

Article

Stress-State-Based Failure Analysis and Modeling of UHPC Columns Confined with High-Strength Spiral Stirrups

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Abstract

This study investigated the failure mechanism and load-bearing capacity of ultra-high-performance concrete (UHPC) columns confined with high-strength spiral stirrups under axial compression. Based on tests of 75 specimens, a structural stability analysis method was employed to convert multi-point strain measurements into the normalized generalized strain energy density ($E_{j,norm}$). The mutation point (Point U) on the $E_{j,norm}$ - F_j curve, identified via the Mann–Kendall criterion, was proposed as a novel indicator for structural instability and the practical failure load. Parametric analysis showed that increasing the UHPC compressive strength from 100 MPa to 180 MPa raised the failure load by 63%, while increasing the stirrup volumetric ratio from 0.9% to 2.0% yields a further 7.5% increase in the failure load. In contrast, the yield strength of stirrups exerts a negligible influence on the failure load, as the stirrups do not reach their yield strength at the failure load of the concrete columns. A new predictive model for the failure load was developed, which exhibited excellent agreement with test results (mean ratio = 1.000, standard deviation = 0.046, errors within $\pm 13\%$). The proposed method provided a reliable and stable approach for evaluating the failure load-bearing capacity of confined UHPC columns. The validated predictive model enabled engineers to determine the failure load of confined UHPC columns through simple calculation rather than expensive experimental testing, reducing project costs by 5–10% through optimized material selection and accelerating design timelines by weeks, thereby making UHPC columns more economically competitive for mainstream infrastructure applications.

Keywords: axial compression; characteristic parameter; failure load; generalized strain energy density; stress state; spiral stirrups; UHPC column



Academic Editor: Salvatore Verre

Received: 2 March 2026

Revised: 19 March 2026

Accepted: 23 March 2026

Published: 27 March 2026

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1. Introduction

In recent years, ultra-high-performance concrete (UHPC) has gained widespread application in civil engineering due to its exceptional mechanical properties, including a compressive strength exceeding 120 MPa and a tensile strength surpassing 7 MPa, as well as superior durability [1–6]. Those exceptional properties make UHPC particularly attractive for load-bearing columns in high-rise structures, bridge piers, and seismic-resistant frames, where reduced column sizes translate directly to increased usable floor space, reduced foundation loads, and enhanced architectural flexibility.

However, the increased compressive strength of UHPC is often accompanied by brittle failure under axial compression. Steel tube concrete columns significantly enhanced load-bearing capacity and ductility by filling steel tubes with concrete, utilizing the confinement effect of steel tubes on the core concrete. The failure modes of steel tube concrete columns were primarily influenced by cross-sectional geometric parameters (such as radius-to-thickness ratio and length-to-diameter ratio), while the core concrete substantially affected ductility, stiffness, and axial compressive strength. Fiber-reinforced plastic (FRP)-constrained concrete columns leveraged the high tensile strength, corrosion resistance, and lightweight properties of FRP materials. By employing FRP tubes or FRP fabric wrapping for lateral confinement, those columns markedly improve axial compressive load-bearing capacity and deformation capability. Studies indicated that FRP confinement effectiveness was comprehensively influenced by fiber type, number of layers, orientation, and resin matrix properties, with FRP confinement demonstrating superior environmental erosion resistance compared to steel tube confinement. Recent research has explored novel systems such as FRP-steel composite tube-constrained concrete columns and epoxy concrete concrete (ECC)-reinforced concrete columns. ECC, a high-ductility fiber-reinforced cement-based composite material exhibiting strain hardening characteristics, can be used for full-encapsulation or localized reinforcement of conventional concrete columns, significantly improving failure modes, peak load capacity, and ductility performance. This study focuses on ultra-high-performance concrete (UHPC) columns constrained by embedded high-strength spiral stirrups. This confinement method provided lateral restraint through discrete spiral stirrups, whose confinement mechanism fundamentally differs from continuous tubular confinement. The confinement force of spiral stirrups exhibits a discrete distribution along column height, with confinement effectiveness determined by the combination of stirrup spacing, diameter, and yield strength. Through stress state analysis methods, this study revealed a unique phenomenon where stirrups remained in the elastic stage at the instability point of such structural components, elucidating the mechanical mechanism where constraint efficiency was primarily determined by stirrup volume ratio rather than yield strength. This finding contrasts sharply with conventional principles in reinforced concrete structures, where restraint forces were dominated by steel pipe yield strength, and in FRP constraints, restraint forces are governed by FRP tensile strength. The study highlights the distinctive working mechanism of high-strength spiral stirrups in UHPC column restraint systems, providing a scientific basis for optimizing design methodologies of such structural components.

In spiral stirrups confined concrete columns, existing studies have demonstrated that the lateral confinement effect of stirrups diminished near the peak stress of confined concrete as the compressive strength of concrete increases [7–9], leading to a pronounced post-peak softening behavior in the axial load-deformation curves of confined concrete columns. Traditionally, the peak axial load has been adopted as the design load-bearing capacity for axially compressed concrete columns [10,11]. However, the steep ascending branch of the load-deformation curve near the peak load indicated an unstable stress state in confined columns. Consequently, a comprehensive evaluation of the stress state in spiral stirrup confined UHPC columns is essential to ensure structural safety and service performance.

Researchers have also studied the working state of UHPC confined with stirrups under axial compression. Baduge investigated the compression behavior of very high-strength concrete (>100 MPa) columns confined with spiral stirrups and indicated that the axial compressive stress-strain curves could be divided into three parts, including elastic linear stage, nonlinear stage, and descending branch [12,13]. In addition, the axial stress drops abruptly after the peak stress and then stabilizes at a stress plateau. Deng et al. investigated the compression behavior of UHPC confined with stirrups and found that the axial stress–

strain curves presented three stages: elastic stage, elastic-to-plastic stage, and plastic stage [14–17]. They pointed out that UHPC with a low stirrup volumetric ratio exhibits brittle failure after the peak stress, while both the peak stress and peak strain increased with the stirrup volumetric ratio. Chang et al. analyzed the effects of stirrups' volumetric ratio, stirrup configuration, stirrup spacing, and steel fiber volume fraction on the peak stress and peak strain of confined UHPC [18]. The results showed that confined UHPC with a high stirrup volumetric ratio, small stirrup spacing, and high steel fiber content featured a gentle descending branch in the stress–strain curve, along with an improved deformation capacity of the UHPC column. Yang et al. explored the compression behavior of UHPC with 2% steel fibers in volume fraction confined with spiral stirrups with a tensile strength of 414 MPa, concluding that the peak stress and the ultimate strain of UHPC were increased by 108 MPa and 1.37% in the maximum, respectively [19]. Chang et al. indicated that high-strength spiral stirrups enhanced the compressive behavior of confined UHPC, while the axial stress of confined UHPC at the peak stress declined abruptly, but the stress-unstable state of confined UHPC was not considered [20]. Shin et al. [21] researched UHPC columns to study the influence of configurations and volumetric ratio of transverse reinforcement on compressive behaviors of the specimens. It was demonstrated that closely spaced or well-detailed configurations of transverse reinforcement can improve the compressive behavior of UHPC columns. Hoang et al. [22,23] tested the axial compression behavior of steel tube confined UHPC and indicated that all specimens had good ductility in the post-peak stress; the strength enhancements of confined UHPC were not more obvious than those of unconfined UHPC. Vogel et al. [24] found that the triaxial compressive strength of UHPC followed a power law function of the confining pressure, and the development of triaxial compressive strength of UHPC was different from that of NSC and HSC.

Previous studies have mainly focused on the compressive behavior and axial stress–strain curves of stirrup-confined UHPC columns. However, with the increase in UHPC compressive strength, axially compressed UHPC columns tended to undergo brittle failure, implying that such columns were in an unstable stress state at the peak stress. In addition, the lateral stress of stirrups at the peak stress decreases with the increase in UHPC compressive strength, and stirrups may not reach their yield strength at the peak stress of confined concrete. As a result, the lateral confinement effect of stirrups at the peak stress of confined UHPC cannot be accurately quantified. In previous studies [10,25], the axial load–deformation or stress–strain curves of confined concrete were the main characteristic curves used to analyze the compressive behavior of confined UHPC, and predictive models for the axial stress–strain curves of confined UHPC were developed. Moreover, the failure load of UHPC columns confined with high-strength spiral stirrups has been determined based on a semi-empirical and semi-theoretical approach with considerable inaccuracy, leading to a relatively conservative design load in terms of bearing capacity. Therefore, reliable analytical methods were required to accurately predict the failure loads and failure modes of UHPC columns confined with high-strength spiral stirrups.

While previous stress state analyses have successfully employed generalized strain energy density (GSED) to characterize structural behavior [26,27], those studies primarily focused on using GSED as a descriptive tool to identify characteristic points in the loading history. Hou et al. [26] and Liu et al. [27] demonstrated that normalized GSED curves could reveal the elastic limit and yielding points of confined concrete and reinforced concrete members, respectively. However, these investigations stopped short of establishing a direct, physically meaningful link between these energy-based characteristic points and a definitive failure criterion for design. The identified points were often correlated with traditional material limits rather than being proposed as a fundamental indicator of structural instability itself. This study shifted the focus from merely describing the

stress state to predicting its terminal stable point. Employing the Mann–Kendall trend test identified the mutation point (Point U) on the $E_{j,norm}$ - F_j curve. The point U was rigorously defined as the transition from a stable to an unstable internal stress state, representing the true physical limit of stable load-bearing capacity. The proposed framework provided a unified and objective methodology for failure load determination that was independent of subjective interpretations of the stress-strain curve's shape. Traditional methods often rely on identifying the peak load or a visual assessment of the curve's descending branch, which can be ambiguous, especially for brittle materials with a sharp post-peak drop. In contrast, the Mann–Kendall criterion applied to the FI_j - F_j curve offered a repeatable, statistical basis for pinpointing the onset of instability, enhancing the reliability and comparability of results across different specimens and test setups.

In this study, an axial compression test involving seventy-five specimens was carried out to explore the structural stress state of UHPC columns confined with high-strength spiral stirrups. The general strain energy density values (E_j) of specimens at each load (F_j) were normalized as $E_{j,norm}$ to describe the structural stress state. Then, the stress state characteristics and the failure mechanism of confined UHPC columns were analyzed according to the $E_{j,norm}$ - F_j curves of specimens. Meanwhile, the failure load of confined UHPC columns was determined by the Mann–Kendall criterion and the $E_{j,norm}$ - F_j curves slope criterion. Furthermore, the effects of the compressive strength of UHPC, the volumetric ratio, and the yield strength of stirrups on the failure load of confined UHPC columns were analyzed. Finally, the prediction models for evaluating the failure load of confined UHPC columns were proposed.

2. Structural Stress State Theory

2.1. Description of Structural Stress State

The structural stress state was defined as the mechanical behavior of structural components or units under a specific loading condition [28,29]. Commonly, measured strains were used to describe the stress state mode and characteristic parameters of a structure [30–33]. However, strains were directional quantities, which complicated the characterization of the overall stress state of a structure. To address this issue, the measured strains were redefined as a state variable (namely generalized strain energy density, GSED). As a scalar quantity, the normalized GSED values of the structural components or units can be easily integrated to characterize the overall stress state behavior of a structure [26,28].

In this study, the stress state analysis of concrete columns confined with spiral stirrups followed the following procedure: (a) treat the measured strains as state variables; (b) construct the stress state characteristic parameter from the state variables; (c) plot the curve of the characteristic parameter against the applied load and adopt a criterion to identify the mutation point in the curve; (d) define the mutation point as the failure load corresponding to the characteristic parameter of the column.

The state variable E_i at the i th measuring point can be calculated as follows:

$$E_i = \int \sigma_1 d\varepsilon_1 + \int \sigma_2 d\varepsilon_2 + \int \sigma_3 d\varepsilon_3 \quad (1)$$

where E_i was the state variable of the i th measure point; σ_1 , σ_2 , and σ_3 were the principal stresses in the three directions; ε_1 , ε_2 , and ε_3 were the principal strains in the three directions.

For the measured strains, Equation (1) can be written as follows:

$$E_{ij} = \frac{1}{2} E \varepsilon_{ij}^2 \quad (2)$$

where E_{ij} and ε_{ij} were the state variable and strain of the i th measured point at the j th load, respectively; E was the elastic modulus of the material.

The stress state characteristic parameter $E_{j,norm}$ of the confined concrete, can be defined as in Equation (3).

$$E_{j,norm} = \frac{\sum_{i=1}^N E_{ij}}{N \times E_M} \quad (3)$$

where N was the number of measured points; E_M was the maximum GSED value over the loading process. In the following sections, the $E_{j,norm}$ - F_j curve of the concrete column confined with spiral stirrups was investigated to reveal the mutation point.

2.2. Criteria for Detecting Mutation Point

2.2.1. Slope Increment Criterion

The slope increment criterion reflected the speed of increasing and decreasing amplitude at every point in the $E_{j,norm}$ - F_j curve. In other words, the characteristic points in the $E_{j,norm}$ - F_j curves can be identified by the slope change trend of the $E_{j,norm}$ - F_j curve. The slope of the $E_{j,norm}$ - F_j curve can be expressed as the index FI_j , listed in Equation (4).

$$FI_j = \frac{E_{j,norm} - E_{j-1,norm}}{F_j - F_{j-1}} (j > 2) \quad (4)$$

where FI_j was the slope index at the j th load. The FI_j - F_j curve can be plotted to define the mutation point in the $E_{j,norm}$ - F_j curve.

2.2.2. Mann–Kendall Criterion

The Mann–Kendall test statistic was applied to analyze the sign differences between earlier and later data points in a sequence [34]. The core idea is that a consistent upward or downward trend in the sequence will result in a continuous increase or decrease in the sign values of the data points. Thus, in this paper, the Mann–Kendall method was applied to identify the mutation point of the stress state in concrete columns confined with spiral stirrups based on the FI_j - F_j curves. For the numerical sequence of the FI_j - F_j curves, the Mann–Kendall criterion can be implemented through the following steps:

(1) Based on FI_j - F_j curves, take the cumulative number r_i that E_i was greater than E_j ($1 \leq j \leq i$) from the sequence $(FI_1, FI_2, FI_3, \dots, FI_n)$, where n was the number of measurement points in the sequence. The cumulative number r_i was defined in Equation (5).

$$r_i = \begin{cases} 1 & FI_i > FI_j \\ 0 & \text{Otherwise} \end{cases} \quad (5)$$

(2) Construct a sequence s_k , listed in Equation (6). The mean values $E(s_k)$ and the variance $\text{var}(s_k)$ of the constructed sequence can be calculated in Equations (7) and (8), respectively.

$$s_k = \sum_{i=1}^k r_i (2 \leq k \leq n) \quad (6)$$

$$E(s_k) = \frac{k(k-1)}{4} \quad (7)$$

$$\text{var}(s_k) = \frac{k(k-1)(2k+5)}{72} \quad (8)$$

(3) Equation (9) was applied to normalize s_k to obtain the GF - F curves of specimens.

$$GF_k = \frac{s_k - E(s_k)}{\sqrt{\text{var}(s_k)}} \quad (9)$$

(4) Inverse sequence ($FI_1, FI_2, FI_3, \dots, FI_n$) to be a backward sequence ($FI_n, FI_{n-1}, FI_{n-2}, \dots, FI_1$). According to the procedures (1)~(3), the r'_i and s'_k can be calculated by Equations (5) and (6). The normalized s'_k can be calculated by Equation (10), and the GF - F_j curves of specimens were obtained.

$$GB_k = \frac{-(s'_k - E(s'_k))}{\sqrt{\text{var}(s'_k)}} \quad (10)$$

(5) The intersecting points between the GF - F curves and GB_j - F curves were the leap points of the FI_j - F_j curves, and also were the leap points of the $E_{j,norm}$ - F_j curves.

3. Experimental Program

A total of 75 axially compressed UHPC columns confined with high-strength spiral stirrups were designed in compliance with GB/T 50010-2010 [35]. All specimens had a diameter of 265 mm and a height of 1100 mm, and were divided into five groups according to the UHPC strength grade. Each group included three types of stirrups with five different volumetric ratios, ensuring a comprehensive parametric investigation. All specimens were reinforced with four longitudinal steel bars. The confinement system consisted of spiral stirrups with two diameters: 7 mm (with spacing of 65 mm, 50 mm, and 40 mm) and 9 mm (with spacing of 60 mm and 50 mm). Figure 1a illustrates the geometry of the specimens, and Table 1 provides the complete design parameters of all test specimens.

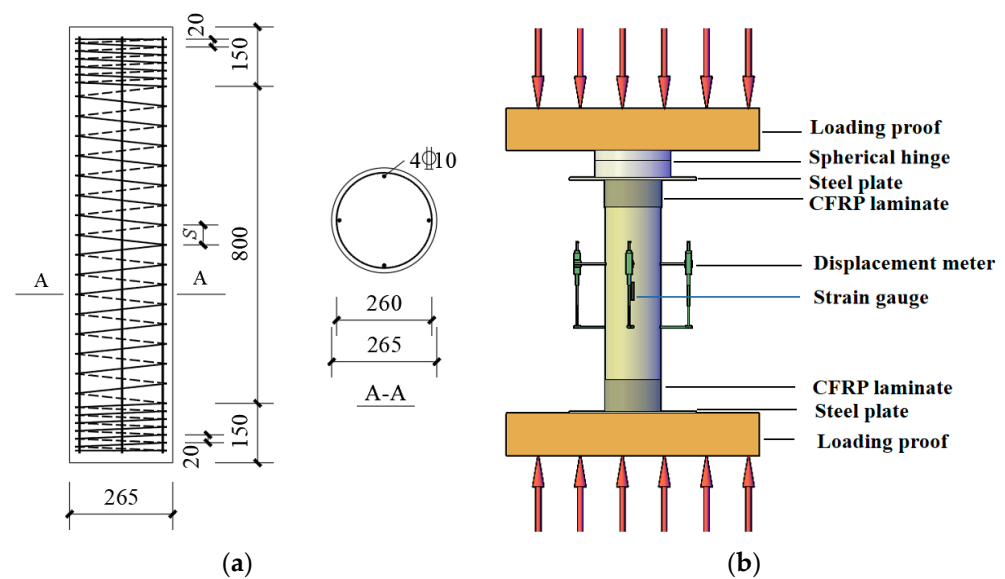


Figure 1. Specimens geometry and test setup: (a) specimens geometry details of UHPC column specimens (unit: mm), showing the arrangement of the longitudinal reinforcement and the high-strength spiral stirrups; (b) test setup, showing the placement of a specimen within the loading frame, the instrumentation (displacement transducers), and the data acquisition system. Reprinted with permission from Ref. [20]. Copyright 2021, Springer Nature.

Table 1. Design details of specimens.

Specimens	f_c (MPa)	$f_{0.2}$ (MPa)	s (mm)	d_s (mm)	ρ_v (%)	ρ_{lr} (%)	f_{cc} (MPa)	ε_{cc} ($\varepsilon \times 10^{-6}$)	ε_{sv0} ($\mu\varepsilon$)
UHPC100-800-0.9	84.72	818	65	7	0.9	0.590	97	3295	1630
UHPC100-800-1.2	84.72	818	50	7	1.2	0.590	109	4320	2440

Table 1. Cont.

Specimens	f_c (MPa)	$f_{0.2}$ (MPa)	s (mm)	d_s (mm)	ρ_v (%)	ρ_{lr} (%)	f_{cc} (MPa)	ε_{cc} ($\varepsilon \times 10^{-6}$)	ε_{sv0} ($\mu\varepsilon$)
UHPC100-800-1.4	84.72	818	40	7	1.4	0.590	115	4585	2710
UHPC100-800-1.6	84.72	818	60	9	1.6	0.590	119	4896	2900
UHPC100-800-2.0	84.72	818	50	9	2.0	0.590	127	5632	3270
UHPC100-970-0.9	84.72	926	65	7	0.9	0.590	102	3596	1742
UHPC100-970-1.2	84.72	926	50	7	1.2	0.590	110	4287	2465
UHPC100-970-1.4	84.72	926	40	7	1.4	0.590	114	4714	2667
UHPC100-970-1.6	84.72	926	60	9	1.6	0.590	119	5198	2998
UHPC100-970-2.0	84.72	926	50	9	2.0	0.590	124	5613	3293
UHPC100-1270-0.9	84.72	1190	65	7	0.9	0.590	101	3503	1744
UHPC100-1270-1.2	84.72	1190	50	7	1.2	0.590	109	4169	2290
UHPC100-1270-1.4	84.72	1190	40	7	1.4	0.590	114	4716	2800
UHPC100-1270-1.6	84.72	1190	60	9	1.6	0.590	120	5206	3074
UHPC100-1270-2.0	84.72	1190	50	9	2.0	0.590	125	5614	3234
UHPC120-800-0.9	101.66	818	65	7	0.9	0.590	121	3974	1625
UHPC120-800-1.2	101.66	818	50	7	1.2	0.590	127	4501	2242
UHPC120-800-1.4	101.66	818	40	7	1.4	0.590	133	5096	2615
UHPC120-800-1.6	101.66	818	60	9	1.6	0.590	136	5546	2797
UHPC120-800-2.0	101.66	818	50	9	2.0	0.590	143	5998	3006
UHPC120-970-0.9	101.66	926	65	7	0.9	0.590	119	4033	1635
UHPC120-970-1.2	101.66	926	50	7	1.2	0.590	130	4836	2268
UHPC120-970-1.4	101.66	926	40	7	1.4	0.590	133	5163	2627
UHPC120-970-1.6	101.66	926	60	9	1.6	0.590	136	5574	2809
UHPC120-970-2.0	101.66	926	50	9	2.0	0.590	142	6096	3016
UHPC120-1270-0.9	101.66	1190	65	7	0.9	0.590	120	4086	1641
UHPC120-1270-1.2	101.66	1190	50	7	1.2	0.590	128	4872	2273
UHPC120-1270-1.4	101.66	1190	40	7	1.4	0.590	133	5174	2633
UHPC120-1270-1.6	101.66	1190	60	9	1.6	0.590	137	5594	2816
UHPC120-1270-2.0	101.66	1190	50	9	2.0	0.590	142	6023	3020
UHPC140-800-0.9	121.81	818	65	7	0.9	0.590	142	4478	1589
UHPC140-800-1.2	121.81	818	50	7	1.2	0.590	147	4923	2031
UHPC140-800-1.4	121.81	818	40	7	1.4	0.590	153	5416	2410
UHPC140-800-1.6	121.81	818	60	9	1.6	0.590	158	5792	2589
UHPC140-800-2.0	121.81	818	50	9	2.0	0.590	165	6481	2794
UHPC140-970-0.9	121.81	926	65	7	0.9	0.590	144	4506	1602
UHPC140-970-1.2	121.81	926	50	7	1.2	0.590	149	4816	2034
UHPC140-970-1.4	121.81	926	40	7	1.4	0.590	152	5236	2424
UHPC140-970-1.6	121.81	926	60	9	1.6	0.590	155	5761	2603
UHPC140-970-2.0	121.81	926	50	9	2.0	0.590	164	6298	2810
UHPC140-1270-0.9	121.81	1190	65	7	0.9	0.590	142	4623	1634
UHPC140-1270-1.2	121.81	1190	50	7	1.2	0.590	147	4815	1866
UHPC140-1270-1.4	121.81	1190	40	7	1.4	0.590	154	5396	2430
UHPC140-1270-1.6	121.81	1190	60	9	1.6	0.590	159	5632	2608
UHPC140-1270-2.0	121.81	1190	50	9	2.0	0.590	165	6403	2825
UHPC160-800-0.9	134.47	818	65	7	0.9	0.590	151	5090	1406
UHPC160-800-1.2	134.47	818	50	7	1.2	0.590	158	5283	1833
UHPC160-800-1.4	134.47	818	40	7	1.4	0.590	167	5899	2131
UHPC160-800-1.6	134.47	818	60	9	1.6	0.590	171	6090	2334
UHPC160-800-2.0	134.47	818	50	9	2.0	0.590	176	6890	2630
UHPC160-970-0.9	134.47	926	65	7	0.9	0.590	151	5090	1406
UHPC160-970-1.2	134.47	926	50	7	1.2	0.590	160	5290	1853
UHPC160-970-1.4	134.47	926	40	7	1.4	0.590	165	5830	2100
UHPC160-970-1.6	134.47	926	60	9	1.6	0.590	170	6110	2354
UHPC160-970-2.0	134.47	926	50	9	2.0	0.590	178	6840	2663
UHPC160-1270-0.9	134.47	1190	65	7	0.9	0.590	151	5089	1419
UHPC160-1270-1.2	134.47	1190	50	7	1.2	0.590	160	5310	1873
UHPC160-1270-1.4	134.47	1190	40	7	1.4	0.590	165	5830	2177
UHPC160-1270-1.6	134.47	1190	60	9	1.6	0.590	169	6140	2373
UHPC160-1270-2.0	134.47	1190	50	9	2.0	0.590	179	6840	2669
UHPC180-800-0.9	155.45	818	65	7	0.9	0.590	170	5250	1109
UHPC180-800-1.2	155.45	818	50	7	1.2	0.590	180	5480	1330
UHPC180-800-1.4	155.45	818	40	7	1.4	0.590	186	6070	1607
UHPC180-800-1.6	155.45	818	60	9	1.6	0.590	195	6400	2308
UHPC180-800-2.0	155.45	818	50	9	2.0	0.590	202	7066	2407
UHPC180-970-0.9	155.45	926	65	7	0.9	0.590	171	5298	1132
UHPC180-970-1.2	155.45	926	50	7	1.2	0.590	180	5480	1320
UHPC180-970-1.4	155.45	926	40	7	1.4	0.590	185	6110	1620
UHPC180-970-1.6	155.45	926	60	9	1.6	0.590	196	6340	2318
UHPC180-970-2.0	155.45	926	50	9	2.0	0.590	203	7060	2434
UHPC180-1270-0.9	155.45	1190	65	7	0.9	0.590	172	5230	1151

Table 1. Cont.

Specimens	f_c (MPa)	$f_{0.2}$ (MPa)	s (mm)	d_s (mm)	ρ_v (%)	ρ_{lr} (%)	f_{cc} (MPa)	ε_{cc} ($\varepsilon \times 10^{-6}$)	ε_{sv0} ($\mu\varepsilon$)
UHPC180-1270-1.2	155.45	1190	50	7	1.2	0.590	179	5570	1349
UHPC180-1270-1.4	155.45	1190	40	7	1.4	0.590	186	6170	1640
UHPC180-1270-1.6	155.45	1190	60	9	1.6	0.590	195	6340	2282
UHPC180-1270-2.0	155.45	1190	50	9	2.0	0.590	201	6890	2447

Note: f_c was the axial compressive strength of UHPC; MPa, $f_{0.2}$ was the nominal tensile strength of stirrups; MPa, s was the spacing of stirrups; mm, d_s was the diameter of stirrups; mm, ρ_v was the volumetric ratio of stirrups; %, ρ_{lr} was the ratio of longitudinal reinforcement; %, f_{cc} was the peak stress of confined UHPC; and MPa, ε_{cc} was the peak strain of confined UHPC.

The desired UHPC was prepared in the experiment to obtain five types of UHPC. Ordinary Portland cement, silica fume, and two types of quartz sand in the diameters of 0.425–0.85 mm, 0.18–0.425 mm were used to obtain the high strength. A polycarboxylic acid high-performance water-reducing admixture was added to obtain the required workability. For each strength concrete series, three $100 \times 100 \times 100$ mm concrete cubes and three $100 \times 100 \times 300$ mm concrete prisms were tested under axial compression after 28 days curing to obtain the compressive strength.

Three samples for each type of reinforcing bars were tested under axial tension load according to GB/T 228-2021 [36]. The yield strength of Grade 800, Grade 970, and Grade 1270 was defined at an offset strain of 0.2%.

The strain gauges and displacements were placed on the specimens. Four strain gauges on the longitudinal reinforcements were used to measure the deformation of concrete and reinforcing bars. Specifically, four strain gauges were placed on the longitudinal reinforcement to measure the vertical deformation of longitudinal reinforcements; four strain gauges were placed around the perimeter of a circle spiral stirrups at the middle of specimens to measure the lateral deformation of stirrups; two horizontal, and two vertical strain gauges were placed on the opposite direction to measure the horizontal and vertical deformation of concrete cover. In addition, four displacement meters were placed at 90° intervals with 300 mm regions to measure the vertical deformation of specimens. The deformation test data from displacement meters and strain gauges were collected by static strain acquisition equipment with a sampling rate of 5 Hz. The load cells were automatically collected and stored in a computer. The test setup was shown in Figure 1b. A sample of 10 strain gauges from each production batch (5 concrete gauges and 5 reinforcement gauges) was tested on a calibrated cantilever beam apparatus with known strain levels (0, 500, 1000, 2000, and 5000 $\mu\varepsilon$). The measured strain outputs were compared with theoretical values to verify the manufacturer-specified gauge factor. Deviations were consistently below 0.5%.

4. Test Results and Analysis

4.1. Test Results

Figure 2 shows the axial stress–strain curves of all specimens. In Figure 2, the gray point meant that the stirrups reached the nominal yield strength. And the axial stress–strain curves were plotted according to the volumetric ratio of stirrups. The axial strain of confined concrete was the average value from two vertical displacement meters divided by the gauge length (300 mm), while the axial stress of confined concrete was obtained by subtracting the axial force of longitudinal reinforcements and concrete cover from the total axial force.

As shown in Figure 2, the first stage exhibited linear elasticity, where axial stress demonstrated a proportional relationship with axial strain up to 60–85% of peak stress. During this phase, the confined UHPC behaved similarly to unconfined UHPC, with minimal lateral strain development in the stirrups and negligible confinement effects.

The second stage marked the transition to nonlinear behavior, spanning from 60 to 85% of peak stress to the ultimate stress point. This elastic-to-plastic transition coincided with significant activation of the confinement mechanism, evidenced by rapid increases in lateral strain as the concrete's transverse deformation engaged the stirrups. Notably, the extent of nonlinearity in the ascending branch correlated positively with the stirrup volumetric ratio.

Post-peak behavior constituted the third stage, characterized by stress reduction followed by stabilization at a residual stress plateau. The magnitude of this plateau stress showed direct proportionality to the stirrup volumetric ratio but inverse relationship with UHPC compressive strength. During this phase, lateral strains accelerated until stirrup fracture, with the transverse reinforcement typically reaching nominal yield stress after the confined concrete's peak stress.

In Figure 2 and Table 1, the stirrups did not attain their nominal yield strength at the peak stress of confined UHPC. The lateral strain in the stirrups at peak stress exhibited a positive correlation with the stirrup volumetric ratio and a negative correlation with the UHPC compressive strength. Notably, the lateral confinement effects became pronounced only when the axial stress exceeded approximately the unconfined UHPC compressive strength. Beyond the peak stress, the stirrups' confinement significantly influenced the post-peak response, altering both the elastoplastic transition and the descending branch of the stress–strain curve.

The peak stress and peak strain of confined UHPC increased with higher stirrup volumetric ratios and greater unconfined UHPC compressive strength. In contrast, the nominal yield strength of the stirrups had minimal impact on these peak parameters, suggesting its limited utility for quantifying lateral confinement effects.

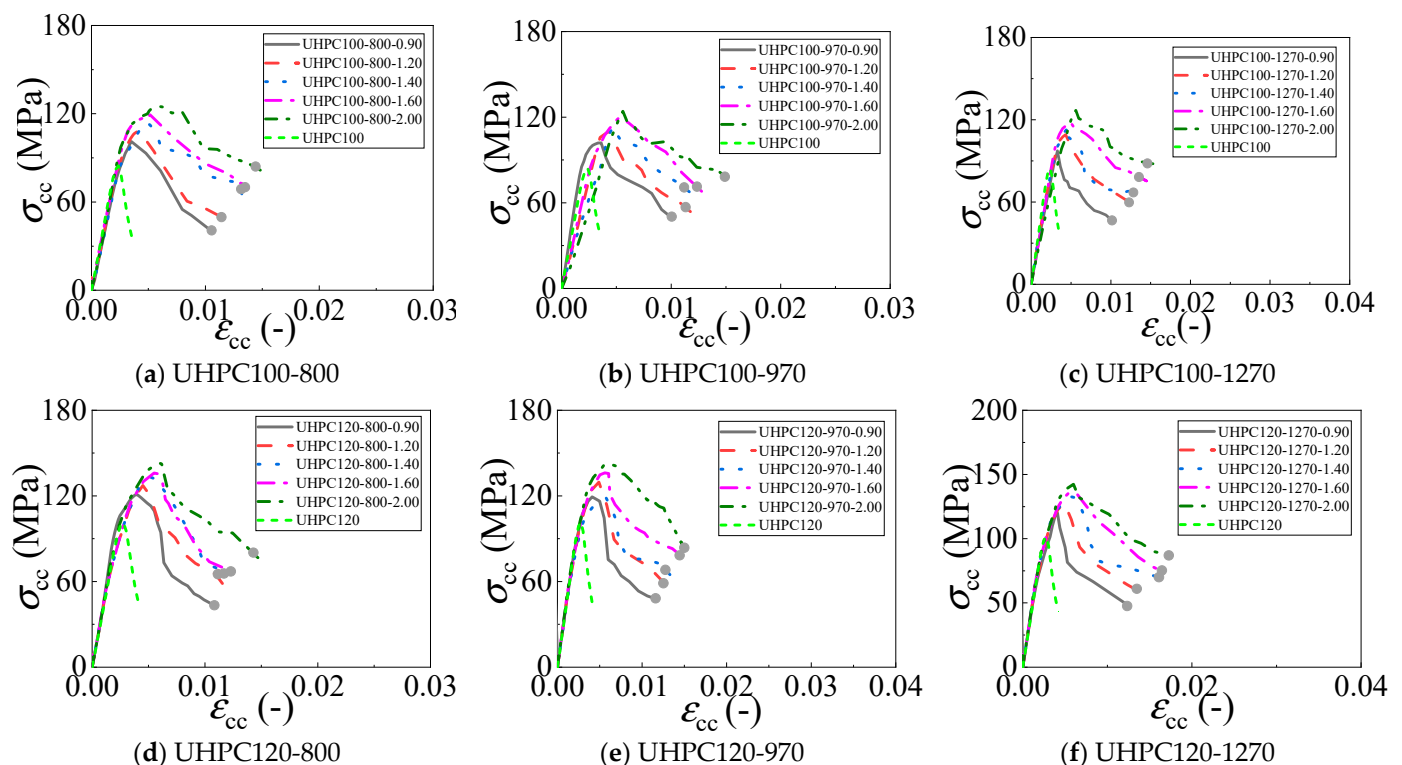


Figure 2. Cont.

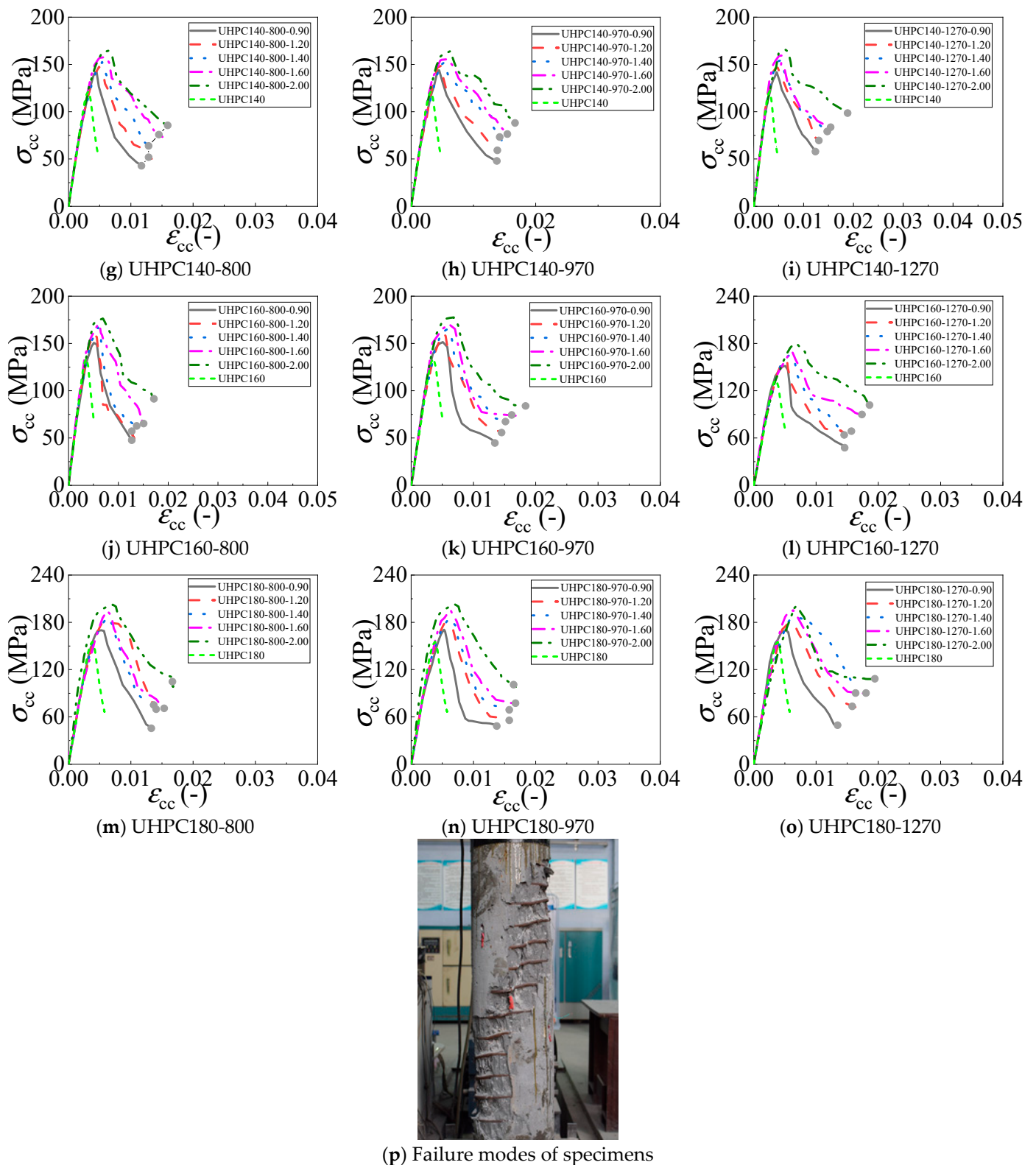


Figure 2. Axial stress–strain behavior and failure modes of UHPC confined with high-strength spiral stirrups. The axial stress–strain curves for all UHPC columns confined with spiral stirrups are grouped by UHPC compressive strength and stirrup yield strength. The curves were categorized by stirrup volumetric ratio (ρ_v). Gray markers on the curves indicated the load step at which the spiral stirrups first reached their nominal 0.2% offset yield strength, demonstrating that yielding typically occurs after the peak stress.

However, as the UHPC compressive strength increased, the columns demonstrated more brittle failure modes. This behavior underscores the necessity of employing higher stirrup volumetric ratios to enhance ductility. Consequently, establishing minimum limits for the stirrup volumetric ratio is critical to ensuring adequate ductility in confined UHPC columns.

4.2. Stress State Analysis of Confined Concrete Columns

4.2.1. Characteristic Points in the $E_{j,norm}$ - F_j Curve

The state variable E_{ij} at each load F_j can be normalized by Equation (3), and the $E_{j,norm}$ - F_j curves of all specimens were obtained. The slope of the $E_{j,norm}$ - F_j curve was obtained according to Equation (3). Take the specimen UHPC100-800-1.6, for example, the $E_{j,norm}$ - F_j curve, and FI_j - F_j curve are shown in Figure 3. As shown in Figure 3, the $E_{j,norm}$ - F_j curve of specimen UHPC100-800-1.6 can be divided into three stages according to the FI_j - F_j curve: linear-elastic state, elastic-to-plastic state, and unstable state. Two point characteristic points (Points P and U) are determined and drawn in Figure 3, representing that the slope of the $E_{j,norm}$ - F_j curve obviously changes.

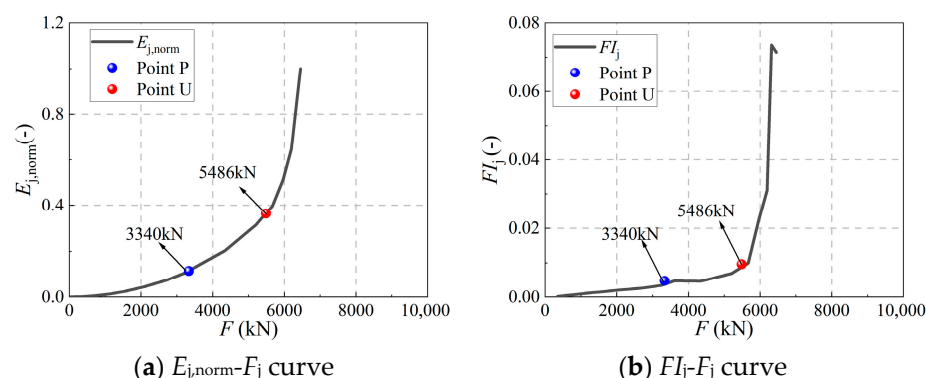


Figure 3. The $E_{j,norm}$ - F_j curve, and FI_j - F_j curves of specimen UHPC100-800-1.6. (a) The normalized generalized strain energy density ($E_{j,norm}$) plotted against the applied axial load (F_j), showing the transition through three distinct stress states. (b) The corresponding slope index (FI_j) of the $E_{j,norm}$ - F_j curve, is used with the Mann-Kendall criterion to objectively identify characteristic points P (onset of plastic deformation) and U (onset of structural instability, defined as the failure load).

In the first stage, the $E_{j,norm}$ - F_j curve of specimen UHPC100-800-1.6 showed the linear elastic behavior, and the specimen did not have cracks before the 70% of the maximum axial load, corresponding to characteristic point P in the $E_{j,norm}$ - F_j curve. The small $E_{j,norm}$ increased slowly with the axial load and presented an approximately linear relationship with the axial load. Meanwhile, the slope of the $E_{j,norm}$ - F_j curve remained almost constant and at a low level. The reason was that the lateral strains of spiral stirrups were at a low level, around $152 \mu\epsilon$, and the corresponding lateral stress of spiral stirrups was 29.64 MPa, meaning that the lateral confinement effect of stirrups on the concrete is not significant. The first stage of the $E_{j,norm}$ - F_j curve corresponds to the first stage of the axial stress-strain curve of confined concrete, and Point P can be defined as the demarcation between the linear elastic stage and the elastic to plastic stage.

When the axial load was in the range of Point P to Point U (the axial load was around 90% of the maximum axial load), the specimen entered the second stage (elastic-plastic stage). In this stage, the cracks appeared on the surface of the specimens and began to widen and deepen. The lateral strain of spiral stirrups reached $2500 \mu\epsilon$, corresponding to the lateral stress 487.5 MPa of stirrups, implying that the lateral confinement effects of stirrups began to become obvious, and the plastic deformation of specimens increased stably. In addition, the slope of the $E_{j,norm}$ - F_j curve increased with the axial load, and $E_{j,norm}$

increased steadily with the axial load. Moreover, the second stage of the $E_{j,norm}$ - F_j curve corresponded to the part of the second stage of the axial stress-strain curves of confined concrete, and Point U can be defined as the demarcation between the elastic to plastic stage and the unstable stage in the ascending branch of axial load-deformation of confined concrete columns.

Finally, after Point U, the specimen entered the third stage corresponding to the axial load range from Point U to the maximum axial load. In this stage, the concrete cover spalled, and an inclined crack was formed on the surface of the specimen. The lateral strain of stirrups increased rapidly, and the lateral confinement effect of stirrups on concrete increased significantly. Thus, the slope of the $E_{j,norm}$ - F_j curve increased sharply with the axial load, and $E_{j,norm}$ increased rapidly with the axial load until the peak axial load. Thus, after Point U, the concrete column under axial load entered the unstable stress state, and the axial load at Point U can be defined as the updated failure load of the confined column. The axial load at Point U was lower than the peak axial load, but the axial load at Point U reflected the general and common failure behavior of the confined column's stress state.

4.2.2. Characteristic Points Determination

A similar behavior was observed in the other 74 specimens. The $E_{j,norm}$ - F_j curves of all specimens are shown in Figure 4. In Figure 4, two characteristic points were identified in these curves: Point P (marked in blue) and Point U (marked in red).

The axial load at Point P showed the strong dependence on concrete compressive strength but minimal sensitivity to both stirrup volumetric ratio and yield strength. When all specimens maintained identical longitudinal reinforcement ratios and yield strengths, concrete compressive strength emerged as the primary determinant of Point P behavior.

In contrast, Point U behavior was predominantly influenced by two key parameters: (a) concrete compressive strength and (b) stirrup volumetric ratio. The yield strength of stirrups exhibited only a marginal effect on the characteristic of Point U.

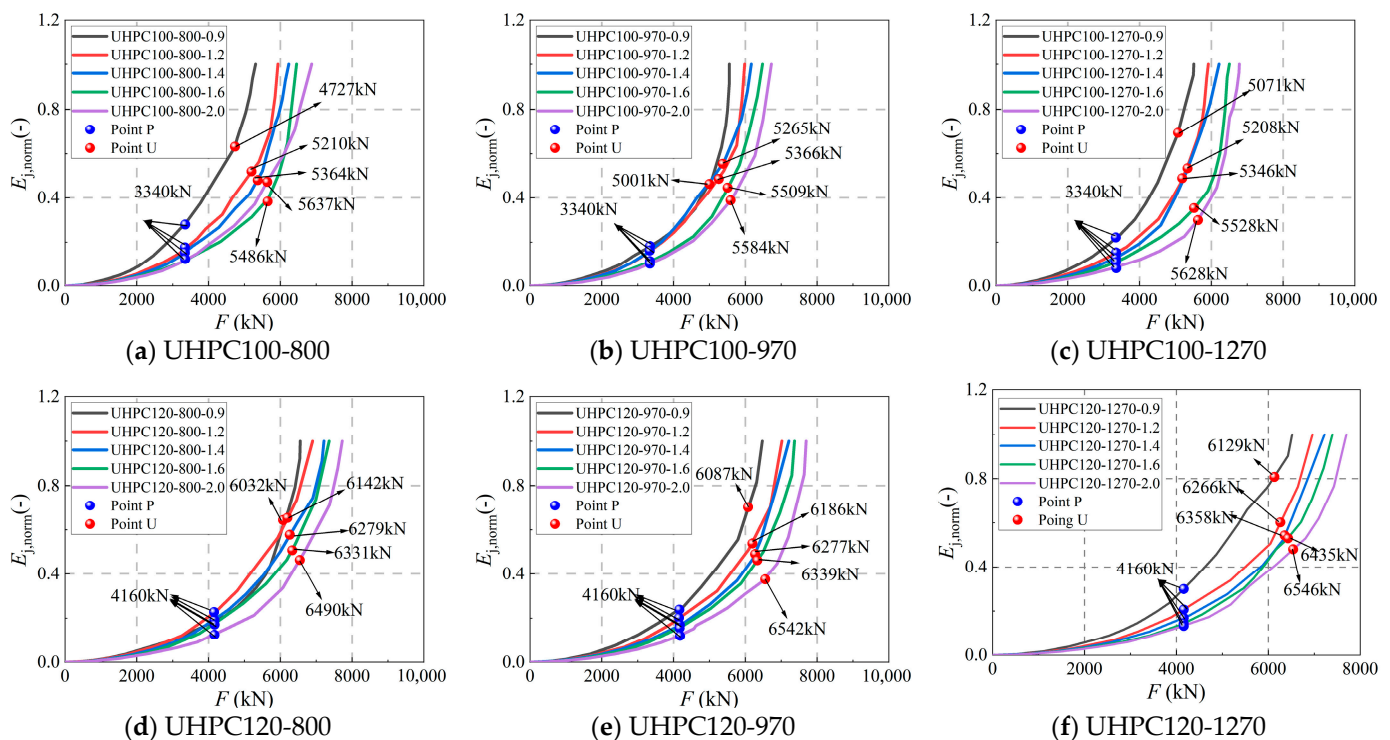


Figure 4. Cont.

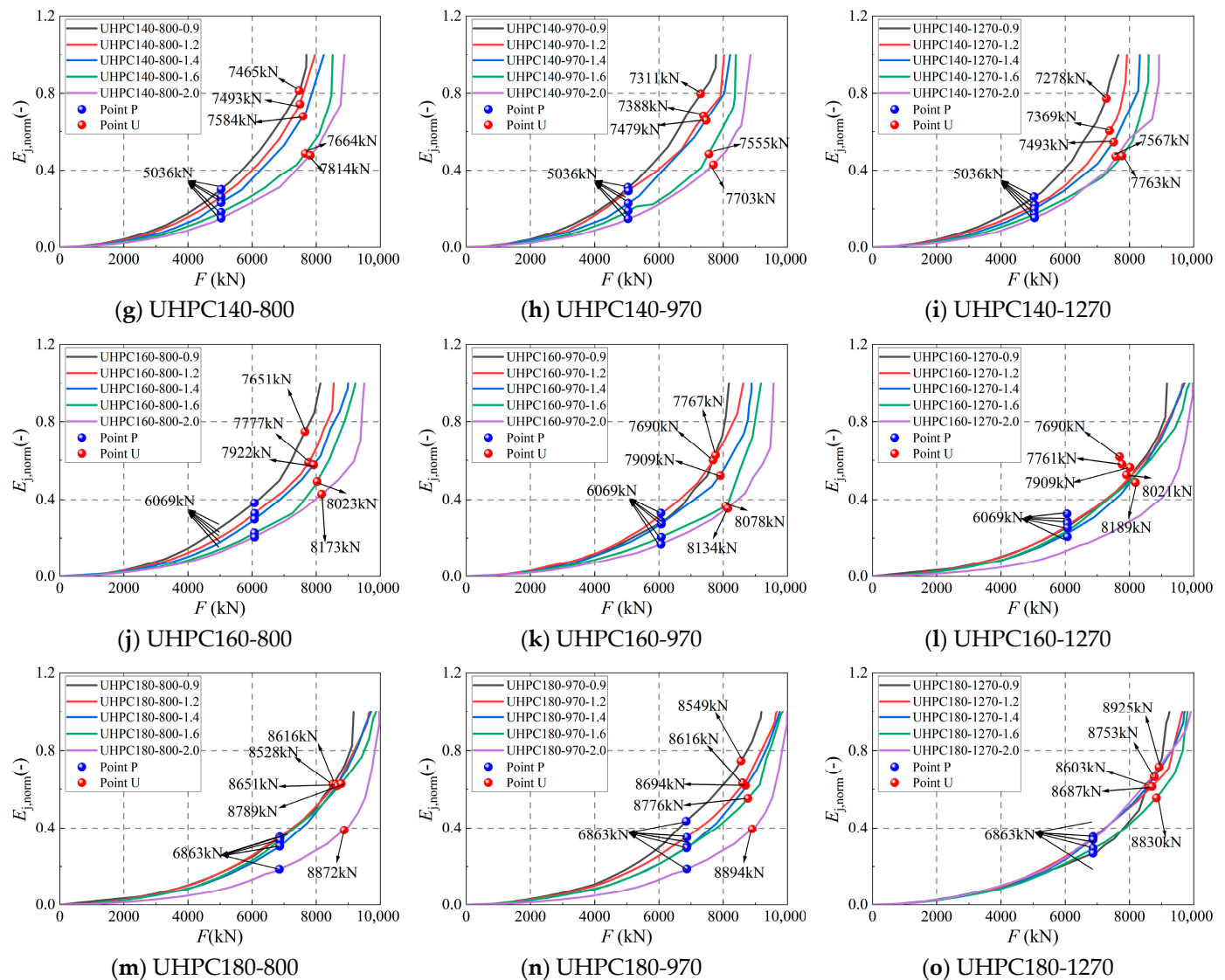


Figure 4. The $E_{j, norm}$ - F_j curves of all specimens. Normalized generalized strain energy density ($E_{j, norm}$) versus axial load (F_j) curves for all 75 test specimens, organized by UHPC compressive strength (rows) and stirrup yield strength (columns). On each curve, the blue marker denotes characteristic Point P (elastic limit) and the red marker denotes characteristic Point U (proposed failure load at the onset of instability).

Point U did not simply represent a convenient statistical point; it embodied a critical transition in the internal damage state, cracking morphology, and confinement activation of the UHPC column. Prior to Point U, damage in the UHPC matrix was characterized by the initiation and stable growth of distributed micro-cracks. This phase corresponded to the elastic-plastic stage in Figure 3, where the slope of the $E_{j, norm}$ - F_j curve increased steadily but controllably. The strain energy density ($E_{j, norm}$) increased at a moderate rate because the material can still redistribute stresses internally without significant loss of stiffness. At Point U, the distributed micro-cracks coalesce into one or several dominant macro-cracks. This marked the transition from damage initiation to damage localization. Once localization occurred, the deformation of the column ceased to be uniform and became concentrated in a critical failure plane. This localization event was precisely what the Mann–Kendall criterion detects as a mutation in the FI_j - F_j curve, as the rate of energy absorption changed discontinuously. After Point U, all further deformation and damage concentrated in this localized zone, making the structural response path-dependent and unstable. The UHPC

matrix, having exhausted its capacity for distributed cracking, can no longer sustain the increasing load, and the column enters a state of impending failure.

Point U also represented a critical threshold in the cracking behavior observable on the specimen surface. As documented in Section 4.2.1, the region between Points P and U corresponded to the appearance and gradual widening of surface cracks. Those cracks were initially fine and well-distributed, and the concrete cover, while cracked, remained largely intact and bonded to the core.

The onset of Point U coincided with the moment when those surface cracks propagated rapidly, and the concrete cover began to spall. This spalling was not merely a cosmetic feature; it had profound mechanical consequences. The concrete cover, which contributed to the overall load-bearing capacity and provided lateral restraint to the longitudinal reinforcement, became effectively disengaged from the structural action. The loss of the cover reduced the effective cross-sectional area and exposed the core concrete to a more severe stress state. Simultaneously, the spalling removed a layer of material that was providing passive confinement to the core, accelerating the dilation of the core and increasing the demand on the spiral stirrups, making Point U the last stable point before runaway failure.

4.3. Parametric Analysis

4.3.1. Concrete Compressive Strength

Figure 5 illustrates the significant influence of UHPC compressive strength on the failure loads of specimens. For specimens confined with 970 MPa stirrups at a volumetric ratio of 1.4%, increasing the UHPC compressive strength from 100 MPa to 180 MPa resulted in a substantial failure load enhancement from 5366 kN to 8694 kN, representing a 63% improvement. This pronounced increase demonstrated that the inherent compressive strength of UHPC constituted a primary governing factor in determining the load-bearing capacity of confined columns.

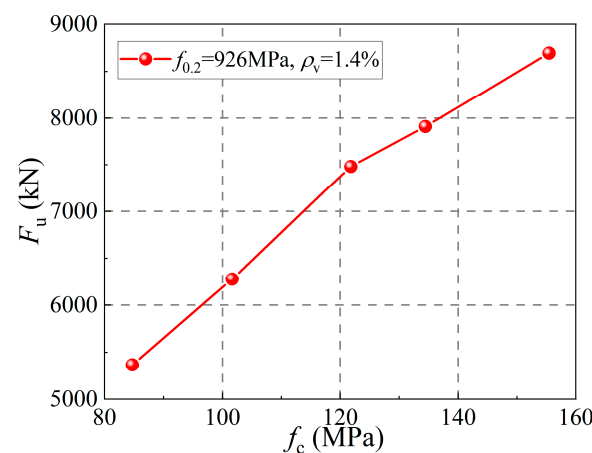


Figure 5. The effect of compressive strength of UHPC on the failure loads of specimens.

4.3.2. Volumetric Ratios of Stirrups

Figure 6 demonstrates the influence of stirrup volumetric ratio on the failure loads of confined UHPC specimens. For specimens with a stirrup yield strength of 970 MPa and concrete compressive strength of 120 MPa, increasing the volumetric ratio from 0.9% to 2.0% resulted in a corresponding increase in the failure loads from 6087 kN to 6542 kN, representing a 7.5% enhancement. This improvement can be attributed to the intensified lateral confinement provided by higher volumetric ratios of stirrups, which effectively enhanced both the plastic deformation capacity and axial stress-bearing capability of the concrete.

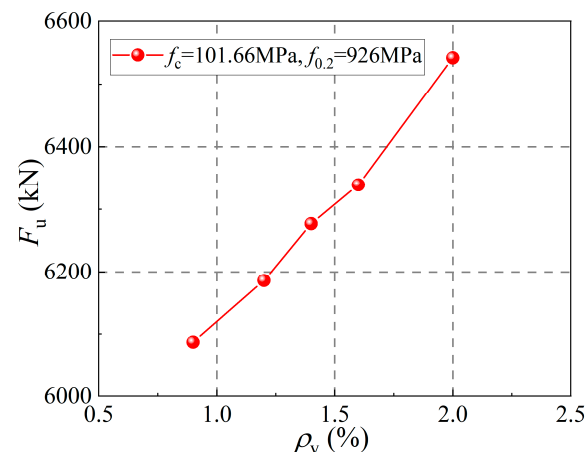


Figure 6. The effect of the volumetric ratio of stirrups on the failure loads of specimens.

4.3.3. Yield Strength of Stirrups

Figure 7 illustrates the effect of stirrup yield strength on the failure loads of confined UHPC specimens. When the volumetric ratio of stirrups was 2.0%, the compressive strength of UHPC was 120 MPa, the yield strength of stirrups improved from 800 MPa to 1270 MPa, the failure loads of specimens remained nearly constant, and the start point of unstable state (Point U) was primarily governed by the loss of stability of the core concrete. For the UHPC (the compressive strength in the range of 84.7 MPa~155.45 MPa), the lateral expansion at Point U could not allow stirrups to reach the yield strength. Thus, the potential of the high-yield-strength stirrups was not developed when the columns were in the unstable state, which resulted in a saturation effect, where improving the yield strength of stirrups beyond a certain threshold did not translate to higher failure loads.

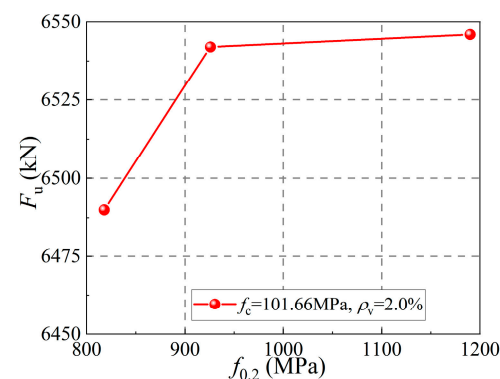


Figure 7. The effect of the yield strength of stirrups on the failure loads of specimens.

As for the stirrups confined concrete, especially for the very-high-strength concrete, improving the yield strength of stirrups may not be an effective strategy to enhance the initial instability load of columns. However, it was crucial to note that stirrup yield strength remained critically important for other performance criteria not directly addressed by Point U, such as (1) post-peak ductility and residual capacity: higher yield strength stirrups can significantly improve the toughness and sustain a higher load platform after the peak load; (2) for normal or high strength concrete (e.g., <80 MPa), where lateral expansion was greater, stirrups were more likely to yield, which improved the peak and post-peak load response of columns; (3) it was vital for the energy dissipation and buckling restraint of columns provided by higher strength spirals under reversed loads.

4.4. Failure Loads Calculation and Significance

4.4.1. Failure Load Calculation

Figure 4 shows that the failure loads of all specimens were determined by the stress state analysis above. Based on the design parameters and the failure loads of specimens, a formula for predicting the failure loads between a base confined UHPC column and a predicted one can be expressed in Equation (11) [34].

$$\frac{F_u^{\text{obj}}}{F_u^{\text{base}}} = \left(\frac{f_c^{\text{obj}}}{f_c^{\text{base}}} \right)^{\alpha} \left(\frac{\rho_v^{\text{obj}}}{\rho_v^{\text{base}}} \right)^{\beta} \left(\frac{f_{0.2}^{\text{obj}}}{f_{0.2}^{\text{base}}} \right)^{\gamma} \quad (11)$$

where F_u^{obj} and F_u^{base} were the failure loads of objective and base confined UHPC columns, respectively, kN; f_c^{obj} and f_c^{base} were the compressive strength values of objective and base UHPC, respectively, MPa; ρ_v^{obj} and ρ_v^{base} were the volumetric ratios of objective and base stirrups, respectively, %; $f_{0.2}^{\text{obj}}$ and $f_{0.2}^{\text{base}}$ were the nominal yield strength values of objective and base stirrups, respectively, MPa.

Noticeably, the base confined UHPC column was a confined column whose failure load had been obtained. The objective confined concrete column was a confined column whose failure load needed to be calculated according to the base confined concrete column. The coefficients α , β , and γ were the fitted coefficients.

When specimen UHPC100-800-0.9 was chosen as the base confined UHPC column, α , β , and γ were 0.92, 0.16, and 0.18, respectively. The failure loads of the objective confined UHPC columns can be obtained.

The comparison between the predicted and detected failure loads of confined UHPC columns is shown in Figure 8. The distribution of the $F_{u,\text{pre}}/F_{u,\text{test}}$ is shown in Figure 9. In Figure 8, the predicted failure loads of confined UHPC columns were near the detected ones, and the errors are in the range of -11% – 13% , with the average value (1.000) of the ratio between the predicted and test results and the standard deviation (0.046). The $F_{u,\text{pre}}/F_{u,\text{test}}$ values were in the range of 0.88–1.13. Hence, the proposed calculation could be suitable for evaluating the failure loads of UHPC columns confined with high-strength spiral stirrups.

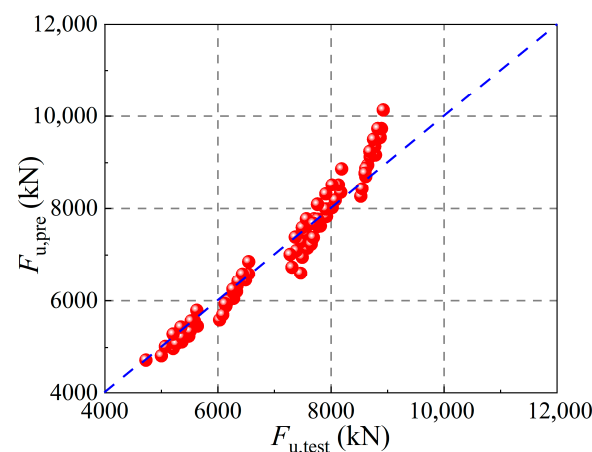


Figure 8. The comparison between predicted and test failure loads of confined UHPC columns. Correlation between the failure loads predicted by the proposed model ($F_{u,\text{pre}}$) and the experimentally detected failure loads ($F_{u,\text{test}}$) for all 75 specimens. The blue dotted line represented perfect agreement, demonstrating the high accuracy of the predictive model. The red dots were the predicted results of failure load, the blue dotted line meant that the predicted results equaled the test results.

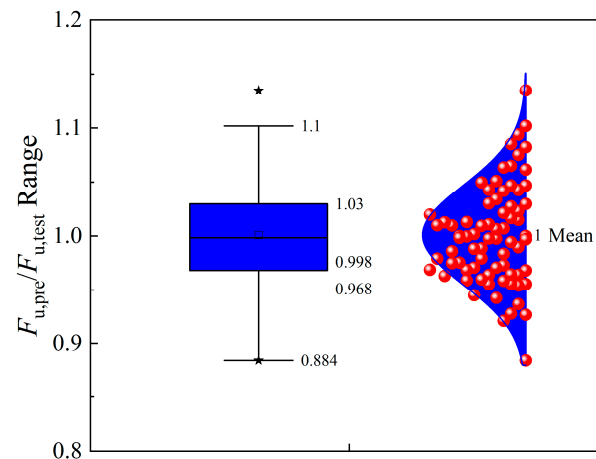


Figure 9. Distribution of the $F_{u,pre}/F_{u,test}$. Frequency distribution of the ratio of predicted to experimental failure load ($F_{u,pre}/F_{u,test}$). The distribution had a mean of 1.000 and a standard deviation of 0.046, with all errors confined within a $\pm 13\%$ range, confirming the model's reliability and unbiased nature. * means the abnormal value, which was 1.15 times of mean value. The blue box meant that the $F_{u,pre}/F_{u,test}$ values was in the percentage in the 25–75%; the red dot was the $F_{u,pre}/F_{u,test}$ values; the blue curve was the distribution of $F_{u,pre}/F_{u,test}$ values.

4.4.2. Failure Load Significance

Point U represented the internal stress state of the structure under a transition from stable to unstable evolution. The rapid widening of existing cracks, the concrete cover starts to spall, and a nonlinear acceleration in the lateral straining of stirrups. While the external load can still increase slightly, the internal system began to deform in an increasingly unstable manner, relying on rapidly diminishing reserves of stability. The peak load was the maximum sustained load. However, the critical load was the point of bifurcation, where stable equilibrium was lost. For UHPC columns, which exhibit brittleness under axial compression, Point U was analogous to this bifurcation point, marking the loss of stable deformation progression.

For UHPC columns, the peak load was an unstable point: the axial stress-axial strain curves showed that the axial stress had a sharp decline after the peak stress of confined UHPC. The UHPC columns could not maintain the peak load; any further deformation led to a rapid load drop. Therefore, the peak load represented the start of failure, not a sustainable resistance. Point U was the last stable state of specimens: it represented the highest load at which the structure's internal state was still evolving in a stable manner. Beyond Point U, the axial load of specimens could rapidly reach the peak load and then collapse. Thus, Point U defined the true functional limit state. Structural design codes were fundamentally based on preventing loss of stability and serviceability. Defining the failure load at the last stable state (Point U) was inherently more conservative for brittle systems than using an unstable maximum (peak load).

Adopting the Point U failure load had direct, practical applications: (1) current design methods applied empirical safety/partial factors to a semi-empirical peak load estimate, which combined uncertainty in predicting the peak with uncertainty in the peak's stability. The failure load model in this paper predicts the stable limit load (Point U), to which standard safety factors can be applied more rationally to guard against material variability and unforeseen loads. (2) The analysis revealed that to raise Point U, increasing the stirrup volumetric ratio (ρ_v) was effective, while not merely using higher yield strength stirrups. This guided engineers to prioritize denser confinement detailing over simply specifying higher-grade stirrups for improving the stable load capacity of UHPC columns. (3) The $E_{j,norm}$ methodology, and the search for a mutation point provided a unified analytical

framework to define the failure state of different structural systems and materials, which moved design towards a more rigorous, system-level stability assessment.

5. Conclusions

In this paper, for the test results of the 75 UHPC columns confined with high-strength spiral stirrups under axial compression, the stress state analysis reveals the inherent working characteristic of columns, which provides a reference to predict the failure loads of confined UHPC columns. The conclusions can be drawn as follows:

(1) The ascending branch of the axial stress–strain curve corresponded to three distinct stages in the structural energy evolution ($E_{j,norm}$ - F_j curve), demarcated by characteristic Points P and U. The load at Point U, which marked the onset of an unstable internal state, was established as the governing failure load for design, preceding the traditional peak load.

(2) The failure load was highly sensitive to the UHPC compressive strength and moderately influenced by the stirrup volumetric ratio. Specifically, increasing the UHPC strength from 100 MPa to 180 MPa enhanced the failure load by 63%, while increasing the stirrup ratio from 0.9% to 2.0% provided a 7.5% increase. In contrast, the yield strength of the stirrups demonstrated a negligible effect.

(3) A practical predictive model was formulated to estimate the stability-based failure load. The model demonstrates high accuracy, with predictions falling within $\pm 13\%$ of experimental values, a mean prediction-to-test ratio of 1.000, and a standard deviation of 0.046. This offers a reliable and rational tool for the design of high-strength spiral stirrup confined UHPC columns, moving beyond empirical peak-load estimates toward a stability-centered design paradigm.

(4) Future research: (i) While the current study focused on circular columns with spiral stirrups, future work will investigate square and rectangular columns confined with rectilinear ties and combined spiral–rectilinear reinforcement configurations; the stress state of columns under eccentric and cyclic load. (ii) A constitutive model for confined UHPC will be developed that explicitly links the onset of instability (Point U) to micro-mechanical damage parameters (crack density, fiber bridging stress, and aggregate interlock). (iii) Based on the validated predictive model (Equation (11)) and the parametric insights, a comprehensive set of design recommendations will be developed, including: minimum stirrup volumetric ratios for ensuring stable behavior, design charts and nomograms for rapid estimation of failure loads, simplified empirical relationships for preliminary design, and detailing requirements for confinement reinforcement in UHPC columns.

Author Contributions: Conceptualization, Y.Z. and W.C.; methodology, X.X.; validation, Z.X., M.Z. and X.L.; formal analysis, X.X.; investigation, Z.X.; data curation, Y.Z.; writing—original draft preparation, Y.Z.; writing—review and editing, W.C.; funding acquisition, Y.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Fujian Provincial transportation technology project (YB202410); Wuyi University to introduce talents research start-up funding project (YJ202309).

Data Availability Statement: The data presented in this study are available in the article.

Conflicts of Interest: Authors Xiong Xie and Zhen Xu were employed by the Nanping Highway Development Center. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The funding support for this study was primarily provided by the Fujian Provincial Transportation Technology Project (YB202410), jointly applied for by Nanping Highway Development Center, Wuyi University, and Harbin Institute of Technology. The three institutions have established a collaborative foundation.

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