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ON THE IMPACT PERFORMACE AND CRACK BEHAVIOR OF STEEL-FIBER REINFORCED CONCRETE BEAMS WITH SHCC AND UHPC STRENGTHENING LAYERS

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Abstract. Fiber-reinforced concrete (FRC) is widely used in structures subjected to high strain-rate loadings, such as military facilities, earthquake-resistant buildings, hydroelectric dams, and industrial and highway pavements. Despite significant advances in recent decades, certain structural behaviors remain underexplored, particularly when combining different concretes, such as thin strengthening layers with distinct characteristics, and incorporating different fibers like strain-hardening cementitious composites (SHCC) or even ultra-high-performance concrete (UHPC). Additionally, the application of carbon textiles in these strengthening layers warrants further investigation. This study aims to evaluate the impact resistance of steel fiber reinforced concrete (SFRC) short beams under flexural impact loading, with the addition of SHCC, UHPC, and UHPC layers reinforced with carbon textiles on the tensile face of the beams. The mechanical performance of the composite specimens was assessed through flexural impact tests at varying energy levels. A custom-built drop-weight testing machine, developed at the Structures and Materials Laboratory at PUC-Rio, was used for this purpose. Furthermore, Digital Image Correlation (DIC), in conjunction with high-speed cameras, was employed to measure energy absorption, deformation, and crack propagation in the beams under different configurations and impact energies. The results demonstrated that the SHCC layers significantly improved energy absorption and reduced crack formation. At the same time, the UHPC composites, particularly those reinforced with carbon textiles, exhibited enhanced ductility, energy absorption capacity, and crack control under impact loading. These findings suggest that the improved performance of these composite materials can reduce future repair and reinforcement needs for structures exposed to such demanding conditions.

1 INTRODUCTION

Concrete structural components are frequently exposed to impact loading of varying intensities and durations throughout their service life. Since materials respond differently to dynamic loads compared to static loads, understanding key properties—such as energy absorption, stress-strain relationships, dynamic strength, damage propagation, and the mechanical behavior of concrete in structural applications—is essential [1].

Incorporating fibers into concrete is a straightforward and cost-effective method to enhance its performance under dynamic loading [2]. This modification addresses the material's inherent brittleness, improving its resistance to impact and enhancing durability. Fibers facilitate better stress transfer within the concrete matrix, enabling fiber-reinforced concrete (FRC) to withstand occasional impacts and overloads more effectively than traditional concrete, with reduced damage [3].

A range of impact tests has been developed to assess the behavior of Steel Fiber Reinforced Concrete (SFRC) under dynamic loads. These tests are categorized based on the impact mechanism and monitored parameters. They can be classified according to the energy source, including potential energy-based tests [4, 5], kinetic energy-based methods [6], high-strain-rate testing using servo-controlled actuators [7], and shock wave propagation tests [8].

In efforts to further improve the impact resistance of concrete, the application of thin layers of high-performance cement-based composites has proven effective. These layers dissipate or absorb impact energy transferred to the structure, mitigating damage from high-strain loading conditions [9]. Although these composites are more expensive than conventional concrete, they can be strategically applied to critical areas of a structure, optimizing performance while managing costs.

Strain Hardening Cementitious Composites (SHCC), also known as Engineered Cementitious Composites (ECC), is an example of such high-performance materials. SHCC is a highly ductile composite designed using micromechanics and mineral additives combined with a substantial volume of polymeric microfibers. This unique composition allows SHCC to sustain tensile strains ranging from 2% to 10% [10]. The loading rate significantly influences the mechanical performance of SHCC. Under higher loading rates, particularly in impact scenarios, SHCC exhibits increased strength but reduced deformation capacity. Research indicates that while stiffness, first crack load, ultimate strength, and interface bond improve with higher loading rates, the material's deformation capacity diminishes [11].

However, challenges exist in applying SHCC as a repair material, primarily related to achieving a strong bond with the existing concrete substrate. Factors such as the SHCC preparation method, substrate surface roughness, surface treatments, and concrete strength influence bond quality [11, 12]. Studies [13, 14] have shown that adhesion improves with increased concrete strength, particularly when the surface roughness is up to 4 mm; beyond this threshold, additional improvements in adhesion become negligible. Conversely, research [15] suggests that smoother surfaces may minimize small crack formation, while rougher surfaces can promote a single macrocrack, potentially leading to premature failure. This indicates that a smoother interface may better facilitate load redistribution and strain-hardening behavior in SHCC applications [16].

Another promising strengthening material is Ultra-High-Performance Concrete (UHPC), an advanced cement-based composite engineered for superior mechanical and durability properties. UHPC is formulated with cement, fine sand, microsilica, water-reducing agents, and a very low water-to-binder ratio, often incorporating short steel fibers for enhanced ductility. UHPC typically achieves compressive strengths exceeding 120 MPa [17].

The dense microstructure of UHPC significantly improves its resistance to chemical and physical deterioration, substantially enhancing structural durability and service life. Its low shrinkage properties make it an excellent choice for non-shrink grout applications. Furthermore, UHPC enables the design of thinner structural elements, offering aesthetic flexibility and facilitating the creation of more complex architectural forms [18].

The combination of carbon textile layers embedded within the UHPC layer (TUHPC) further enhances the material's ultimate stress and strain capacity, improving impact resistance and potentially extending the structure's durability [19,20].

This study aims to examine the crack formation, propagation, and failure modes in SFRC short beams strengthened with 25 mm layers of SHCC, UHPC, and carbon textile-reinforced UHPC. This research emphasizes cost-effectiveness in the strengthening process under impact loading conditions while evaluating the materials' impact resistance in terms of crack opening and failure modes.

2 MATERIALS AND METHODS

2.1 Materials and mixing design

In this study, SFRC short beams were used as reference under impact loading. Moreover, additional SFRC short beams were reinforced on the bottom surface with a thin layer of SHCC, UHPC, or TUHPC to evaluate the contribution of each combination under impact loading.

The self-compacting SFRC was produced using a set of materials and following strict methods and procedures to ensure optimal performance. The primary binder was CEM III/A cement, conforming to EN 197-1 [21], supplemented by silica fume with a BET surface area of 19 m^2/g as a secondary cementitious material. Natural sand, with a maximum particle size of 4.75 mm and a fineness modulus of 2.58, served as the fine aggregate, while coarse aggregate with a maximum size of 12.5 mm was used. The mix also included ADVA® 753 superplasticizer and MiraSet® 818 polyfunctional additives, both supplied by GCP Applied Technologies, to enhance workability and performance. Hooked-end steel fibers (Dramix® 3D 65/35 BG, Belgo Bekaert) with a length of 35 mm, an aspect ratio of 65, and a tensile strength of 1345 MPa were incorporated into the mix to improve ductility and impact resistance. The SFRC mix design details are presented in Table 1.

The SFRC mixing process was conducted in a 600-liter planetary mixer, following a structured procedure to ensure uniformity. The process involved: (a) combining sand and coarse aggregate with 70% of the mixing water, (b) adding silica fume and cement, (c) incorporating the remaining 30% of water along with the additives, (d) introducing steel fibers, and (e) completing the final mixing to ensure a homogeneous matrix with even fiber distribution. One side of the short-beam molds was treated with a retarder release agent (Ortolan-SR, MC-Bauchemie) to enhance bonding with the strengthening layers, which inhibited cement hydration on the contact surface. This treatment exposed aggregates and fibers, creating a roughened surface for improved mechanical interlock.

Table 1: Mix proportion of the designed SFRC, SHCC and UHPC (kg/m^3). Fiber proportion for the SHCC and UHPC are presented in volumetric percentage based on the total concrete volume.

Material	Mixture proportions		
	SFRC	SHCC	UHPC
Cement	577	505	800
Silica	66	-	80
Fly ash	-	621	80
Sand	668	536	536
Coarse aggregate	577	-	-
Water	300	336	166
Superplasticizer	2.5	12	20
Polyfunctional	2.5	-	-
Steel fiber	40	-	2%*
PVA fiber	-	2%*	-
VMA	-	1	-
Quartz	-	-	200

After mixing, short beams and cylinders were cast and covered with plastic film to minimize water loss and drying shrinkage. Specimens were demolded after 48 hours and cured under controlled humidity and temperature conditions until reaching 28 days of age. Cylindrical specimens (200 mm in height and 100 mm in diameter) exhibited a compressive strength of 34.7 MPa and a Young's modulus of 33.7 GPa.

The Strain-Hardening Cementitious Composite (SHCC) matrix was formulated with CEM I cement (as per EN 197-1 [21]), fine sand (particle size: 0.075–0.212 mm), fly ash, a superplasticizer, and a viscosity-modifying agent (VMA). Polyvinyl alcohol (PVA) fibers (Kuralon^{TM} KII – REC15, Kuraray), characterized by a length of 12 mm, an aspect ratio of 300, and a tensile strength of 1600 MPa, were used to impart strain-hardening behavior and enhance tensile performance. Detailed proportions of these materials are provided in Table 1.

The SHCC mixing process followed a systematic five-step protocol in a 20-liter planetary mixer to ensure consistent material properties. The steps included: (a) dry mixing of cement, sand, mineral additives, and VMA, (b) gradual addition of water and superplasticizer, (c) thorough blending of all materials, (d) incorporation of PVA fibers, and (e) final mixing to achieve uniform fiber dispersion.

After mixing, a 25 mm thick SHCC strengthening layer was applied to the roughened surface of the SFRC beams. Specimens were demolded after 24 hours, sealed, and stored under controlled environmental conditions. Compressive strength tests on cylindrical specimens (100 mm in height and 50 mm in diameter) at 7, 14, and 28 days indicated significant early strength development due to the fine particle size of CEM I cement, which accelerates hydration. Results are presented in Table 2.

Table 2: SHCC compression strength at different ages.

Age	7 days	14 days	28 days
Compression Strength (MPa)	24.5	32.4	37.1
Standard Deviation (MPa)	1.9	1.7	1.7

The Ultra-High-Performance Concrete (UHPC) was designed for superior mechanical properties and durability. The mix comprised Portland cement CEM I (EN 197-1 [21]), fine sand (particle size: 0.075–0.212 mm), and mineral additives such as silica fume, fly ash, and quartz powder. SILMIX type D silica fume was included to improve particle packing density, while POZOFLY® fly ash enhanced rheology and reduced cement content. Quartz powder (Jundu), with a density of 2.63 g/cm^3 and an average particle diameter of 10.81 µm, was added for further refinement of the mix. The water-to-cementitious materials ratio was kept at 0.2, and MasterGlenium® 51 superplasticizer (BASF) ensured workability at this low ratio. Steel fibers (Dramix® 3D 80/30 BGP, Bekaert), with Young's modulus of 210 GPa and tensile strength of 3070 MPa, were included to enhance ductility and toughness. The UHPC mix proportions are detailed in Table 1.

The UHPC mixing procedure was similarly methodical, comprising: (a) dry mixing of cement and other solids for 5 minutes, (b) gradual addition of water and superplasticizer during mixing, lasting approximately 1 minute, (c) continuous mixing for an additional 13 minutes, (d) gradual incorporation of fibers to prevent clumping, and (e) blending for a further 5 minutes to ensure homogeneity.

Following mixing, a 25 mm thick UHPC layer was applied to the roughened surface of the SFRC beams. Specimens were demolded after 24 hours and cured in a controlled environment for up to 28 days. Cylindrical specimens (100 mm in height and 50 mm in diameter) exhibited a mean compressive strength of 124.6 MPa and a Young's modulus of 49.10 GPa.

Lastly, a third configuration of the strengthening layer was developed by incorporating a bidirectional epoxy-coated carbon textile (GRID Q 140/110-CEP-13/17, Solidian GmbH) into the UHPC matrix, with a tensile strength of 2700 MPa and a Young's modulus of 220 GPa.

2.2 Testing procedure

The geometry of the SFRC short beams used in this experimental program consisted of prismatic specimens with dimensions of 550 mm in length and a cross-section of 150 mm × 150 mm, conforming to the guidelines provided in EN 14651 [22] and as presented in Figure 1.

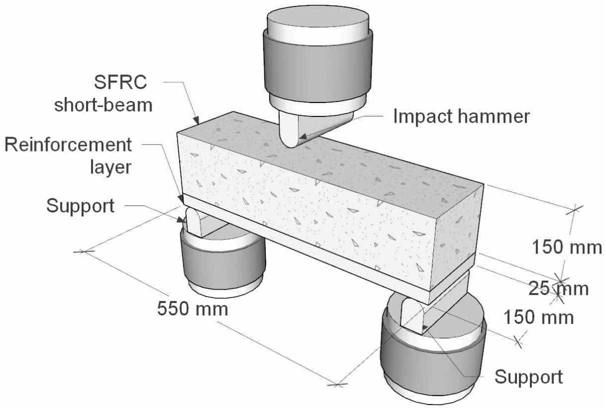


Figure 1: Impact three-point bending test setup.

The experimental program assessed the performance of three configurations of thin strengthening layers applied to the SFRC short beams. The first configuration involved the application of a 25 mm SHCC layer, while the second utilized a 25 mm UHPC layer. The third configuration incorporated a 25 mm UHPC layer reinforced with carbon textile, as detailed in the materials and mixing design section (Subsection 2.1).

To perform the impact loading tests, a custom-designed drop-weight tower, developed at PUC-Rio, was utilized (Figure 2). The setup employed a three-point bending test configuration with a span of 500 mm, as illustrated in Figure 1. The test strain rate was set between 5.0 s^{-1} and 8.7 s^{-1}, corresponding to impact energies of 112.8 J and 338.4 J, respectively.

Data acquisition was meticulously carried out using load cells positioned at the supports, in addition to a load cell and an accelerometer mounted on the impact hammer. The data were recorded at a sampling rate of 20 kHz to ensure high precision in capturing the dynamic responses. Furthermore, a high-speed Digital Image Correlation (DIC) system was employed to monitor and analyze the crack opening displacement (COD) throughout the tests, providing detailed insights into the crack propagation and failure mechanisms.

The short beams tested under these impact loading conditions are listed in Table 3. Up to six specimens were tested for each configuration to ensure statistical reliability and robust analysis of the results.

Figure 2: Drop-weight machine at PUC-Rio.

Table 3: Impact loading test conditions and specimen naming.

Specimens	Impact Energy
SFRC	112.8 J
SFRC + SHCC	112.8 J
SFRC + UHPC	112.8 J
SFRC	338.4 J
SFRC + UHPC	338.4 J
SFRC + Textile UHPC	338.4 J

3 RESULTS AND DISCUSSIONS

Fiber-reinforced concrete (FRC) is widely acknowledged for its ability to enhance the mechanical performance of concrete by mitigating crack formation and propagation. Unlike ordinary concrete, FRC demonstrates superior residual strength after cracking, contributing to improved durability and structural integrity. This enhanced performance is particularly critical under impact loading conditions, where ordinary concrete fails to sustain crack openings induced by quasi-static or dynamic loads.

This study employed Digital Image Correlation (DIC) technology to measure and analyze the crack opening displacement (COD) in SFRC specimens subjected to various impact scenarios. The results provide insights into the effectiveness of fiber additions and strengthening layers in resisting crack propagation and maintaining structural performance under demanding conditions, and the results will be discussed below.

3.1 Crack opening

The performance of steel fiber-reinforced concrete (SFRC) and advanced cementitious composites, including strain-hardening cementitious composites (SHCC) and ultra-high-performance concrete (UHPC), was evaluated under impact loading conditions to assess their crack resistance and energy absorption capabilities.

As shown in Figure 3, SFRC short beams containing 40 kg/m³ of steel fibers demonstrated significant energy dissipation under an impact energy of 112.8 J. The SFRC beam exhibited a maximum crack opening displacement (COD) of 1.25 mm, with a residual crack width of approximately 1.0 mm after the impact. These results highlight the inherent ability of SFRC to sustain residual strength post-cracking, a characteristic that distinguishes it from ordinary concrete.

SFRC reinforced with thin layers of SHCC and UHPC, containing 2% fiber addition, offered superior performance compared to SFRC. These materials demonstrated exceptional energy absorption capacity, as evidenced by their ability to reduce crack openings under the same impact energy significantly. The improved behavior of SHCC and UHPC can be attributed to their dense microstructure, high tensile strength, and effective stress transfer provided by the fiber reinforcement.

Figure 3 further illustrates the enhanced impact resistance achieved by incorporating a thin 25 mm layer of SHCC or UHPC beneath the SFRC short beams. This configuration dramatically reduced both the maximum and residual COD, with an approximate decrease of 80% compared to plain SFRC.

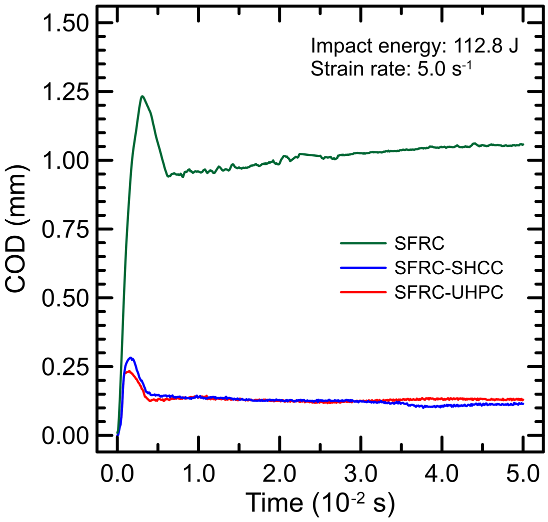
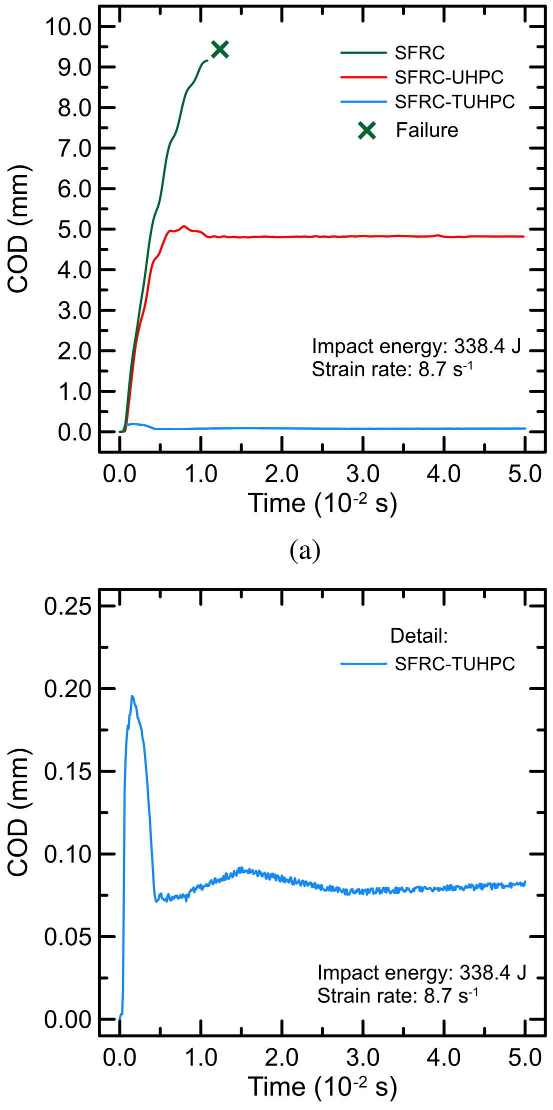


Figure 3: COD over time curves for impact energy of 112.8 J.

The impact resistance of steel fiber-reinforced concrete (SFRC) and its reinforced configurations with ultra-high-performance concrete (UHPC) and carbon textile layers was analyzed under higher energy impacts to assess their crack behavior and energy absorption capacity.

When the impact energy was increased to 338.4 J, the performance of the SFRC short beams indicated a limitation in their energy absorption capacity. As illustrated in Figure 4a, the SFRC beams experienced complete rupture under this energy level. The cracks propagated in an unstable manner, culminating in structural failure. This outcome demonstrates that the energy absorption capacity of plain SFRC was insufficient to withstand the applied energy, rendering it unsuitable for conditions involving higher impact loads.



(a)

(b)

Figure 4: COD over time curves for impact energy of 338.4 J. (a) SFRC, SFRC-UHPC and SFRC-TUHPC specimens and (b) Detail on SFRC-TUHPC curve.

In contrast, the SFRC beams reinforced with UHPC exhibited significantly improved behavior under the same loading conditions. Despite reaching a maximum crack opening displacement (COD) of 2.5 mm during the tests, the UHPC-reinforced beams maintained residual strength and achieved a final residual COD of 4.7 mm. This highlights the effectiveness of the UHPC layer in enhancing the post-cracking behavior and energy dissipation capability of the SFRC beams.

Further improvement was observed by adding a single carbon textile layer within the UHPC reinforcement. This configuration achieved exceptional performance, reducing the maximum COD to 0.20 mm and the residual COD to approximately 0.08 mm. This represents a remarkable 96% reduction in crack opening compared to the UHPC-reinforced configuration without textile. The carbon textile layer's presence significantly enhanced the composite system's energy absorption capacity by improving stress distribution and mitigating crack propagation under high-energy impacts.

3.2 Failure mode

The failure modes and crack patterns of SFRC short beams and their reinforced configurations were analyzed using the Digital Image Correlation (DIC) method under different impact energies. This approach allowed for detailed strain field visualization and comparison of crack behavior at the maximum COD for each specimen.

At an impact energy of 112.8 J, the plain SFRC beam exhibited a single crack with a width of 1.25 mm, as shown in Figure 5. The strain field revealed a localized failure mode, demonstrating the material's inability to distribute stresses effectively under dynamic loading conditions.

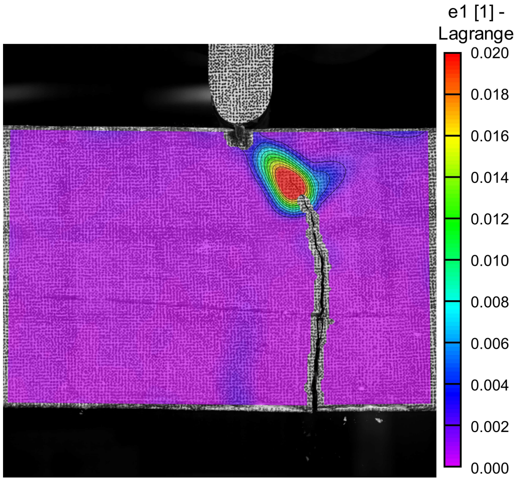


Figure 5: SFRC specimen characteristic failure under 112.8 J impact energy.

In contrast, the SFRC short beam reinforced with a 25 mm SHCC layer displayed a similar single crack but significantly lower strain magnitude than the plain SFRC beam (Figure 6). This reduction in strain indicates an improvement in energy absorption and crack control due to the addition of the SHCC layer.

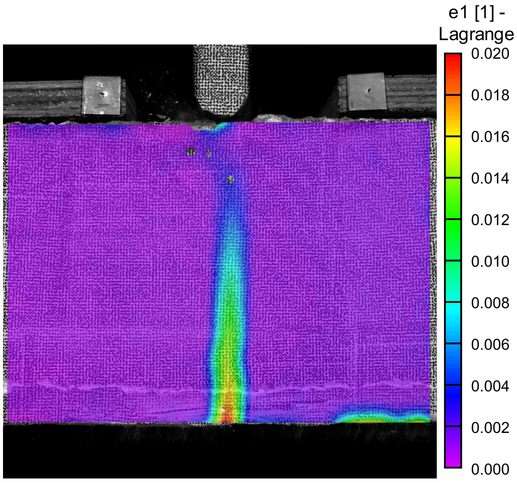


Figure 6: SFRC-SHCC characteristic behaviour under 112.8 J impact energy.

For the SFRC short beam reinforced with a 25 mm UHPC layer, Figure 7 reveals a further reduction in crack opening compared to both the plain SFRC and the SFRC-SHCC configurations.

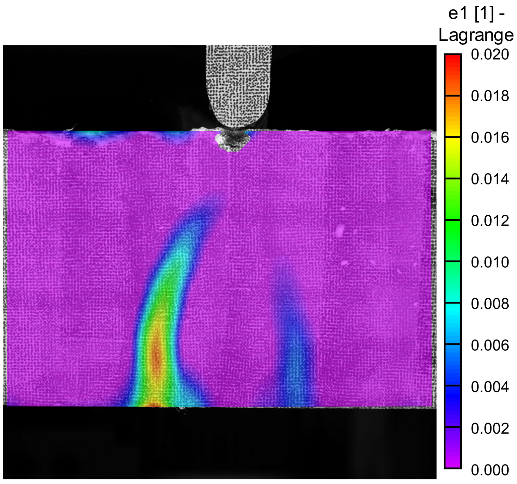


Figure 7: SFRC-UHPC characteristic behaviour under 112.8 J impact energy.

Additionally, the appearance of a secondary crack suggests enhanced energy absorption capacity, as the UHPC reinforcement distributed the stresses more effectively and mitigated crack propagation.

Under a higher impact energy of 338.4 J, the failure mode of the plain SFRC beam was characterized by complete rupture, as illustrated in Figure 8. A single, substantial straight crack formed, indicating that the energy absorption capacity of the plain SFRC was insufficient to prevent catastrophic failure under these conditions.

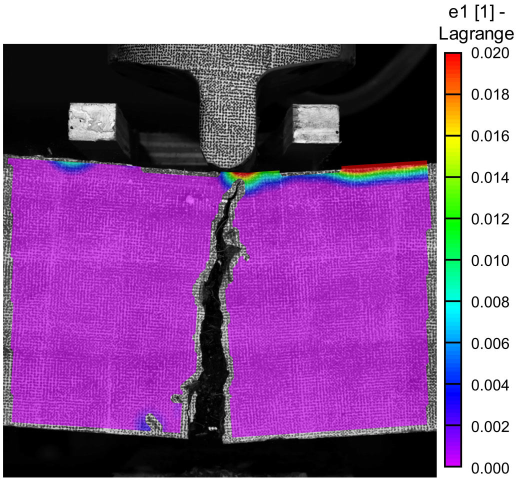


Figure 8: SFRC total failure under 338.4 J impact energy.

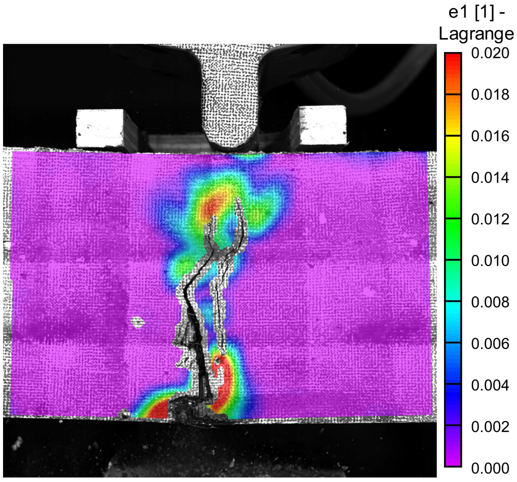


Figure 9: SFRC-UHPC characteristic behaviour under 338.4 J impact energy.

The crack pattern in the SFRC beam reinforced with a 25 mm UHPC layer under a higher impact energy of 338.4 J, shown in Figure 9, exhibited significant differences. The cracks contained curves and turns, suggesting a higher energy absorption capacity. The UHPC reinforcement resisted crack propagation and redistributed the stresses more effectively, resulting in a more ductile failure mode.

Finally, the addition of a carbon textile layer within the UHPC reinforcement led to notable improvements in crack control and failure behavior. As seen in Figure 10, the crack pattern transformed into a multiple crack formation, drastically reducing the COD and indicating superior control over crack initiation and propagation. This multiple-crack pattern reflects enhanced energy absorption and stress dissipation, contributing to improved structural performance and preventing catastrophic failure.

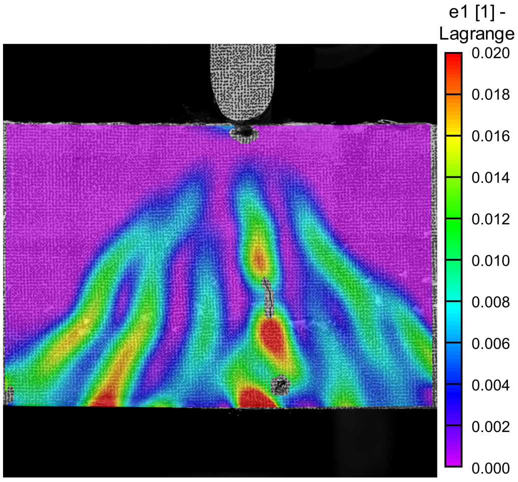


Figure 10: SFRC-TUHPC characteristic multiple-crack formation under 338.4 J impact loading.

Overall, the results demonstrate the critical role of advanced reinforcements in modifying the failure modes and enhancing the impact resistance of SFRC short beams.

4 CONCLUSION

These findings underscore the critical role of advanced cementitious composites and reinforcement strategies in enhancing concrete elements' impact resistance and structural integrity. The study demonstrated that fiber-reinforced concrete (FRC) improves post-cracking performance and durability compared to ordinary concrete, particularly under dynamic loading conditions. However, incorporating strain-hardening cementitious composites (SHCC), ultra-high-performance concrete (UHPC), and carbon textile reinforcement further enhanced crack control, energy absorption, and failure resistance, highlighting their superior performance in mitigating the effects of high-impact loads.

Based on the analyses presented in this study, the following conclusions can be drawn:

- Performance of SFRC: SFRC short beams with 40 kg/m³ of steel fibers exhibited significant energy dissipation under moderate impact energy (112.8 J), achieving residual strength post-cracking. However, under higher impact energy (338.4 J), the SFRC beams suffered catastrophic failure, indicating their limited energy absorption capacity.

- Effectiveness of SHCC Layers: The addition of a 25 mm SHCC layer to SFRC beams resulted in reduced strain and improved crack control compared to plain SFRC. This demonstrates the material's ability to enhance the energy absorption capacity and mitigate damage under dynamic loading.

- UHPC Reinforcement: SFRC beams reinforced with a 25 mm UHPC layer exhibited further improvements in performance, including reduced crack opening and increased energy absorption. The appearance of secondary cracks under moderate impact energy suggests better stress distribution and structural resilience.

- Carbon Textile Addition: Including a carbon textile layer within the UHPC reinforcement provided exceptional crack control, reducing maximum and residual crack opening by 96% under high-impact loads. The multiple crack formation observed highlights the superior energy dissipation and stress redistribution capabilities of this configuration, preventing catastrophic failure and improving overall structural behavior.

These results validate the effectiveness of SHCC, UHPC, and carbon textile reinforcements in enhancing the impact resistance of concrete structures, offering valuable insights for designing resilient infrastructure capable of withstanding dynamic and extreme loading conditions.

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