A COMPREHENSIVE REVIEW OF THE FLEXURAL AND SHEAR BEHAVIOUR OF REINFORCED CONCRETE BEAMS USING HIGH-PERFORMANCE CONCRETE UNDER STATIC AND CYCLIC LOADING

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ABSTRACT

High-performance concrete (HPC) is now extensively used in RC beams owing to its superior mechanical properties, high resistance to cracking, and good durability. In this review paper, an extensive study on the flexural and shear behavior of HPC reinforced concrete beams subjected to static and cyclic loading is presented. The review paper is concerned with aspects of flexural and shear strength, initiation and propagation of cracks, stiffness reduction, ductility, energy dissipation, and modes of failure. The influence of different parameters, such as the concrete strength, longitudinal and shear reinforcing bars, steel and FRP fibers, number of reinforcing bars, beam dimensions and aspect ratio, is also considered in this study. Experimental methods for testing the behavior of RC beams include flexural, shear, and cyclic loading tests, digital image correlation (DIC), and crack monitoring, while numerical and finite element methods for the prediction of structural response are briefly discussed. The review suggests that the proper use of reinforcements and fibers in HPC RC beams can significantly improve crack resistance, post-cracking behavior, ductility, and energy dissipation, especially under cyclic loading. Finally, key challenges, research gaps, and future research directions are identified for improving the reliability, durability, and structural performance of HPC reinforced concrete beams.

Keywords: *High-Performance Concrete; Reinforced Concrete Beams; Flexural Behaviour; Shear Behaviour; Cyclic Loading; Crack Propagation.*

1. INTRODUCTION

Reinforced concrete (RC) beams are extensively applied in various structures owing to their strength, toughness, flexibility, and economy of construction [1]. Nonetheless, traditional concrete is known to have poor tensile strength, making it vulnerable to cracking and damage under flexural and shear loads. High-performance concrete (HPC) has emerged as an advanced version of concrete that possesses better compressive strength, stiffness, impermeability, and durability. The use of HPC in reinforced concrete beams may have substantial effects on load-carrying capacity, cracking, deformations, and failure modes.

Figure 1: Reinforced Concrete (RC) [2]

The performance of HPC reinforced concrete beams is a result of the interaction between the concrete matrix and the reinforcing bars. In bending, cracks tend to form in the tensile region, and continue to grow with increasing loads, whereas in the case of shearing, the formation of diagonal cracks and interaction among the concrete, longitudinal steel, and stirrups play an important role. These behaviours may be affected by many factors including concrete strength, reinforcement percentage, shear reinforcement, dimensions of the beam, fiber addition, and bond properties. Fibers could add extra toughness to the beams, especially if a proper selection of fibers is made.

Aside from static loading, the study of the structural response of reinforced concrete beams made of high-performance concrete (HPC) under cyclic loading is equally important, especially when dealing with structures that experience repetitive or reversed loading conditions. Cyclic loading may lead to the progression of cracking, stiffness degradation, residual deformations, strength reduction, and fatigue, among other forms of damage that will make the structure's behavior more complicated than when exposed to monotonic loading. Consequently, this paper highlights the flexural and shear behavior of HPC reinforced concrete beams under static and cyclic loading, specifically in relation to cracking behavior, strength, stiffness, ductility, energy absorption, failure modes, experimental methods, and modeling approaches [3].

1.1 Objectives of the study

The main review objectives are:

- To evaluate the behaviour of HPC-reinforced concrete beams subjected to static and dynamic loading.
- To investigate the effect of various structural/material variables on the performance of such beams.
- To evaluate current state-of-the-art approaches and research gaps.

2. REVIEW METHODOLOGY

The current review has employed an integrative literature review methodology in order to provide a systematic analysis of the flexural and shear behavior of reinforced concrete beams made using high-performance concrete subjected to static and cyclic loads. Literature review was conducted based on concrete strength, longitudinal and shear reinforcements, fiber reinforcements, reinforcement ratios, beam sections, cracking, stiffness, ductility, energy dissipation, and failure modes [4]. Various experimental methodologies such as flexural, shear, and cyclic testing, Digital Image Correlation (DIC), and crack testing, along with the finite element modeling technique, were used for synthesizing existing knowledge, identifying the research gap, and finding the future direction of the research. This methodology is compatible with the integrative literature review method utilized in the sample paper.

3. FLEXURAL AND SHEAR BEHAVIOUR OF HPC REINFORCED CONCRETE BEAMS

The performance of reinforced concrete beams with high-performance concrete (HPC) is determined by the interaction between the HPC matrix, longitudinal reinforcement, shear reinforcement, and, if provided, fiber reinforcement. High-performance concrete is usually stronger and stiffer than conventional concrete; hence, it may enhance the load-carrying capability of the beams [5]. On the other hand, the density and brittleness of the HPC matrix may affect crack formation and failure behavior. Consequently, flexural and shear behaviors should be taken into consideration.

3.1 Flexural Behaviour

Flexural behaviour is defined as the behaviour of an HPC reinforced concrete beam under bending loads. In the first stages, the HPC reinforced concrete beam will behave elastically with contributions from both concrete and steel reinforcements in resistance to applied loads. Once the tensile stresses on the concrete exceed the capacity of concrete in tension, the cracks will begin developing along the tension zone of the section and continue increasing as the loads get higher. Post-cracking, the reinforcing bars become the major elements in tension while the concrete resists compression [6]. High strength and stiffness of HPC could increase the cracking load, stiffness and flexural strength of the beam. However, too much reinforcement might cause compression control failure and thus ductile design is critical.

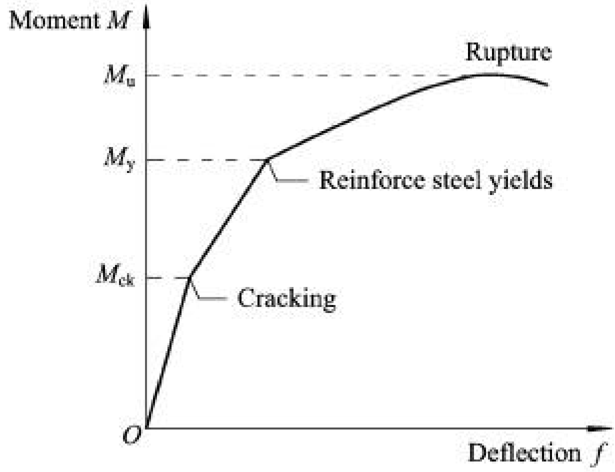

Figure 2: Flexural Behaviour [7]

Further modification in the flexural behavior of the specimens is possible using fibers in such a way that the cracks are bridged and the tensile forces are transferred across the cracked sections. These processes may help decrease crack width, delay the crack propagation and enhance the post-cracking resistance and energy absorption capability. Likewise, the attached specimen highlights the role played by fiber bridging, fiber pull-out and fiber breakage in crack resistance and energy dissipation [8]. Hence, the flexural behavior of HPC beams is dependent not only on concrete compressive strength but also on tensile strength.

3.2 Shear Behaviour

The mechanics of shear failure are more complicated than that of flexural failure as several resisting actions work concurrently in the beam. As the applied loads continue to increase, there could be development of flexural cracks, followed by shear or diagonal cracks in the regions where shear takes place. The diagonal cracks could then grow rapidly until shear failure occurs owing to lack of sufficient shear strength. In HPC beams, the increased strength of the concrete contributes towards increased resistance to diagonal cracking and improved contribution of the compressive region of the concrete [9].

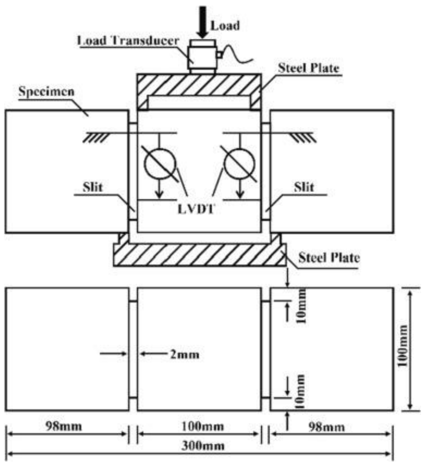

Figure 3: Shear Behaviour [10]

These include transverse reinforcements, longitudinal reinforcements, concrete strength, shear span-to-depth ratio, and fibers reinforcement. Transverse reinforcements help to constrain the openings at the diagonal cracks while fibers allow bridging of the diagonal cracks and maintain their resistance even after cracking. The efficiency of crack bridging is affected by fiber content, length, aspect ratio, orientation, dispersion and fiber-matrix bond, as indicated in the sample review [11]. It is crucial due to the fact that diagonal tension/compression failure happens abruptly than a flexural failure.

3.3 Crack Initiation and Propagation

Cracking is an important phenomenon in the behavior of concrete beams. In case of HPC beams, cracking could be due to heterogeneous materials, shrinkage, temperature, applied loads, porosity, and weak areas in the concrete matrix. With increasing loads in the structure, initially formed microcracks will interact and evolve into macro cracks. When subjected to bending, cracks are mainly developed perpendicular to the longitudinal direction of the beam, while in shear loading, cracks are developed diagonally [12].

The addition of fibers can alter this process of crack formation through bridging effects that can act across the growing cracks. Rather than forming one main crack that grows rapidly, fibers can disperse the loads through multiple cracks. Fiber pullout and fiber breakage also serve to dissipate energy when a beam fractures. Monitoring crack width, crack spacing, crack angle, and crack growth is essential in HPC beams in order to evaluate serviceability and ultimate capacity.

3.4 Failure Mechanisms

The failure modes in high-performance concrete beams may be categorized into four general types, namely flexural failure, shear failure, compression failure, and flexure-shear failure. The flexural failure usually entails tensile crack development followed by yielding of the longitudinal steel bars, ultimately leading to the crushing of the concrete compression zone [13]. The mode of flexural failure is always desirable since it allows for a considerable deformation capability and warnings prior to failure. On the other hand, shear failure normally involves the formation of diagonal cracks quickly once the shear strength of the beam has been exceeded.

The failure mode depends largely on the strength of concrete, longitudinal and transverse reinforcements, the shape of the beam, loading conditions, and fiber reinforcement. In case of cyclic loading, cracking and reopening of cracks could lead to increased stiffness loss, residual deformations, and damage. Fiber bridging will allow load transfer and dissipate more energy. From the literature provided, fiber properties and their interaction with concrete have also been identified as important variables in terms of fracture and post-fracture behavior. It is thus essential that ductile failure mode be an important objective when designing HPC reinforced concrete beams.

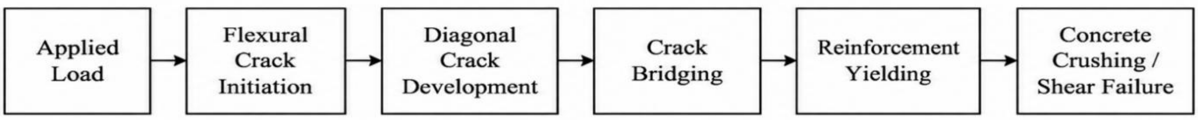

Figure 4: Progressive Failure Sequence of HPC Reinforced Concrete Beams Under Loading [14]

Failure process of an HPC reinforced concrete beam is illustrated in Figure 1. This failure process involves loading, initiation of flexural cracks, formation of diagonal cracks, cracking bridging, yielding of reinforcement, and failure of concrete.

4. INFLUENCING PARAMETERS ON STRUCTURAL PERFORMANCE

The structural behavior of high-performance concrete (HPC) reinforced concrete beams depends on various factors. These include material, reinforcement, and geometry-related factors, which influence the carrying capacity, stiffness, cracking, ductility, and failure modes. The relationship between strength of the concrete, reinforcement properties, fibers, and geometry of the beam is crucial because enhancement in one factor may not be accompanied by enhancement in the structural behavior [15].

4.1 Concrete Strength

The compressive strength of the concrete is one of the major factors that influence the behavior of HPC beams. High-strength concrete results in better resistance to compression and stiffness in the beam. The higher strength concrete also delays cracking. But very high-strength concrete may be more brittle after cracking; therefore, proper reinforcement is required.

4.2 Longitudinal and Shear Reinforcement

The longitudinal reinforcement controls the flexural behavior and flexural strength of the beam, whereas shear reinforcement controls diagonal cracking and shear failure. Increase in the amount of transverse reinforcement helps in increasing the shear strength as well as controlling the diagonal cracking. Proper design of reinforcement is very important for controlling the mode of failure of the beam [16].

4.3 Fiber Reinforcement

The performance of HPC beams in terms of cracking and behavior after cracking may be improved using the use of fibers. The bridging effect caused by the presence of fibers across the crack's aids in the transfer of tensile stresses across the cracks. These effects are influenced by the nature of the fibers, their amount, length, and bond between fiber and matrix.

4.4 Beam Geometry and Span-to-Depth Ratio

The geometry of the beam plays an important role in deciding which failure mode governs the design. Span-depth ratio determines the flexural/shear stress distribution and thus decides if the beam will behave in a flexural/shear manner. Therefore, variations in beam dimensions, such as depth, width, effective span, and shear span will change its stiffness, cracking pattern, capacity, and deformation.

Table 1: Influence of Major Parameters on the Structural Performance of HPC Reinforced Concrete Beams [17]

Parameter	Major Influence	Expected Structural Effect
Concrete strength	Controls compressive resistance and stiffness	Higher strength generally increases capacity and stiffness
Longitudinal reinforcement	Controls flexural resistance	Increases flexural strength and influences ductility
Shear reinforcement	Resists diagonal cracking	Improves shear capacity and crack control
Fiber reinforcement	Bridges cracks and transfers tensile stresses	Improves crack resistance, toughness and post-cracking behaviour
Beam geometry	Controls stress distribution	Influences stiffness, cracking and failure mode
Span-to-depth ratio	Governs flexural/shear dominance	Lower ratios generally increase shear influence
Reinforcement ratio	Controls strength–ductility balance	Appropriate ratios provide better strength and deformation capacity

As noted in Table 1, the behavior of HPC beams is related to the interplay between materials properties, reinforcement, fibers properties, and geometric factors as opposed to concrete compressive strength. It is especially the case when the beams are under cyclic loading, whereby cracking, loss of stiffness, and damage accumulation can significantly change their behavior.

5. BEHAVIOUR UNDER STATIC AND CYCLIC LOADING

The loading conditions have a great impact on the response of high-performance concrete beams. Static loading controls their strength, stiffness, crack development, and failure behaviour, whereas cyclic loading induces further damage due to repetitive loading and unloading [18].

- **Static Loading Response:** In static loading, HPC beams usually display stiffness and carrying capacity. As the load increases, cracks appear, then yielding of reinforcement takes place, followed by concrete crush or shear. Fibers may be used to increase post-cracking behavior and crack resistance.
- **Cyclic Loading Response:** During cyclic loading, there is progressive crack formation, deformation, and strength reduction. Cyclic response is affected by concrete strength, reinforcement design, fiber amount, and loading size.
- **Stiffness Reduction:** Repeated loading leads to progressive stiffness reduction as a result of crack formation, damage of concrete, and deterioration of bond. Stiffness reduction is used as an index of cumulative structural damage [19].
- **Ductility and Energy Dissipation**: Ductility and energy dissipation are key factors for cyclic response evaluation. Fiber bridging, pull-out, and rupture may lead to energy dissipation and improved post-cracking behavior. Thus, adequate reinforcement and fiber amount can help to increase ductility and cyclic response of structures.

Table 2: Summary of Previous Studies on HPC/UHPC and Fiber-Reinforced Concrete Structural Behaviour [20]

Reference	Focus of Study	Key Findings
Zhu et al. (2022) [21]	Flexural behaviour of BFRP- and steel-fiber-reinforced concrete beams under cyclic loading	Steel fibers improved crack control, post-cracking behaviour, and cyclic response.
Ali & Moosa (2023) [22]	Structural behaviour of spliced RC girders under static and cyclic loading	Splice design and development length significantly affected load transfer and structural integrity.
Safaa & Kadhim (2025) [23]	UHPC-based strengthening and repair of RC beams for shear	UHPC strengthening substantially improved shear capacity; performance depended on strengthening configuration and bond quality.
Noor et al. (2025) [24]	Experimental and numerical assessment of steel fiber-reinforced concrete beam-column joints	Fiber reinforcement improved crack resistance, ductility, and energy absorption; numerical modelling supported structural performance evaluation.

6. EXPERIMENTAL AND NUMERICAL APPROACHES

Numerical and experimental methods are widely employed to study the behavior of HPC reinforced concrete beams under flexure, shear, cracking, and cyclic loading. This helps gain knowledge about the load-carrying capacity, deformation, cracking, stiffness reduction, and failure modes [25].

6.1 Flexural and Shear Tests

The flexural tests are usually performed by means of three-point or four-point load tests to find out the cracking load, ultimate load, deflection, and flexural strength [26]. Flexural strength can be described by:

$$f_r = \frac{M}{Z}$$

where f_r is the flexural tensile strength, M is the applied bending moment, and Z is the section modulus.

For a simply supported beam subjected to central point loading:

$$M_{max} = \frac{PL}{4}$$

where P is the applied load and L is the span length.

For calculation of shear, the nominal shear stress can be written as:

$$\tau_v = \frac{V}{bd}$$

where V is the shear force, b is the beam width, and d is the effective depth.

6.2 Cyclic Loading Tests

Cyclic tests are carried out to evaluate hysteretic behavior, ductility, stiffness degradation, and energy dissipation [27]. The displacement ductility is generally represented as:

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y}$$

where Δ_u is the ultimate displacement and Δ_y is the yield displacement.

Estimation of energy loss during the loading cycle can be made from the area within the load versus displacement hysteresis loop:

$$E_d = \oint P \, d\Delta$$

where $P$is the applied load and $\Delta$is the corresponding displacement.

6.3 DIC and Crack Monitoring

The Digital Image Correlation method (DIC) is employed in determining surface displacement, strain, and crack growth under loadings. Crack width and growth are determined at all stages of the test. The sample paper recognizes the DIC as an appropriate method to determine full-field deformation and crack growth [28].

6.4 Numerical and Finite-Element Modelling

The method of finite element modelling is employed for simulating stress, strain, cracking, concrete crushing, reinforcing bar action, and failure [29]. Stress-strain relationship may generally be expressed as:

$$\sigma = E\varepsilon$$

where $\sigma$is stress, $E$is the elastic modulus, and $\varepsilon$is strain.

Further modeling can be performed by numerical and mesoscale models in regard to the concrete matrix, aggregates, interfacial regions, reinforcements, and fibers. This allows for crack propagation prediction in static and cyclic loading cases [30].

7. CONCLUSION

The review has shown that use of HPC could greatly improve performance of reinforced concrete beams in terms of increasing their strength, stiffness, cracking, and durability characteristics. Flexural and shear behaviour depend on many factors, including concrete strength, longitudinal and shear reinforcement, fiber reinforcement, reinforcement ratio, cross section parameters, and span to depth ratio. Whereas use of HPC could increase load carrying capacity and stiffness, the brittle nature of HPC requires appropriate reinforcement and crack control system in order to ensure proper ductility of the element. In case of cyclic loading crack propagation, stiffness loss, residual deformations, and strength reduction become essential issues, while fibers provide better post-cracking and energy absorption properties. Flexural, shear, cyclic and DIC testing, as well as numerical and finite element modeling could be considered as good methods of evaluation and prediction of beam performance. As conclusion it should be mentioned that there is a necessity for further investigation in order to develop reliable design techniques for HPC reinforced concrete beams under static and cyclic loading.

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