres resulted in a noticeable increase in total absorbed energy across all reinforcement types, particularly for GFRP-reinforced slabs, where fibres compensated for the limited ductility of the reinforcement.

Overall, the results confirm that steel fibres enhance the post-cracking energy absorption capacity, while reinforcement type governs the ultimate energy dissipation potential of concrete slabs subjected to repeated low-velocity impact loading.

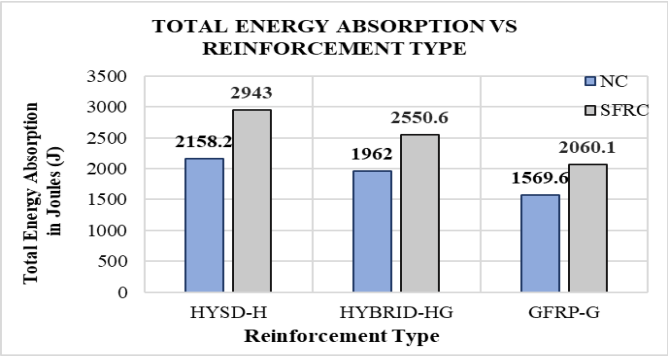

Chart-3: Total Energy Absorption Vs Reinforcement Type

5. CONCLUSIONS

This paper experimentally examined the repeated low impact-velocity behaviour of concrete slabs reinforced with HYSD steel, hybrid reinforced (HYSD + GFRP) and GFRP bars, which were cast in normal concrete (NC) and steel fibre reinforced concrete (SFRC). The following conclusions are made based on the results obtained:

1. This reinforced system had a strong effect on the impact response of slabs. Slabs reinforced with HYSD showed the greatest ability to endure the cracking process and final failure, followed by hybrid and GFRP-reinforcement slabs.

2. Slabs reinforced with HYSD steel took the longest number of blows to first crack and longest number of blows to fail which can be explained by the fact that steel reinforcement is stiffer and also ductile in its yielding behaviour.

3. The hybrid-reinforced slabs showed intermediate results, which implies that the mixed application of steel and GFRP reinforced slabs helps redistribute stress partially, and enhances the post-cracking capacity, which is superior to fully GFRP-reinforced slabs.

4. Compared to other reinforcement types, GFRP-reinforced slabs were found to be relatively less resistant to repeated impact loading because of the linear elastic reaction and brittle failure nature of GFRP bars which restrained the post-cracking energy dissipation.

5. All slab specimens were considerably improved in impact performance due to the addition of steel fibre. The slabs of SFRC always had significantly later crack initiation, more blows to failure and larger total energy absorption when compared to their NC counterparts.

6. The reinforcement ductility as well as fibre inclusion controlled total energy absorption. The highest cumulative impact energy was absorbed in HYSD-reinforced SFRC slabs whereas fibre addition was very effective to enhance the post-cracking response of hybrid and GFRP-reinforced slabs.

In general, the findings validate that steel fibres are important in improving post-cracking toughness, and the selection of the reinforcement system also dictates the total impact resistance and the energy-dissipation ability of post-cracking concrete slabs under repeated low-velocity impact loading.

6. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

1. HYSD-reinforced SFRC slabs are recommended for structural applications where repeated low-velocity impact loading is anticipated, owing to their superior cracking resistance, damage tolerance, and energy absorption capacity.

2. Hybrid reinforcement systems may be considered as a viable alternative in situations where a balance between impact resistance and durability is required, particularly in aggressive environments.

3. The use of GFRP reinforcement in impact-prone structures should preferably be accompanied by steel fibre incorporation to compensate for the limited ductility and energy dissipation capacity of GFRP bars.

4. Steel fibre inclusion is recommended for impact-resistant slab design irrespective of reinforcement type, as it consistently improves crack control and post-cracking performance.

5. Future research should focus on the effects of fibre volume fraction, reinforcement ratio, slab thickness, and elevated temperature exposure on repeated impact behaviour, supported by numerical simulations to extend the applicability of experimental findings.

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