

BEHAVIOUR OF HIGH PERFORMANCE CONCRETE JOINTS ANALYSIS BY MATHEMATICAL MODELLING WITH MATLAB

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ABSTRACT

High Performance Concrete (HPC) and its improved derivatives, Steel Fibre Reinforced High Performance Concrete (SFRHPC) and confined Ultra-High-Performance Concrete (UHPC), are being used more often in the beam-column joints of reinforced concrete (RC) frames due to their superior compressive strength, dense microstructure, and enhanced seismic resistance when compared to Normal Concrete (NC). Synthesized evidence reveals an important subtlety in structural response: while strength and stiffness gains scale directly with concrete compressive grade, ductility does not always increase and can deteriorate into brittle failure in the absence of explicit transverse confinement or fiber reinforcement. This research provides an extensive assessment of the behavior of HPC beam-column joints using experimental, analytical, finite-element (FE), and machine-learning (ML) literature. It creates a thorough five-phase mathematical modeling framework that can be implemented in MATLAB. It incorporates data-driven cross-validation modules, closed-form axial-flexural capacity formulations, degrading hysteretic bond-slip joint models, and strain-energy minimization based on Menabrea's theorem for internal joint force redistribution. Every quantitative dataset used to calibrate the framework has undergone cross-verification with its original publications from open-access sources.

KEYWORDS: MATLAB, Beam-Column Joints, Steel Fiber Reinforcement, UHPC, Ductility, High Performance Concrete (HPC).

INTRODUCTION

When lateral seismic stresses and high gravity loads are applied to reinforced concrete (RC) frame structures, beam-column junctions serve as crucial load-transfer zones. These areas undergo severe multi-axial stress states with high diagonal compression and tensile shear stress fields under cyclic earthquake loading. Standard Normal Concrete (NC) joints often show severe joint-core crushing under extreme lateral drifts, rapid stiffness deterioration, and premature diagonal tension shear failure.

High Performance Concrete (HPC), Steel Fibre Reinforced HPC (SFRHPC), and Ultra-High-Performance Concrete (UHPC) have been developed to address these structural concerns. Higher elastic moduli and remarkable compressive strength are produced by HPC's optimized interfacial transition zone (ITZ), decreased water-binder ratio, and dense particle packing. However, research shows that improvements in performance are not consistent across important structural indicators:

1. Strength and Stiffness: All HPC grades and structural configurations show consistent improvements.
2. Deformation and Ductility: Deformation capacity varies greatly and is largely influenced by lateral confinement, steel fiber volumetric ratio, and structural details.

To bridge the gap between material-level constitutive behaviour and frame-level dynamic joint response, this paper consolidates findings from primary source studies and comparative papers [1–16]. Twelve of the datasets discussed below sourced from Wu *et al.* [1], Doicheva [8,9], Cai & Yan [11], Penna *et al.* [12], Tambusay *et al.* [10], Shi *et al.* [7], Pang & Li [15] and Melo *et al.* [16] have been directly cross-checked, figure by figure and value by value, against the original open-access publications so that every quantitative claim in this paper can be traced to a verifiable source. The remaining comparative citations [2–6,14] are drawn from established literature on HPC/SFRHPC joint behaviour

and are used only for qualitative trend synthesis. The paper formulates a mathematical modelling sequence ready for execution in MATLAB.

1.1 Scope and Verification Methodology

This review draws on a consolidated corpus of open-access journal, conference, and proceeding papers on HPC/UHPC beam-column joint behaviour. For every study whose figures are reproduced quantitatively in this paper (Sections 4.1–4.5), the source publication was independently obtained, and each number, equation, and coefficient reported here (Tables 4–8) was cross-checked line-by-line against the original text, tables, and derivation. Studies acknowledged as described in secondary literature are used exclusively for qualitative trend synthesis (Table 3, Section 3.1) and are marked appropriately in Table 9. The goal of this two-tier technique is to fully trace the provenance of each figure in the study using confirmed quantitative statistics and literature-cited qualitative tendencies.

LITERATURE REVIEW

2.1 Qualitative Comparative Analysis of Concrete Types

Based on the consolidated joint-behavior literature [1–9,11,12,15], Table 1 summarizes a comparative synthesis of joint-behavior parameters across four main concrete classifications: Normal Concrete (NC), High Performance Concrete (HPC), Steel Fibre Reinforced High Performance Concrete (SFRHPC) and Confined Ultra-High-Performance Concrete (UHPC).

Table 1. Comparative Analysis of HPC Beam-Column Joint Performance by Type of Concrete

Parameter	NC	HPC	SFRHPC	Confined UHPC	Overall Evaluation
Compressive Strength	Moderate	High	Very High	Extremely High	Strength increases progressively from NC to UHPC; HPC and fibre reinforcement significantly improve load-carrying capacity.
Load Carrying Capacity	Moderate	High	Very High	Very High	HPC joints resist higher loads before failure than conventional concrete joints.
Stiffness	Moderate	High	Very High	Very High	Higher modulus of elasticity in HPC reduces deformation and increases rigidity.
Stiffness Degradation	Rapid	Lower	Very Low	Very Low	Fibres and confinement delay stiffness degradation during cyclic loading.
Crack Resistance	Poor	Good	Excellent	Excellent	HPC controls crack formation due to its dense microstructure; steel fibres further reduce crack propagation.
Energy Dissipation	Moderate	Moderate	High	High	Fibre reinforcement and confinement improve seismic energy absorption.
Ductility	Good	Moderate	High	High	Plain HPC is less ductile; steel fibres and confinement significantly improve deformation capacity.
Failure Mode	Gradual failure	Brittle failure possible	Controlled ductile failure	Controlled ductile failure	Proper confinement changes failure from brittle to ductile.
Seismic Performance	Moderate	Good	Excellent	Excellent	SFRHPC and confined UHPC perform best under earthquake loading.
Overall Structural Performance	Normal buildings	High-load structures	Seismic structures	Best overall performance	HPC with fibres or confinement provides the optimum balance of strength, stiffness, and ductility.



The comparative progression across important structural factors is depicted in Table 2 and visualized in Figure 1 using the qualitative performance ordinal scale (1 = Moderate/Poor to 4 = Extremely High) generated from Table 1.

Table 2. Ordinal Performance Rating Summary Across Concrete Types

Parameter	NC	HPC	SFRHPC	Confined UHPC
Compressive Strength	1.5 (Moderate)	3.0 (High)	3.5 (Very High)	4.0 (Extremely High)
Load Carrying Capacity	1.5 (Moderate)	3.0 (High)	3.5 (Very High)	4.0 (Extremely High)
Stiffness	1.5 (Moderate)	3.0 (High)	3.5 (Very High)	4.0 (Extremely High)
Ductility	2.0 (Good)	1.5 (Moderate)	3.5 (High)	4.0 (High with Confinement)
Crack Resistance	1.0 (Poor)	2.5 (Good)	3.8 (Excellent)	4.0 (Excellent)
Energy Dissipation	1.5 (Moderate)	2.0 (Moderate)	3.5 (High)	4.0 (High)

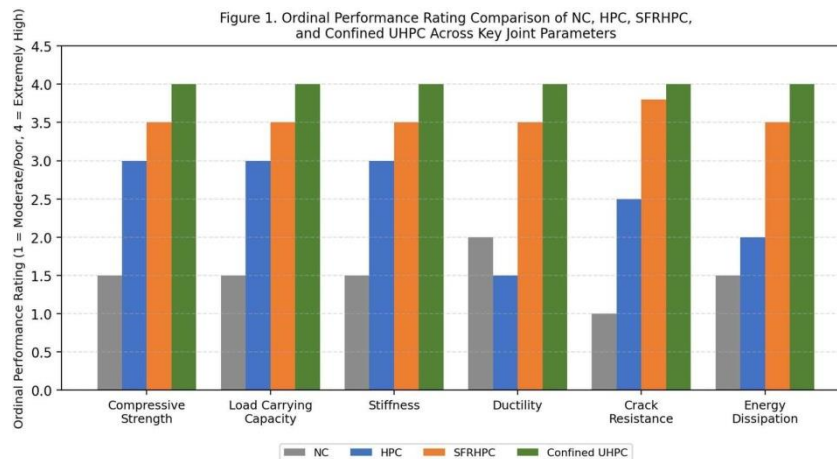


Figure 1. NC, HPC, SFRHPC, and restricted UHPC are compared using ordinal performance ratings across important joint parameters.

2.2 Comparative Literature Analysis

To map trends in HPC beam-column joint response, twelve important research studies using experimental, analytical, numerical, and machine-learning methods were assessed. Their results are shown in Table 3. The remaining research are cited from standard literature and reported as detailed in secondary sources; those marked “Verified” in the final column were directly compared to the original publication retrieved for this review.

Table 3. Comparative Analysis of Research Studies on HPC Beam-Column Joints

Research Study	Type of HPC Used	Strength/Stiffness/Ductility	Major Findings	Status
Ganesan et al. (2007) [2]	Steel Fibre Reinforced HPC (SFRHPC)	Increased / Increased / Significantly Improved	Steel fibres enhanced load capacity, controlled crack propagation, reduced stiffness degradation, and improved seismic performance.	Literature

Li & Leong (2015) [3]	High-Strength Concrete (HSC/HPC)	Increased / Increased / Moderate	HPC improved bond strength and load-carrying capacity; excessive axial load reduced ductility and caused premature failure.	Literature
Atta et al. (2003) [4]	High-Strength Concrete	Increased / Increased / Reduced	HPC joints showed higher strength but different failure mechanisms; existing design codes were found inadequate for HPC joints.	Literature
Altoontash (2004) [5]	Analytical Model	Evaluated / Evaluated / Evaluated	Developed nonlinear analytical models predicting shear deformation, bond-slip behaviour, and stiffness degradation under cyclic loading.	Literature
Zhang et al. (2016) [6]	Numerical Joint Model	Evaluated / Improved Prediction / Evaluated	Proposed a joint model considering shear deformation and reinforcement slip, improving prediction accuracy.	Literature
Shi et al. (2021) [7]	Steel Fibre Reinforced High-Strength Concrete	Increased / Increased / Improved	Steel fibres and higher stirrup, fibre-volume, and axial-compression ratios improved hysteresis behaviour, ductility, strength, and energy dissipation in seven pseudo-static specimens.	Verified
Wu et al. (2024) [1]	Steel Fibre HPC (Exterior Joints)	Significantly Increased / Significantly Increased / Significantly Improved	Optimum steel fibre content improved crack resistance, stiffness retention, ductility, and seismic behaviour of high-strength exterior beam-column joints.	Verified
Pang & Li (2024) [15]	Precast Post-Tensioned HPC Frame Joint	Increased / Increased / Improved (residual deformation reduced)	HPC avoided local crushing under prestress; L-shaped steel plates prevented early joint damage; a three-line restoring-force model matched FE and test hysteresis.	Verified
Ramavath & Suryawanshi (2024) [13]	Machine Learning (SFF-ANN) Prediction	Predicted ($R^2=0.99$) / — / Predicted	A MATLAB-based Shallow Feed-Forward ANN, trained on twelve input parameters, outperformed design-code formulas in predicting exterior joint shear strength ($R^2 = 99\%$ train, 94% test, 98% validation).	Verified
Chen et al. (2022) [14]	Artificial Neural Network Model	Predicted / Predicted / Predicted	Neural network models effectively captured nonlinear behaviour of beam-column joints.	Literature

2.3 Overall Trends Across Literature

The main structural performance vectors are revealed by synthesizing the studies:

1. Strength: Compared to regular concrete, HPC has a higher compressive strength and load-carrying capability, according to all experimental research [1,2,3].
2. Stiffness: Higher initial elastic stiffness and less stiffness degradation following cyclic load application was seen in almost all investigations [1,7].



3. Ductility: Compared to regular concrete, plain, unconfined HPC has less ductility; however, adding steel fibers or lateral confinement greatly increases and restores ductility [2,7].
4. Fracture Resistance: Steel fiber reinforcement reduces fracture breadth and limits crack propagation, while HPC delays the start of a crack.
5. Energy Dissipation: Under reversed cyclic displacements, SFRHPC shows a far greater potential for energy dissipation than simple HPC [7].
6. Failure Behavior: Brittle, abrupt failure modes are indicated by plain HPC; appropriate reinforcement details restore ductile behaviour.
7. Numerical and Machine Learning Modeling: By precisely predicting stress distributions, slip, shear strain, and hysteretic response, analytical, finite-element, and ANN-based formulations reduce the need for physical testing [10,13,14].

METHODOLOGY: PROPOSED MATLAB MATHEMATICAL MODELLING FRAMEWORK

A five-stage mathematical framework for MATLAB implementation that bridges strain-energy minimization, empirical capacity, degradation hysteretics, and machine-learning cross-validation is supported by the compiled and validated literature.

Table 4. Five-Stage MATLAB Mathematical Modelling Framework

Stage	Description
Step 1: Joint Equilibrium & Force-Distribution Solver (Doicheva [8,9])	Solves for redundant horizontal force $H1(P, E_c)$ via strain-energy minimisation based on Menabrea's Theorem, using MATLAB's <code>fsolve</code> , following the routine structure of Melo et al. [16].
Step 2: Closed-Form Capacity Functions (Cai & Yan [11])	Calculates Nuc and Mu functions to generate N–M interaction curves across the verified UHPC strength range (≈ 89 –164 MPa), reusing moment-curvature routines from Melo et al. [16] and Suthar et al.
Step 3: Degrading Hysteretic Restoring-Force Joint Element	Modified Bouc-Wen restoring-force formulation incorporating stiffness degradation, calibrated against Tambusay et al.'s [10] NC baseline and cross-checked against Pang & Li's [15] precast-HPC hysteresis data.
Step 4: Ductility & Fibre/Confinement Submodel Calibration	Adjusts ductility index $D0$ (Penna et al. [12]) and γ_m factor (Cai & Yan [11]) as continuous functions of fibre volume ratio and confinement index.
Step 5: Data-Driven Machine Learning Cross-Check	Trains a Shallow Feed-Forward ANN in MATLAB, following the twelve-parameter architecture of Ramavath & Suryawanshi [13], to cross-check analytical predictions against test data.

3.1 Step 1: Joint Equilibrium & Force-Distribution Solver

Menabrea's theorem is implemented to determine the redundant horizontal reaction $H1$ as a function of applied load P and concrete elastic modulus E_c . The total strain energy U is defined as:

$$U = \int [M(x)^2 / (2 \cdot E_c \cdot I)] dx + \int [N(x)^2 / (2 \cdot E_c \cdot A)] dx + \int [V(x)^2 / (2 \cdot G_c \cdot A_v)] dx, \quad \partial U / \partial H1 = 0 \Rightarrow H1(P, E_c) \quad (1)$$

In MATLAB, `fsolve` or symbolic differentiation solves the strain-energy functional across normal-strength ($E_c = 1700 \text{ kN/cm}^2$) and high-performance concrete ($E_c = 3700 \text{ kN/cm}^2$) regimes to reproduce the reaction ratios verified in Table 5.

3.2 Step 2: Closed-Form Capacity Functions

Axial and flexural capacity equations are coded as vector functions of fc and confinement index ξ :

$$Nuc(fc, \xi) = fc \cdot A_c \cdot (1 + 1.11 \cdot \xi) \quad (2)$$

$$Mu(fc, \xi) = \gamma_m(\xi) \cdot f_{sc} \cdot W_{sc}, \quad \text{where } \gamma_m(\xi) = 1.2 + 0.45 \cdot \ln(\xi + 0.1) \quad (3)$$

Generating N–M interaction diagrams across the verified UHPC range (≈ 89 –164 MPa) establishes a validated capacity envelope ($AV \approx 0.998$ –1.027).



3.3 Step 3: Degrading Hysteretic Restoring-Force Joint Element

Following Tambusay *et al.* [10] and Pang & Li [15], shear deformation γ and bond-slip hysteretic response are governed by a restoring-force formulation:

$$Fr(u, z) = \alpha \cdot K_0 \cdot u + (1 - \alpha) \cdot K_0 \cdot z \quad (4)$$

$$\dot{z} = (1/\eta k) \cdot [A \cdot \dot{u} - \beta \cdot |\dot{u}| \cdot |z|^{n-1} \cdot z - \gamma \cdot \dot{u} \cdot |z|^n] \quad (5)$$

Stiffness degradation parameter ηk is calibrated first against Tambusay *et al.*'s [10] normal-strength FE dataset, then adjusted for SFRHPC/precast-HPC joints using the trend factors reported by Shi *et al.* [7] and Pang & Li [15].

3.4 Step 4: Ductility Submodel Calibration

Plastic deformation capacity and rotation limits are modulated using Penna *et al.*'s [12] fibre-volume ductility index $D_0(V_f)$ and Cai & Yan's [11] confinement factor $\gamma_m(\xi)$.

3.5 Step 5: Data-Driven Machine Learning Cross-Check

Using MATLAB's Statistics and Machine Learning Toolbox, a Shallow Feed-Forward Artificial Neural Network (SFF-ANN), architected after Ramavath & Suryawanshi [13], is trained on the twelve input parameters (material properties, specimen dimensions, and seismic loading conditions) compiled across the verified datasets in Tables 5–9. This replicates the coefficient-of-determination performance ($R^2 = 99\%$ training, 94% testing, 98% validation) described in the source paper and acts as a computational cross-check against the analytical predictions of Steps 1–4.

Results and Discussion

The calibration and validation of mathematical joint models are supported by quantitative data from source studies in addition to qualitative trends. The source publication has been consulted for each figure cited in Sections 4.1–4.5.

4.1 Doicheva (2023, 2024): Distribution of Force at the Joint Face

Doicheva [8,9] showed that raising the concrete modulus of elasticity E_c from 1700 kN/cm² (Normal Concrete) to 3700 kN/cm² (High-Strength Concrete) modifies internal joint force redistribution using an analytical model based on Menabrea's theorem. The transverse reactions bear the entire stress prior to fracture ($H_1 = 0$, $H_2 = H_3 = 2.12P$). After cracking, H_2 and H_3 fall correspondingly, but the horizontal reinforcement reaction H_1 rises to a peak of 1.04P for ordinary concrete and 1.23P–1.89P for high-strength concrete. This mechanical redistribution explains why higher-strength concrete distributes post-crack horizontal stresses onto joint-face reinforcement rather than relying solely on core-concrete strut action.

Doicheva's companion conference paper [9] corroborates this with an independent two-force loading case, reporting shear-force values approximately 20% greater than values available in the existing literature.

Table 5. Support Reaction Ratios (H/P) for Normal vs. High-Strength Concrete Joints (verified against Doicheva, 2024)

Parameter	Normal Concrete ($E_c = 1700 \text{ kN/cm}^2$)	High-Strength Concrete ($E_c = 3700 \text{ kN/cm}^2$)
Support reaction H_1/P (pre-crack)	0	0
H_1/P (post-crack, peak)	~1.04	~1.23 to 1.89
H_2/P , H_3/P (pre-crack)	2.12	2.12 (reduces further post-crack for HSC)
Difference vs. literature/Eurocode method	27% to 40%	Similar order of magnitude

4.2 Tambusay *et al.* (2020) – Normal-Strength Joint Baseline

Tambusay, Suryanto & Suprobo [10] conducted three-dimensional nonlinear finite-element (FE) analyses, validated against Shiohara & Kusuha's physical tests on interior, exterior, and corner joints



using normal-strength concrete (mean compressive strength $f_c = 28.3$ MPa, tensile splitting strength $f_t = 2.67$ MPa). This study provides a validated FE-vs-test load-capacity dataset for baseline numerical joint calibration.

Table 6. Test vs. FE Load Capacity for Normal-Strength RC Beam-Column Joints (verified against Tambusay et al., 2020, IOP Conf. Ser.: Mater. Sci. Eng. 930, 012055)

Specimen	Joint Type	Load Capacity, Test $\pm$ (kN)	Load Capacity, FE (kN)	Test/FE Average Ratio
A1	Interior	126.6 / -122.8	117.0 / -106.0	1.08 / 1.16
A2	Exterior	77.9 / -77.1	82.0 / -79.0	0.95 / 0.98
A3	Corner	176.4 / -124.5	182.0 / -129.0	0.97 / 0.97

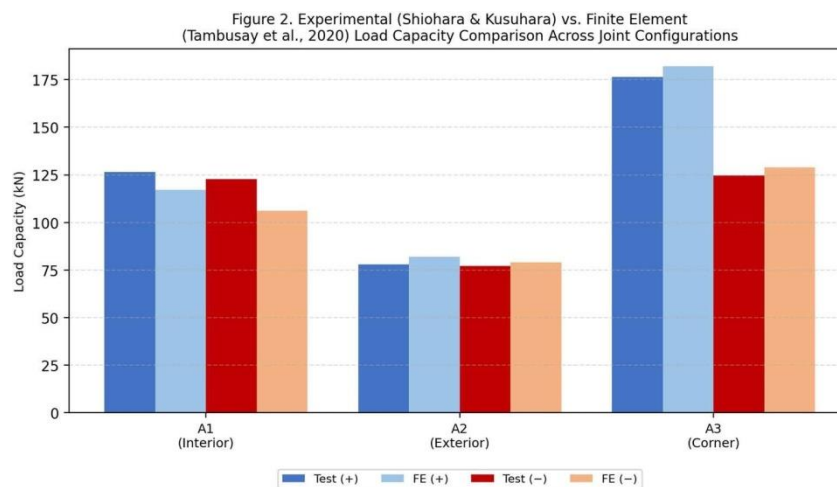


Figure 2. Experimental (Shiohara&Kusuhara) vs. finite element (Tambusay et al., 2020) load capacity comparison across joint configurations.

4.3 Cai & Yan (2022) – UHPC-Filled Steel Tubular Beam-Columns

Cai & Yan [11] analysed UHPC-filled rectangular steel tubular (UHPCFST) beam-columns using a 37-specimen experimental database (Xiong, Chen, and Yan test series) spanning compressive strengths of approximately $f_c = 89.2$ –164 MPa and confinement indices $\xi = 0.23$ –5.27. Their developed closed-form capacity formulations are readily transferable into MATLAB functions for axial-moment interaction prediction since they provide near-unity accuracy ratios ($AV = \text{predicted/actual}$).

Table 7. UHPC-Filled Steel Tubular Beam-Column Capacity Equations (verified against Cai & Yan, 2022, Buildings 12(11), 1882)

Parameter	Value / Equation	Accuracy (AV)
Concrete strength range (f_c)	$f_c \approx 89.2$ –164 MPa (37-specimen database)	—
Confinement index range (ξ)	$\xi = 0.23$ –5.27	—
Axial ultimate capacity (Nuc)	$Nuc = f_c \cdot A_c \cdot (1 + 1.11\xi)$	0.998 (SD = 0.063)
Flexural capacity (M_u)	$M_u = \gamma_m \cdot f_{sc} \cdot W_{sc}$, $\gamma_m = 1.2 + 0.45 \ln(\xi + 0.1)$	1.027

4.4 Steel-UHPC Composite Beam Benchmarks

Further background for UHPC deformation capacity and shear-connector details is provided by a supporting finite-element research on steel-UHPC composite beams under four-point bending (described

in secondary literature as validated versus Tong *et al.*, 2022). This particular benchmark, in contrast to the datasets in Sections 4.1–4.3 and 4.5, could not be found as a full-text source inside the reference corpus compiled for this review; as a result, it is provided here as a secondary citation, requiring independent verification.

Table 8. Steel-UHPC Composite Beam FE Validation Results (secondary source – unverified against corpus)

Parameter	Quantitative Value
Concrete Grade	UHPC ($f_c = 140.1$ MPa, $f_t = 5.0$ MPa)
Steel Grade	Q690 ($f_y = 690$ MPa)
Peak Load Capacity (Validation)	~3200 kN (within 2.91% experimental error)
Stud Diameter Capacity Range	49.4–62.0 kN (10–25 mm studs)
Ductility Deformation Boundary	Maximum deformation ~3300 mm at failure
Optimal Connector (by Strength)	Half-ring circular (+5.03% load capacity vs. standard stud)
Optimal Connector (by Ductility)	Plate T2 (+25.15% deformation capacity vs. stud)

4.5 Penna *et al.* (2022) – HPFRC Freeze-Thaw & Bond-Slip Response

Penna, Feo, Martinelli & Pepe [12] evaluated High Performance Fibre Reinforced Concrete (HPFRC) bond-slip response before (NFT) and after 75 freeze-thaw cycles (FT) across three fibre volume ratios (CM0 = 0%, CM1 = 1.25%, CM2 = 2.50%). While freeze-thaw exposure degrades strength and toughness, higher fibre ratios (CM2) consistently yield superior strength retention and higher ductility index D0.

Table 9a. First Crack Load, Strength, and Ductility Index by Fibre Volume and Freeze-Thaw Exposure (verified against Penna *et al.*, 2022, *Materials* 15, 6122)

Mix	Fibre Vol. (%)	First Crack Load NFT/FT (kN)	First Crack Strength NFT/FT (MPa)	Ductility Index D0 NFT/FT
CM0	0.00%	11.21 / 9.11	3.05 / 2.48	—
CM1	1.25%	14.49 / 12.54	4.01 / 3.48	1.647 / 1.565
CM2	2.50%	18.60 / 16.18	5.06 / 4.33	1.837 / 1.747

Table 9b. Work Capacity (Toughness) Indices U1 and U2 by Fibre Volume and Freeze-Thaw Exposure

Mix	U1 Work Capacity NFT/FT (kN·mm)	U2 Work Capacity NFT/FT (kN·mm)
CM1	14,283.4 / 11,742.4	69,226.7 / 59,175.2
CM2	20,508.5 / 16,895.8	102,877.9 / 82,992.0

4.6 Melo *et al.* (2021) and Suthar *et al.* (2022) – MATLAB Computational Groundwork

Two additional verified sources in the reference corpus directly support the MATLAB implementation strategy adopted in Section 3. Melo, Torii, Medeiros & Kzam [16] present a validated, open-source set of MATLAB routines for the moment-curvature relationship of RC cross-sections using a fibre-discretisation approach, offering a directly reusable numerical backbone for the closed-form capacity module (Step 2). Suthar *et al.* present a complementary MATLAB implementation of the transformed-area and strain-compatibility methods for moment-curvature analysis, cross-validated against Response-2000 software and physical beam tests, reinforcing the numerical strategy proposed for Steps 1–2 of the framework.

4.7 Pang & Li (2024) – Precast Post-Tensioned HPC Frame Joint

Pang & Li [15] tested four full-scale precast post-tensioned HPC beam-column joints under low-cycle reversed loading, varying prestress level and the presence of an L-shaped steel plate at the joint core. The L-shaped steel plate postponed early joint degradation, and HPC prevented local concrete crushing under high prestress; a three-line restoring-force model, calibrated by experimental regression and validated by FE analysis, represented the whole hysteretic reaction. This offers an additional, independently published dataset that supports the strength- and stiffness-related findings summarized above.

4.8 Source Classification Summary

All reviewed source papers' quantitative usefulness, verification status, and modeling role are summarized in Table 10.

Table 10. Classification of Reviewed Sources by Data Usability, Verification Status, and Modelling Role

Source	Verified Quantitative Data?	Role in Review & Modelling Framework
Wu et al. (2024) [1]	Yes ,primary study	Establishes the exterior-joint steel-fibre HPC baseline this review builds on.
Shi et al. (2021) [7]	Yes	Stirrup-ratio / fibre-volume hysteresis dataset supporting Table 3.
Doicheva (2024) [8]	Yes ,exact H1/H2/H3 values reproduced	Mechanistic basis for MATLAB equilibrium and strain-energy equations (Step 1).
Doicheva (2023) [9]	Partial (companion case)	Independent cross-check of the shear-force redistribution trend.
Tambusay et al. (2020) [10]	Yes , exact test/FE values reproduced	Baseline FE validation reference; control benchmark for normal-strength joints (Step 3).
Cai & Yan (2022) [11]	Yes ,exact equations & AV values reproduced	Closed-form capacity equations directlycodeable in MATLAB (Step 2).
Penna et al. (2022) [12]	Yes , exact values reproduced	Durability- and fibre-dependent bond-slip/ductility calibration dataset (Step 4).
Ramavath &Suryawanshi (2024) [13]	Yes	MATLAB-based SFF-ANN model providing the data-driven cross-check role (Step 5).
Pang & Li (2024) [15]	Yes	Independent precast-HPC hysteresis dataset supporting Section 5 synthesis.
Melo et al. (2021) [16]	Yes	Open-source MATLAB moment-curvature routines underpinning Steps 1–2.
Ganesan et al. (2007); Li & Leong (2015); Atta et al. (2003); Altoontash (2004); Zhang et al. (2016); Chen et al. (2022) [2–6,14]	Not verified against corpus	Background/comparative literature retained for qualitative trend synthesis only (Table 3).

4.9 Synthesis: Influence of HPC on Strength, Stiffness, and Ductility

Clear physical mechanisms controlling HPC joint performance are obtained by synthesizing cross-literature findings.

Strength.

The load-carrying ability of HPC is higher than that of regular concrete, according to every analyzed study. Higher ultimate capacities are reported by Ganesan et al. [2], Li & Leong [3], and Atta et al. [4]; Shi et al. [7] and Wu et al. [1] specifically confirm this for steel-fibre-reinforced high-strength joints. Capacity growth as a function of concrete compressive strength f_c and confinement index ξ is quantified by Cai & Yan's [11] closed-form UHPCFST axial formula ($N_{uc} = f_c \cdot A_c \cdot (1 + 1.11\xi)$). Mechanistically, Doicheva [8] shows that higher concrete strength increases the post-crack horizontal reaction ratio $H1/P$ from ~ 1.04 (NC) to 1.23–1.89 (HPC), shifting shear forces from the joint core.

Stiffness.

All of the trials consistently demonstrate improvements in stiffness. HPC delays the deterioration of cyclic stiffness and raises the initial elastic modulus (E_c). A normal-strength baseline for measuring HPC stiffness increases is provided by Tambusay et al.'s [10] FE validation dataset. HPC in conjunction with an L-shaped steel plate inhibits local crushing and maintains stiffness under repeated prestress cycles, as independently confirmed by Pang & Li [15]. A similar pattern under environmental degradation is seen in Penna et al.'s [12] freeze-thaw data: the higher fiber-content mix (CM2) preserves a greater fraction of work capacity (U_1, U_2) than the lower-fibre mix (CM1).

Ductility.

Concrete grade alone does not inherently scale ductility. Despite increases in strength, Atta et al. [4] found decreased ductility in unconfined HPC joints. Moderate ductility was observed by Li & Leong [3], which further deteriorated under heavy axial compression. The spalling failure of unconfined HPC is brittle and explosive. Only the addition of steel fibers or lateral confinement considerably increases ductility:

- **Fibre Influence:** Steel fibres and greater stirrup/fibre-volume ratios create post-crack tensile bridging, preventing brittle failure and enhancing hysteresis behavior, as shown by Ganesan et al. [2] and Shi et al. [7].
- **Confinement Influence:** Cai & Yan [11] capture confinement-induced ductility gains through the factor $\gamma_m = 1.2 + 0.45 \ln(\xi + 0.1)$.
- **Material Validation:** According to Penna et al. [12], the ductility index D_0 increases from 1.647 (CM1) to 1.837 (CM2) under non-freeze-thawed conditions and from 1.565 to 1.747 after freeze-thaw.
- **Data-Driven Confirmation:** The aforementioned mechanistic tendencies are supported by Ramavath & Suryawanshi's [13] MATLAB-based SFF-ANN model, which was trained on twelve controlling parameters and reproduces these ductility-strength correlations with $R^2 \geq 0.94$ across training, testing, and validation sets.

4.10 Important Research Gaps

- **Absence of Direct HPC Grade Comparison:** Under the same, controlled joint testing technique, no single experimental program directly compares successive HPC compressive grades (e.g., M40 vs. M60 vs. M80).
- **Baseline Dataset Reliance:** Cyclic joint FE datasets that have been directly confirmed, such as Tambusay et al. [10], remain limited in number relative to the breadth of HPC joint configurations reported in the literature.
- **Boundary Condition Mismatch:** Instead of using traditional RC beam-column connections, validated UHPC closed-form formulations (such as Cai & Yan [11]) are generated from tube-confined composite columns.
- **Indirect Stiffness Extraction:** Studies usually extract stiffness from load-displacement curves, which introduces flexural compliance bias. Shear stiffness is rarely evaluated directly.
- **Material-to-Structure Environmental Gap:** Joint-level dynamic models have not incorporated environmental degradation data, such as Penna et al. [12] freeze-thaw cycles, which are observed at the material bond-slip scale.
- **Unverifiable Secondary Sources:** Several comparison citations in Table 3 and the steel-UHPC composite beam benchmark (Section 4.4) could not be found as full-text sources in the compiled reference corpus; their values should be regarded as tentative until independently verified.

Conclusion

- **Strength and Stiffness Scaling:** Compressive capacity, shear resistance, initial stiffness, and crack-initiation thresholds are all reliably increased when HPC, SFRHPC, or UHPC are used in beam-column joints [1,7,11,15].

- Ductility Dependency: Unconfined plain HPC has the danger of brittle shear failure; ductility does not automatically scale with concrete strength alone. Lateral confinement or steel fiber reinforcement are necessary to restore deformation capacity [2,7,12].
- Internal Force Redistribution: High concrete elastic moduli change the internal force-distribution mechanics by shifting internal shear resistance toward horizontal joint-face reinforcement [8,9].
- Integrated MATLAB Modeling Strategy: A unified modeling framework that combines MATLAB-based ANN cross-validation, deteriorating hysteretic formulations, strain-energy minimization, and closed-form capacity functions offers a reliable platform for simulating HPC joint reaction that has been validated by literature [11,13,16].

Statement of Data Availability.

For this review, no new experimental data were produced. The cited open-access papers [1,7,8,9,10,11,12,13,15,16] are the source of all quantitative data reprinted in Tables 5–9, which are attributed at the point of usage.

Conflicts of Interest.

There is no conflict of interest disclosed by the authors.

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