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# APPLICATION OF UHPFRC IN COMPOSITE STRUCTURES FROM A SUSTAINABILITY PERSPECTIVE

***Abstract:***

Composite steel and concrete structures are widely used in modern civil engineering due to their structural efficiency and economic performance. However, conventional composite systems limit the possibility of full structural disassembly and reuse of steel structure elements and composite slabs, which is increasingly important in sustainable construction. Ultra-High-Performance Fiber Reinforced Cementitious Composites (UHPFRC) provide very high strength, improved tensile behavior and enhanced durability, enabling thinner slabs and reduced structural weight, as well as reduced $CO_2$ consumtion. This paper reviews the most important mechanical and rheological characteristics of UHPFRCC and discusses its potential application in composite structures from a sustainability circular economy perspective.

*Keywords: UHPFRC, composite steel and concrete structures, sustainability, circular economy, creep and shrinkage*

# ПРИМЈЕНА UHPFRC У СПРЕГНУТИМ КОНСТРУКЦИЈАМА СА АСПЕКТА ОДРЖИВОСТИ

***Сажетак:***

Спрегнуте конструкције од челика и бетона се широко примењују у савременом грађевинарству због своје конструктивне ефикасности и економичности. Међутим, класични спрегнути системи ограничавају могућност потпуне демонтаже и поновне употребе елемената челичне конструкције и спрегнуте плоче, што постаје све значајније у контексту одрживе градње. Бетон ултра високих перформанси ојачан влакнима, (UHPFRC) представља материјал високих механичких карактеристика који омогућава примену тањих плоча и смањење сопствене тежине конструкције а самим тим и потрошње $CO_2$. У раду се даје преглед најважнијих механичких и реолошких својстава UHPFRC и разматра његов потенцијал у примени у спрегнутим конструкцијама са аспекта одрживости и циркуларне економије.

*Кључне ријечи: UHPFRC, спрегнуте конструкције од челика и бетона, одрживост, циркуларна економија, течење и скупљање*

# 1. INTRODUCTION

The construction sector is one of the largest consumers of natural resources and a significant contributor to global greenhouse gas emissions [2]. A large share of these emissions is associated with the production of construction materials, particularly cement and structural steel. Consequently, increasing attention is being devoted to sustainable construction practices aimed at reducing material consumption and the environmental impact of structural systems.

Composite steel and concrete structures are widely used in civil engineering due to their structural efficiency and favorable mechanical performance. By combining steel and concrete, these systems enable efficient structural solutions for buildings and bridges. However, conventional composite systems are typically based on permanent connections between steel beams and reinforced concrete slabs, which limits the possibility of full structural disassembly and reuse of structural components [3].

In recent years, the concept of circular economy has gained increasing importance in the construction sector. The main objective of this approach is to reduce resource consumption and environmental impact by promoting reuse, recycling and longer service life of structural materials. In this context, the possibility of reusing steel structural elements represents an important strategy for reducing embodied carbon in construction [6]. The general principles of circular economy applied to construction are illustrated in Fig. 1.

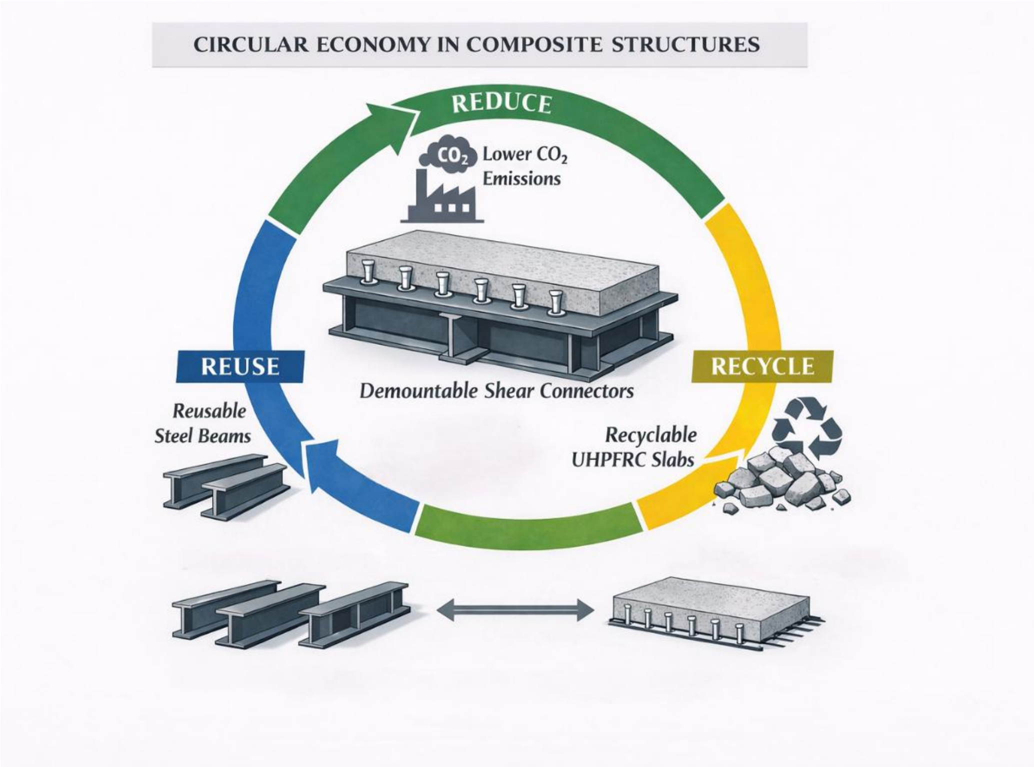


*Figure 15. Circular economy concept applied to composite structures and reusable steel elements and UHPFRC slabs (created by author).*

One of the materials that has attracted significant attention in recent years is Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) [1], [7]. This advanced cement-based material is characterized by very high strength, improved tensile behavior and enhanced durability. Due to these properties, UHPFRC enables the design of thinner structural elements and reduced structural weight compared to conventional reinforced concrete.

The aim of this paper is to review the mechanical and rheological characteristics of UHPFRC and to discuss its potential application in composite structures from the perspective of sustainability and circular economy.

# 2. ULTRA-HIGH PERFORMANCE FIBER REINFORCED CONCRETE (UHPFRC)

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is an advanced cement-based material developed to achieve very high mechanical strength, improved tensile response and superior durability compared to conventional concrete [1], [3]. Its performance is primarily based on optimized particle packing, a very low water-to-binder ratio, elimination of coarse aggregate, and the addition of significant amount of fibers, most commonly steel fibers. Due to these characteristics, UHPFRC has attracted increasing attention in structural engineering, especially in applications where reduced member dimensions, high durability and improved long-term performance are required.

Unlike conventional concrete, UHPFRC is characterized by a dense and homogeneous microstructure with very low porosity and permeability. This is achieved through the use of fine quartz sand, silica fume, other mineral additions and high-range water-reducing admixtures. Typical water-to-binder ratios are in the range of 0.16 to 0.22, while compressive strength values generally exceed 150 MPa [3]. The absence of coarse aggregate improves particle compactness and contributes to the development of a dense cementitious matrix, while fibers control cracking and improve post-cracking tensile behavior.

From a mechanical point of view, UHPFRC combines high compressive strength with increased tensile resistance and ductility [7]. Its tensile response is significantly improved compared to conventional concrete due to fiber bridging across cracks. In structural terms, this means that UHPFRC elements may exhibit controlled crack development, improved energy absorption and reduced crack widths under service loads. These properties are particularly important in thin slabs and other slender structural members, where crack control and serviceability are critical.

At the same time, UHPFRC also exhibits specific rheological characteristics that must be considered in design. Although its creep coefficients are often lower than those of conventional concrete, the long-term behavior of UHPFRC depends on several parameters, including loading age, curing regime, relative humidity, fiber content and stress level. In addition, UHPFRC is known for pronounced autogenous shrinkage caused by its low water content and dense microstructure. For this reason, the structural benefits of UHPFRC should always be assessed together with its time-dependent behavior [9].

In the context of composite steel and concrete structures, these material characteristics are highly relevant because they may enable thinner slabs, lower self-weight and improved durability, while also affecting long-term deflections and stress redistribution between the composite components. Therefore, a brief overview of its key mechanical and rheological characteristics is given in the following sections.

## 2.1. MECHANICAL PROPERTIES

The mechanical performance of UHPFRC is primarily defined by its very high compressive strength, improved tensile resistance and enhanced post-cracking behavior. According to the reviewed literature, compressive strength values above 150 MPa are common, while higher values may be achieved depending on the mix composition and curing regime. This high compressive capacity enables the design of structural elements with reduced thickness and lower self-weight compared to conventional reinforced concrete members.

Another important property is the modulus of elasticity, which is typically reported in the range of approximately 40–55 GPa. Although high than in case of conventional concrete, this value is not proportional to the increase in compressive strength, meaning that stiffness-based design requirements remain important, especially in slender elements. Therefore, the use of UHPFRC does not eliminate serviceability concerns, but rather shifts the design focus toward a balance between reduced dimensions and acceptable deformation levels.

The tensile behavior of UHPFRC is one of its most significant advantages. Due to fiber reinforcement, UHPFRC can develop noticeable tensile strength and post-cracking load-carrying capacity. In contrast to conventional concrete, which behaves in a brittle manner once cracking occurs, UHPFRC may exhibit strain-hardening or at least controlled post-cracking behavior, depending on the type, volume fraction and orientation of fibers. This characteristic is particularly relevant in structural applications where crack control, ductility and energy dissipation are important.

From the structural point of view, the combination of high compressive strength and improved tensile behavior provides several potential advantages. These include thinner slabs, reduced dead load, improved durability and a lower need for conventional reinforcement in some applications. In the case of slabs on special profiled steel sheeting, reinforcement can be completely omitted, however, these benefits must be interpreted carefully. UHPFRC is a high-performance material, but its use should be justified at the structural level rather than only at the material level. In other words, the main advantage is not simply higher strength, but the possibility of optimizing the structural system.

### 2.2. RHEOLOGICAL PROPERTIES

In addition to its mechanical properties, the rheological behavior of UHPFRC plays an important role in structural applications. The long-term response of this material is influenced by creep and shrinkage, both of which affect deflections, stress redistribution and serviceability performance [7].

Available studies indicate that the creep coefficients of UHPFRC are generally lower than those of conventional concrete, especially when loading is applied at mature age and when proper curing is provided.

Reported ultimate creep coefficients for mature UHPFRC specimens are commonly below those typical for ordinary concrete, while early-age loading may still produce significant time-dependent deformation. This shows that the long-term performance of UHPFRC cannot be described by a single simplified assumption, but must be related to loading age, humidity, curing conditions and mixture composition.

Flexural creep is also relevant for structural members such as thin slabs and beams. Experimental studies on UHPFRC under long-term bending have shown that fiber content, water-to-binder ratio, curing regime and stress level may significantly affect delayed deflections.

In cracked elements, creep coefficients in bending were reported in the range of approximately 0.6 to 1.2, depending on geometry, cracking level and loading conditions.

This is particularly important for composite applications, where slab deformation directly affects the global behavior of the structural system.

Shrinkage is another important aspect. Due to the very low water content and dense microstructure, UHPFRC typically exhibits pronounced autogenous shrinkage, while drying shrinkage is generally lower than in conventional concrete. These strains may develop rapidly at early ages and influence cracking risk, interface stresses and the long-term response of restrained members.

A further challenge is that conventional prediction models are not always directly applicable to UHPFRC. Several authors have shown that common code-based creep models require calibration when used for ultra-high-performance materials [9].

This is important for practical engineering applications, since inaccurate estimation of long-term deformations may compromise serviceability-based design decisions.

For composite structures, the rheological characteristics of UHPFRC are especially relevant because they influence slab deflections, stress redistribution and interaction with steel members over time. Therefore, the application of UHPFRC in such systems should not be assessed only through strength and durability, but also through its time-dependent structural response.

## 3. APPLICATION OF UHPFRC IN COMPOSITE STRUCTURES

The application of Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) in composite structures has attracted increasing attention in recent years [3], [11]. Due to their exceptional mechanical properties and enhanced durability, these materials provide new possibilities for improving the performance of steel–concrete composite systems [11].

One of the most significant advantages of UHPFRC is its very high compressive strength and improved tensile behavior compared to conventional reinforced concrete. Compressive strengths typically exceed 150 MPa, while the presence of steel fibers significantly enhances the post-cracking tensile response and crack control [7]. As a result, structural elements made with UHPFRC can achieve significantly reduced thickness while maintaining or even improving structural performance. In composite structures, this characteristic enables the development of thinner slabs and reduced overall structural weight.

Another important benefit of UHPFRC is its excellent durability. The very dense microstructure of the material provides extremely low permeability, which significantly improves resistance to environmental actions such as chloride penetration, freeze–thaw cycles and chemical attack [2]. This property is particularly important for bridge structures and other infrastructure systems exposed to aggressive environmental conditions. Consequently, the use of UHPFRC in composite systems can contribute to longer service life and reduced maintenance requirements, which is also important from sustainability point of view.

Several studies have investigated the structural behavior of composite beams incorporating UHPFRC slabs. Experimental investigations have shown that the improved tensile capacity of UHPFRC can enhance the bending resistance and stiffness of composite members. In addition, the material exhibits improved crack control compared to conventional reinforced concrete slabs, resulting in smaller crack widths and improved long-term performance.

Another research direction focuses on the interaction between steel beams and UHPFRC slabs when demountable shear connectors are used. In such systems, UHPFRC may provide improved load transfer and crack resistance around the connectors, which is particularly relevant for composite structures designed for disassembly and reuse. These aspects are increasingly important within the framework of sustainable construction and circular economy principles.

In addition to experimental studies, numerical simulations have also been widely used to investigate the behavior of UHPFRC composite elements. Finite element models have been developed to capture the nonlinear material behavior of UHPFRC and its interaction with steel elements. These models provide valuable insight into stress distribution, crack development and the overall structural response of composite systems [4], [5].

Although the use of UHPFRC in composite structures shows significant potential, its application is still relatively limited in practical engineering. The main challenges include higher material cost, more complex production processes and the need for further experimental validation for different structural configurations. However, ongoing research continues to demonstrate the potential benefits of this material for developing more efficient and sustainable composite structural systems. A brief overview of selected studies related to the application of UHPFRC and demountable shear connectors in composite structures is presented in Table 1.

*Table 1. Overview of selected studies related to the application of UHPFRC and demountable shear connectors in composite structures*

| Author | Year | Type of study | Structural element | Main findings |
|---|---|---|---|---|
| Graybeal | 2014 | Review | UHPC structural elements | Overview of mechanical properties and durability of UHPC materials |
| Fehling et al. | 2014 | Experimental | UHPC structural members | Structural behavior of UHPC elements and advantages of high-strength cementitious composites |
| Lam & Dai | 2015 | Experimental | Composite beam | Behavior of bolted demountable shear connectors in composite beams |
| Ataei et al. | 2016 | Experimental | Composite beam | Structural performance and slip behavior of demountable shear connectors |
| Hosseini et al. | 2018 | Experimental / numerical | Composite beam | Demountable connectors as a solution for reusable composite structures |
| Isidora Jakovljević (PhD thesis) | 2023 | Experimental / numerical | Composite beam with demountable connectors | Investigation of demountable composite systems and their potential for sustainable and reusable structures |

As shown in Table 1, previous studies mainly focused on the mechanical behavior of demountable shear connectors and the properties of UHPFRC materials. However, the combined application of UHPFRC slabs in demountable composite systems remains relatively unexplored.

## 4. DEMOUNTABLE COMPOSITE SLABS ON PROFILED STEEL SHEETING

Conventional composite steel and concrete structures are typically based on permanent shear connections between steel beams and concrete slabs. The most common solution is the use of welded headed studs, which provide efficient load transfer between steel and concrete components and required ductility. However, these connectors create permanent composite action, making the separation of structural elements extremely difficult once the structure reaches the end of its service life. As a consequence, reuse of steel beams in such systems is rarely possible, which limits the application of circular economy principles in composite construction.

In recent years, increasing attention has been devoted to the development of demountable composite systems. The main objective of these systems is to enable the disassembly of composite structural elements so that steel beams, as well as composite slabs can be reused in future construction projects. In contrast to traditional welded studs, demountable shear connectors are typically based on bolted connections that allow the separation of the steel beam and the concrete slab. Experimental investigations on bolted shear connectors were reported by Lam and Dai [4], while further studies on the behavior of demountable connectors were conducted by Ataei et al. [5].

The basic concept of demountable shear connection in composite beams on profiled sheeting is illustrated in Fig. 2 [10]. In such systems, bolts are used together with welded studs to allow the connection, which is dismantled after the service life of the structure. This enables separation of steel beams and concrete slabs on profiled steel sheeting and therefore facilitates the reuse of steel structural elements and slabs in new construction projects.

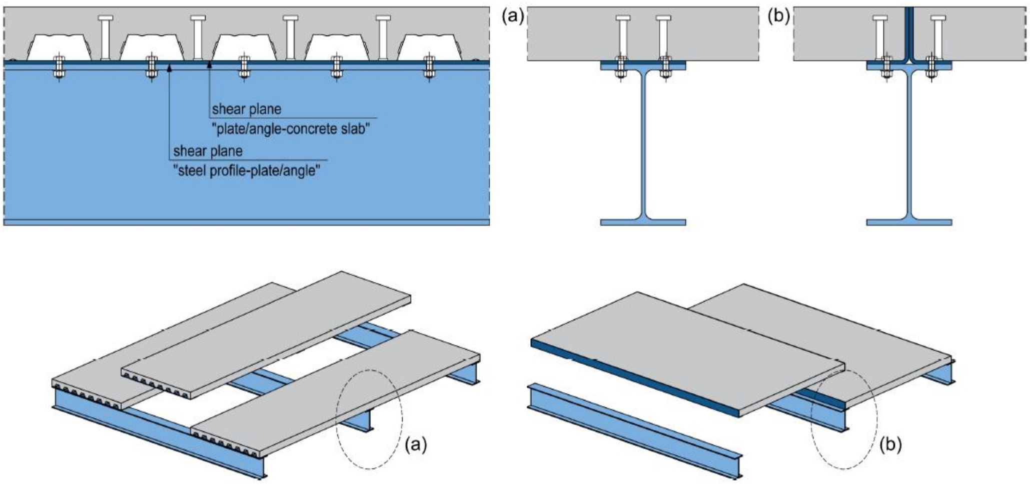


*Figure 1. Concept of demountable shear connection in composite beams (adapted from Jakovljević et al [10]., PhD thesis).*

In addition to the connector type, the material used for the slab also plays a crucial role in the performance of composite systems. Conventional reinforced concrete slabs usually require relatively large thickness and significant reinforcement, which increases the overall structural weight. In contrast, the use of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) enables the design of significantly thinner slabs while maintaining high structural performance.

Application of UHPFRC in composite steel and concrete structures can reduce number or/and size of shear connectors. Namely, in composite slabs with conventional concrete, leading failure mode of studs is generally concrete failure. Considering UHPFRC has importantly higher mechanical properties (even higher than 150 MPa), failure can be achieved by steel studs.

Also, it should be noticed that thinner UHPFRC slabs are more favorable for transport and manipulation during assembling and disassembling for reuse.

Due to its very high compressive strength and improved tensile behavior, UHPFRC provides enhanced crack control and improved post-cracking behavior compared to conventional concrete. These properties allow the development of thinner composite slabs with reduced self-weight. A conceptual comparison between a conventional composite beam with a reinforced concrete slab and a composite beam incorporating a UHPFRC slab is presented in Fig. 3.

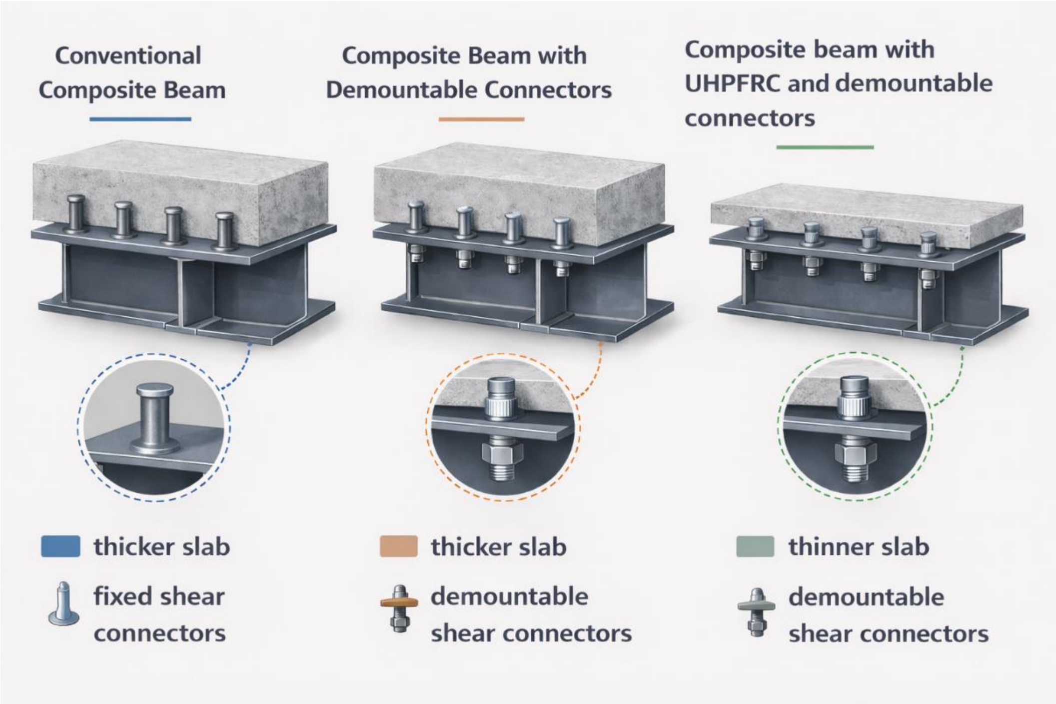


*Figure 2. Comparison of conventional composite beam with reinforced concrete slab and composite beam with UHPFRC slab (created by author).*

The combination of demountable shear connectors and UHPFRC slabs therefore represents a promising approach for the development of more sustainable composite structural systems. Such systems have the potential to reduce material consumption, improve structural efficiency and enable the reuse of steel beams after the end of the service life of the structure. However, further experimental and numerical studies are still required in order to fully understand the structural behavior and long-term performance of these systems [6].

## 5. CONCLUSION

The application of Ultra-High-Performance Fiber Reinforced Cementitious Composites (UHPFRC) in composite structures represents a promising approach for improving structural efficiency and sustainability in modern construction. Due to its exceptional mechanical properties, enhanced durability and improved crack control, UHPFRC enables the development of thinner and more efficient composite slabs compared to conventional reinforced concrete. Also, this type of slabs is very convenient for demountable and reusing.

At the same time, the concept of demountable composite systems provides new possibilities for implementing circular economy principles in structural engineering. Unlike conventional welded shear studs, demountable shear connectors allow the separation of steel beams and concrete slabs after the end of the service life of the structure, enabling the reuse of steel structural elements.

The combination of demountable shear connectors and UHPFRC slabs therefore represents a potentially efficient solution for the development of more sustainable composite structural systems [6], [11]. Reduced slab thickness, improved durability and the possibility of structural disassembly may significantly contribute to lowering material consumption and reducing the environmental impact of construction.

Based on the presented literature review and conceptual considerations, the following conclusions can be drawn:

- UHPFRC provides superior mechanical and durability properties compared to conventional reinforced concrete, enabling the design of thinner composite slabs.
- Demountable shear connectors enable the reuse of steel structural elements and support the implementation of circular economy principles in construction.

- The combination of UHPFRC slabs and demountable connectors represents a promising direction for the development of sustainable composite structural systems.
- Further experimental and numerical research is required in order to better understand the structural behavior and long-term performance of such systems.

Future research will focus on experimental and numerical investigation of composite beams with UHPFRC slabs and demountable shear connectors in order to evaluate their structural behavior and to develop sustainable reusable composite systems.

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