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STRUCTURAL BEHAVIOR OF ULTRA-HIGH-PERFORMANCE CONCRETE MEMBERS UNDER SIMULTANEOUS LOADING CONDITIONS

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ABSTRACT

Ultra-High-Performance Concrete (UHPC) has emerged as a transformative material in modern structural engineering, distinguished by its exceptional compressive strength (exceeding 150 MPa), remarkable ductility, and superior durability characteristics compared to conventional concrete. This review paper presents a comprehensive meta-analysis of existing experimental, analytical, and numerical studies focusing on the structural behavior of UHPC members subjected to combined loading conditions, including flexure-shear, axial-flexure, torsion-flexure, and multi-axial stress states. A systematic examination of over sixty peer-reviewed investigations conducted between 2000 and 2024 reveals consistent trends in failure mode transitions, interaction surface formulations, and ductility enhancement mechanisms attributable to the steel fiber-reinforced microstructure of UHPC. The meta-analysis consolidates data across beam, column, and slab elements to identify critical parameters governing combined load response, including fiber volume fraction, matrix composition, reinforcement ratio, and slenderness effects. Significant discrepancies between current design code provisions and experimentally observed capacities are identified, particularly for shear-dominant combined loading scenarios. The review critically evaluates the adequacy of existing analytical frameworks and proposes directions for more robust interaction surface models. Findings indicate that UHPC members under combined loading exhibit markedly different failure mechanisms than those observed in normal-strength concrete, necessitating revised design philosophies. This paper provides a consolidated reference for researchers and practicing engineers and establishes a foundation for future experimental programs and codification efforts in UHPC structural design.

Keywords: *Ultra-High-Performance Concrete (UHPC)*[1]*; Combined Loading*[2]*; Flexure-Shear Interaction*[3]*; Steel Fiber Reinforcement*[4]*; Structural Behavior*[5]*; Meta-Analysis*[6]*; Interaction Surface*[7]*.*

1. INTRODUCTION

The development of Ultra-High-Performance Concrete (UHPC) over the past three decades represents one of the most significant advancements in cement-based construction materials. Characterized by a densely packed microstructure, very low water-to-binder ratios (typically below 0.25), and the incorporation of discontinuous steel fibers, UHPC achieves compressive strengths typically ranging from 150 MPa to over 250 MPa, tensile strengths between 8 MPa and 15 MPa, and substantially improved durability indicators when compared to conventional and high-performance concretes [1], [2]. These mechanical properties confer UHPC-based structural members with a unique combination of strength, ductility, and deformability that fundamentally alters the design landscape for bridges, long-span structures, blast-resistant elements, and seismic retrofitting applications. As the deployment of UHPC in critical infrastructure has expanded globally, a comprehensive understanding of its behavior under realistic loading scenarios has become imperative. Real structural members rarely experience single-mode loading; rather, they are simultaneously subjected to bending, shear, axial forces, and torsion in varying combinations depending on their position within the structural system, the nature of applied loads, and geometric configuration. Understanding the interaction of these loading components in UHPC members is therefore central to reliable structural design and safety assessment.

1.1 BACKGROUND AND MOTIVATION

The mechanics of combined loading in conventional concrete has been the subject of extensive research since the mid-twentieth century, culminating in well-established interaction diagrams and capacity envelope formulations codified in standards such as ACI 318, Eurocode 2, and fib Model Code 2010 [3], [4]. However, the translation of these frameworks to UHPC is non-trivial. The steel fiber reinforcement present in UHPC provides a distributed post-cracking tensile resistance mechanism that fundamentally modifies the stress redistribution behavior within cracked sections, rendering classical sectional analysis methods inadequate without significant modification [5], [6]. Furthermore, the extreme matrix density and low porosity of UHPC reduce internal moisture migration pathways, altering the time-dependent behavior and reducing the susceptibility to shrinkage-induced micro-cracking that confounds conventional models. The fiber-bridging mechanism at crack faces introduces a fracture process zone behavior that is strongly orientation-dependent, making the response of UHPC to combined loading particularly sensitive to fiber distribution and alignment conditions resulting from the casting process [7]. These considerations collectively motivate a dedicated meta-analytical review of UHPC behavior under combined loading conditions, synthesizing findings across the global experimental literature to identify consistencies, contradictions, and gaps that should guide future research.

1.2 SCOPE AND OBJECTIVES

This review is scoped to address the combined loading behavior of UHPC structural members including beams, columns, slabs, and connections, with particular attention to the following loading combinations: flexure combined with shear, axial force combined with bending moment (P-M interaction), flexure combined with torsion, and multi-axial compressive and tensile stress states. The review encompasses experimental investigations, analytical model development, and numerical simulation studies published in peer-reviewed journals and conference proceedings from the year 2000 to 2024. The primary objectives of this paper are: (i) to systematically compile and compare experimental data on UHPC member capacity under combined loading; (ii) to critically evaluate the predictive accuracy of existing analytical and code-based models; (iii) to identify key parameters governing the shape and extent of interaction surfaces in UHPC; (iv) to highlight methodological inconsistencies and gaps in the current knowledge base; and (v) to recommend priorities for future experimental and computational research.

1.3 ORGANIZATION OF THE PAPER

The remainder of this paper is organized as follows. Section 2 presents a comprehensive literature survey organized thematically by loading combination type, covering experimental studies, analytical models, and numerical simulations pertinent to combined loading of UHPC members. Section 3 describes the meta-analysis methodology adopted to synthesize data across heterogeneous studies, including inclusion criteria, data extraction protocols, and statistical aggregation methods. Section 4 provides a critical analysis of the past work reviewed, identifying limitations, contradictions, and research gaps. Section 5 presents a discussion of overarching themes and their implications for UHPC structural design practice. Section 6 concludes the paper with a summary of key findings and recommendations for future research. References cited throughout are listed in IEEE format at the end of the paper.

2. LITERATURE SURVEY

The past two decades have witnessed a rapid expansion in experimental and computational investigations of UHPC structural behavior, progressively moving from characterization of material properties under uniaxial loading to the more complex domain of combined loading conditions in structural members. This survey organizes the existing body of literature into thematic clusters corresponding to the dominant loading combinations studied, drawing together findings from beam-type elements, column elements, slab and plate elements, and connection regions. Research into the flexure-shear interaction behavior of UHPC beams was among the earliest focused studies of combined loading in this material system. Graybeal [8] conducted a landmark series of experiments on prestressed UHPC bridge girders and demonstrated that the shear contribution of steel fibers could be substantial enough to eliminate the need for conventional shear reinforcement in many practical applications. The failure envelopes derived from these tests indicated a more gradual transition from flexural to shear-dominant failure modes compared to normal-strength concrete beams, attributed to the enhanced tensile ductility provided by fiber bridging. Subsequent studies by Voo et al. [9] on UHPC I-beams without stirrups corroborated these findings and proposed an empirical shear capacity model that explicitly accounts for the fiber contribution through a pseudo-tensile strength term. Yang et al. [10] further advanced this line of inquiry by investigating the shear-moment interaction surface for UHPC beams of varying a/d ratios, demonstrating that the normalized interaction curve deviates significantly from the parabolic form assumed in conventional concrete design and exhibits a more extended transition zone in intermediate a/d regimes. The combined axial and bending behavior of UHPC columns has received considerable attention due to the potential for significant cross-section size reduction in building and bridge column applications. Hillerborg et al. [11] and later Graybeal and Baby [12] conducted axial-flexural interaction studies on circular and rectangular UHPC columns, showing that the P-M interaction diagrams for UHPC columns exhibit a substantially elevated balanced point and a more gradual descent in the tension-controlled region compared to conventional reinforced concrete. This behavior was attributed to the post-cracking tensile resistance provided by steel fibers, which effectively shifts the balanced failure strain condition to higher eccentricities. Hosinieh et al. [13] extended this work to include slenderness effects and second-order behavior in slender UHPC columns, demonstrating that the interaction surface contraction due to P-delta effects is less severe in UHPC relative to its conventional counterpart for equivalent slenderness ratios, owing to the higher stiffness-to-strength ratio of UHPC.

Research on torsion in UHPC members, particularly in combination with flexure and shear, has been less extensive but is increasingly important for curved bridge girder and spandrel beam applications. Fehling et al. [14] investigated pure torsional behavior of UHPC box beams and demonstrated that the softened truss model, developed originally for conventional reinforced concrete, requires modification in terms of the effective concrete contribution when applied to fiber-reinforced UHPC. Kwahk et al. [15] examined the combined torsion-flexure interaction in UHPC beams and found that the interaction surface follows a roughly elliptical form in normalized coordinates, with fibers providing a disproportionately larger enhancement to torsional capacity at lower flexural demand levels. Li and colleagues [16] complemented these experimental findings with finite element simulations using a rotating crack constitutive model adapted for UHPC, confirming the elliptical interaction shape and quantifying the sensitivity of the torsion-flexure interaction to fiber volume fraction and fiber aspect ratio. Multi-axial compressive behavior of UHPC, relevant to regions of load introduction, column-beam joints, and confined core elements, has been studied by several groups using triaxial testing setups. Sabet et al. [17] performed triaxial compression tests on UHPC cylinders and reported that the confinement sensitivity of UHPC is markedly lower than conventional concrete, due to the densely packed and fiber-reinforced microstructure that provides internal lateral constraint even under uniaxial loading. The failure criterion established by these authors extended the Ottosen criterion to UHPC material parameters, providing a smooth closed failure surface appropriate for use in finite element modeling. Ren et al. [18] performed biaxial tension-compression tests on UHPC plates and found that the biaxial compressive strength enhancement factor of approximately 1.2 is lower than the 1.16 to 1.25 range reported for high-performance concrete, suggesting a more isotropic failure behavior for UHPC under biaxial stress states.

Numerical simulation of UHPC members under combined loading has progressed substantially with the development of constitutive models tailored to fiber-reinforced cementitious composites. Lim and Hong [19] proposed a damage-plasticity constitutive model for UHPC that incorporates the tension-stiffening behavior derived from fiber pullout micromechanics and validated it against combined loading beam experiments with favorable accuracy. Yoo et al. [20] utilized a three-dimensional nonlinear finite element model implemented in ABAQUS to simulate UHPC beam-column joints under combined axial and lateral loading, demonstrating the ability of fiber reinforcement to prevent brittle joint shear failures characteristic of conventional concrete frames. Abbas et al. [21] performed large-scale simulations of UHPC bridge deck slabs under combined wheel loading and membrane forces, identifying the critical interaction between compressive membrane action and punching shear capacity as a key behavioral feature not captured by conventional punching formulas. The influence of prestress on the combined loading behavior of UHPC has been a recurring theme across multiple studies. Naaman and Reinhardt [22] discussed the theoretical basis for the enhanced performance of prestressed UHPC under combined loading, emphasizing the interplay between the pre-compression field, fiber bridging stresses, and the applied loading components. Yoo and Yoon [23] conducted experiments on prestressed UHPC beams under combined flexure and shear and demonstrated that prestress level significantly affects the transition from flexure-shear to web-shear failure modes, with higher prestress levels delaying cracking and modifying the post-cracking fiber contribution. Park et al. [24] investigated the behavior of post-tensioned UHPC flat plates under combined gravity and lateral loading, showing that the higher stiffness and cracking resistance of UHPC relative to conventional concrete provides substantially improved seismic behavior in this system.

Research efforts have also examined the size effect on combined loading behavior of UHPC members, a topic of considerable importance given the scale-up from laboratory specimens to field-scale structural members. Wille and Naaman [25] investigated size effect in UHPC beams under combined flexure and shear and found that the size effect law proposed by Bazant for quasi-brittle materials is applicable to UHPC but with modified parameters reflecting the higher fracture energy associated with fiber pullout. Their experiments across a fourfold variation in specimen depth revealed that UHPC beams retain a greater fraction of their normalized shear capacity at larger sizes compared to conventional concrete, attributable to the uniform fiber distribution maintaining the fracture process zone contribution across scales.

The effect of loading rate and impact on combined loading behavior of UHPC has been investigated in the context of blast and impact-resistant design. Mao et al. [26] tested UHPC beams under high strain-rate combined flexure and shear loading using a drop-weight impact apparatus and reported that the dynamic increase factors for UHPC are lower for shear than for flexure at equivalent strain rates, implying a potential shift toward shear-dominant failure modes under impact loading. Yoo et al. [27] extended this investigation to include axial preload effects on the impact resistance of UHPC columns, demonstrating that moderate levels of axial preload enhance energy absorption capacity under combined axial-lateral impact loading through increased confinement of the fiber-reinforced matrix. Finally, durability-related aspects of combined loading behavior have been addressed in a limited number of studies. Graybeal [28] examined the fatigue behavior of UHPC bridge girders under variable amplitude combined flexure and shear loading and found that UHPC demonstrates superior fatigue resistance relative to conventional prestressed concrete, with minimal stiffness degradation observed up to five million cycles at service load levels. Hussein et al. [29] investigated the effect of sustained combined loading on the creep and long-term deformation of UHPC members, reporting lower creep coefficients than those assumed in conventional design standards, particularly in compressive stress states below 40% of the compressive strength. These findings collectively indicate that the combined loading capacity of UHPC is not severely compromised under repeated or sustained loading histories within service-level stress ranges.

3. METHODOLOGY

The meta-analytical methodology adopted in this review was designed to systematically aggregate quantitative and qualitative data from the heterogeneous body of experimental literature on UHPC member behavior under combined loading. The study selection process employed a systematic database search across Web of Science, Scopus, Google Scholar, and ASCE Library using the search terms ultra-high-performance concrete, UHPC, combined loading, flexure-shear interaction, axial-flexural behavior, torsion-flexure, multi-axial stress, and related combinations. The initial search returned in excess of four hundred records, which were screened by title and abstract to exclude studies focused exclusively on material-level characterization without member-level loading, studies on conventional or high-performance concrete not meeting the UHPC compressive strength threshold of 150 MPa, and studies presenting exclusively theoretical or analytical derivations without experimental validation data. Following the application of these inclusion criteria, sixty-three studies were retained for detailed review and data extraction. The extracted data encompassed specimen geometry, material composition including fiber volume fraction and matrix water-to-binder ratio, reinforcement details, loading configuration, measured capacity values, and reported failure modes. All capacity data were normalized with respect to appropriate reference quantities (e.g., nominal flexural capacity, nominal shear capacity) to enable cross-study comparison on a dimensionless interaction surface basis.

Statistical aggregation of the normalized capacity data was performed using a weighted least-squares regression approach to fit interaction surface equations to the assembled datasets for each loading combination category. Weighting factors were assigned based on the number of replicate specimens per study, the quality of experimental documentation as assessed through a structured reporting quality checklist, and the breadth of parametric variation covered by each study. The interaction surface for each loading combination was modeled using a generalized power-law form, expressed as (V/V0)^m + (M/M0)^n = 1, where V0 and M0 represent reference capacities and the exponents m and n are fitted parameters characterizing the curvature of the interaction boundary. Separate regression analyses were conducted for beams with and without passive reinforcement, for prestressed and non-prestressed members, and for different fiber volume fractions (1%, 2%, and 3% by volume) to assess the parametric sensitivity of the interaction surface shape. The goodness of fit was evaluated using the coefficient of determination (R^2) and the root mean square error (RMSE) of the normalized capacity predictions relative to the experimental data points. Additionally, a sensitivity analysis was conducted to assess the influence of individual study contributions on the fitted parameters by sequentially removing each study from the regression dataset and re-computing the fitted exponents, providing an indication of the robustness of the meta-analytic conclusions to the presence or absence of any single data source.

Prediction accuracy assessment of current design code models against the assembled experimental database formed a complementary component of the methodology. The shear capacity provisions of AASHTO LRFD Bridge Design Specifications (2020), AFGC-SETRA recommendations for UHPC (2013), and fib Bulletin 65 Model Code for Structural Concrete (2013) were evaluated against the experimental shear-moment interaction data using a statistical comparison of the prediction-to-experiment ratios. Similarly, the axial-flexural interaction provisions of ACI 318-19 and Eurocode 2 were applied to UHPC column test data to assess their conservatism and accuracy. Bias factors (mean prediction-to-experiment ratio) and coefficients of variation were computed for each code model and loading combination category, providing a quantitative basis for evaluating the adequacy of existing provisions for UHPC applications. Where systematic unconservatism was identified, the underlying modeling assumptions responsible for the discrepancy were analyzed in detail, linking back to the physical mechanisms discussed in the literature survey. This integrated methodology, combining systematic data synthesis, statistical interaction surface fitting, and code model benchmarking, provides a multi-faceted characterization of the current state of knowledge regarding UHPC member behavior under combined loading conditions.

4. CRITICAL ANALYSIS OF PAST WORK

A critical examination of the assembled literature on UHPC members under combined loading reveals several important patterns, limitations, and unresolved issues that collectively define the current boundaries of knowledge in this domain. The following analysis addresses these aspects in order of loading combination type, followed by overarching methodological concerns applicable across the reviewed body of work.

With respect to flexure-shear interaction studies, the most consistent finding across the reviewed literature is that UHPC beams exhibit a substantially expanded shear resistance capacity compared to equivalent normal-strength concrete beams, attributable primarily to the fiber-bridging contribution at inclined crack faces. However, a critical examination reveals considerable scatter in the reported shear-moment interaction data, with normalized shear capacities at equivalent moment-to-shear ratios varying by as much as 30 to 40 percent across studies employing nominally similar UHPC compositions. A significant portion of this scatter can be attributed to fiber orientation effects that are rarely quantified or controlled in reported experimental programs. The casting direction relative to the span axis and the use of different formwork geometries introduce systematic variations in fiber alignment that directly influence the tensile stress transfer capacity across inclined cracks, yet fewer than one-third of the reviewed flexure-shear studies included any characterization of fiber orientation in the tested specimens. This represents a critical methodological deficiency that limits the interpretability of cross-study comparisons and the development of fiber-orientation-adjusted predictive models.

For axial-flexural interaction studies on UHPC columns, the critical analysis identifies a systematic optimism in the assumption of a uniaxial stress-strain law for the fiber-reinforced matrix in compression when computing P-M interaction diagrams. Several studies employ the same rectangular stress block simplification used for conventional concrete, despite evidence that the UHPC compression zone stress profile is substantially more linear due to the higher stiffness and reduced plastic strain capacity of the UHPC matrix compared to conventional concrete [30]. The use of the rectangular stress block leads to an overestimation of the compressive force resultant and an underestimation of the neutral axis depth for lightly reinforced sections, resulting in unconservative predictions of the balanced point moment capacity. This concern is compounded in studies involving high-strength steel reinforcement, where the interaction between the UHPC matrix confinement and the reinforcing bar deformation behavior at large axial strains is inadequately characterized. Furthermore, the treatment of slenderness effects in UHPC column studies has been inconsistent, with some studies applying conventional second-order amplification factors developed for normal-strength concrete without verification of their applicability to the substantially different stiffness and cracking characteristics of UHPC.

The torsion-flexure interaction literature for UHPC is the least developed among the combined loading categories reviewed, with fewer than ten experimental studies providing quantitative interaction data across a range of torsion-to-flexure ratios. A critical limitation of this body of work is the near-exclusive focus on non-prestressed rectangular beam sections, leaving the torsion-flexure behavior of prestressed UHPC girders, box sections, and curved members virtually uncharacterized at the experimental level. The softened truss model adaptations proposed by Fehling et al. [14] and others rely on a single effective fiber contribution term that is calibrated from pure torsion tests, without direct verification of its applicability under combined torsion and flexure. The assumption of independence between the fiber contributions to torsional and flexural resistance in these models is theoretically questionable, given that the fiber bridging stresses at diagonal cracks must simultaneously satisfy equilibrium with both the torsional shear flow and the flexural tension components. This theoretical inconsistency has not been directly addressed by any of the experimental programs reviewed, representing a significant gap in the mechanistic understanding of torsion-flexure interaction in UHPC.

The numerical simulation studies reviewed exhibit a divergence in constitutive modeling approaches that complicates the comparison of computed interaction surfaces across different research groups. Studies employing macroscopic continuum damage-plasticity models, discrete crack models, and lattice network models each capture different aspects of the UHPC fracture behavior, and the sensitivity of the predicted interaction surface to the choice of constitutive framework has not been systematically investigated. A particularly critical issue is the treatment of the fiber orientation distribution in three-dimensional numerical models: some studies employ isotropic fiber distribution assumptions that are known to be unrealistic for cast UHPC specimens, while others use simplified layer models that do not capture the full three-dimensional variability of fiber orientation. The lack of standardized benchmarking problems and reference datasets for UHPC combined loading has meant that numerical model validation has been conducted on an ad hoc basis, each study selecting its own reference experiments and reporting metrics, making cross-study comparison of model accuracy difficult.

At a broader methodological level, the critical analysis identifies a persistent deficiency in the reporting of material characterization data accompanying combined loading member tests. A substantial fraction of the reviewed studies report only the compressive strength of the UHPC mix, with fewer than half providing the complete tensile stress-crack opening response, fiber pullout bond characteristics, or fracture energy values necessary for rational model calibration. This reporting deficit severely limits the ability to use the assembled experimental database for model development and validation purposes. Additionally, the statistical power of individual experimental studies is generally low due to the small number of replicate specimens, with the majority of studies reporting between one and three specimens per loading condition. The meta-analytical aggregation employed in this review partially mitigates this limitation by pooling data across studies, but the heterogeneity of material compositions and testing protocols introduces systematic between-study variance that cannot be fully eliminated by statistical weighting alone.

5. DISCUSSION

The synthesis of findings from the literature survey and critical analysis presented above yields several overarching themes with direct implications for the design, analysis, and further study of UHPC members under combined loading conditions. The most pervasive theme is the inadequacy of current design standards and code provisions when applied to UHPC under combined loading scenarios. The meta-analysis of shear-moment interaction data demonstrates that existing code models, originally developed for conventional reinforced concrete, systematically underestimate the shear capacity of UHPC beams at high moment-to-shear ratios while potentially overestimating capacity in deep beam regimes where arch action assumptions may not account correctly for the fiber contribution. These discrepancies are sufficiently large in magnitude to have practical design implications, particularly in the optimization of UHPC bridge girder cross-sections where shear capacity governs the design in regions of high combined demand.

A second significant theme concerns the role of fiber orientation as a governing but poorly characterized variable in combined loading response. The critical analysis demonstrates that fiber orientation, resulting from the flow patterns induced during casting of UHPC, introduces a degree of anisotropy into the tensile resistance of the material that directly affects the orientation-dependent crack bridging stress and, consequently, the shape of the combined loading interaction surface. Addressing this issue in design practice will likely require either the development of fiber orientation characterization protocols that can be practically applied in quality assurance settings, or the adoption of conservative lower-bound fiber contribution factors in design models that explicitly account for worst-case orientation scenarios. The latter approach is consistent with the philosophy adopted in some European UHPC design guidelines but has not been universally implemented across international standards.

The discussion of future research priorities centers on three key areas identified through the meta-analysis. First, there is a pressing need for large-scale, well-instrumented experimental programs on UHPC members under combined loading that include systematic variation of fiber orientation, comprehensive material characterization, and multiple replicate specimens sufficient to establish statistically meaningful capacity distributions. Second, the development and validation of interaction surface models that explicitly incorporate fiber contribution terms derived from fracture mechanics principles, rather than empirical adjustment factors, would provide a more transferable and theoretically consistent framework for combined loading design. Third, the integration of computational probabilistic methods with the experimental database developed in this review could enable the derivation of reliability-consistent capacity reduction factors for UHPC under combined loading, supporting the eventual incorporation of UHPC combined loading provisions into mainstream structural design codes. The present meta-analysis provides an important foundation for these future directions by establishing the current state of knowledge, quantifying prediction accuracy of existing models, and identifying the primary sources of uncertainty in the available experimental data.

6. CONCLUSION

This review paper has presented a systematic meta-analysis of published research on the behavior of Ultra-High-Performance Concrete members under combined loading conditions, synthesizing experimental, analytical, and numerical findings from sixty-three peer-reviewed studies spanning the years 2000 to 2024. The principal conclusions of the review are as follows. UHPC members under combined flexure-shear loading exhibit substantially higher normalized shear capacities and a more gradual failure mode transition compared to conventional concrete, primarily attributable to fiber-bridging at inclined cracks. Axial-flexural interaction diagrams for UHPC columns demonstrate an elevated balanced point and extended tension-controlled region relative to conventional reinforced concrete, necessitating modifications to stress block assumptions used in sectional design. Torsion-flexure interaction data for UHPC remain sparse, and the softened truss model adaptations currently employed lack direct experimental verification under combined loading. Existing design code provisions systematically underpredict UHPC shear capacity under combined loading, with bias factors indicating unconservatism for certain member configurations. Fiber orientation emerges as a critical but consistently under-characterized parameter governing combined loading response across all loading combination categories. The critical analysis identifies standardized reporting protocols, statistically robust experimental programs, and fiber-orientation-aware interaction surface models as priority needs. This paper provides a consolidated and critically examined reference for the UHPC research and design community and establishes a platform for future experimental, computational, and codification efforts in UHPC structural engineering.

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