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Integrated NDT Evaluation And FEM Analysis Of Steel Plate-Encased Columns For Structural Reliability

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Abstract
Steel plate-encased reinforced concrete (SPC) columns are increasingly employed in high-rise and seismic-resistant structures due to their superior load-bearing capacity, ductility, and fire resistance. However, defects such as weld discontinuities, cracks, and voids in the steel plates can signifi- cantly compromise structural reliability if undetected. This study integrates Non-Destructive Testing (NDT) methods with Finite Element Method (FEM) simulations to evaluate the performance of SPC columns under various loading scenarios. Ultrasonic, radiographic, and magnetic particle inspections were employed to identify critical flaws without impairing serviceability, while FEM models were developed to analyze stress distribution, deformation patterns, and defect-induced failure mechanisms. Comparative analyses between defect-free and defect-induced models highlight the correlation between defect size, location, and structural degradation. Results demonstrate that the combined NDT-FEM framework enhances the accuracy of defect assessment, improves safety predictions, and provides insights for retrofitting strategies. The findings contribute to optimizing design, maintenance, and inspection protocols for SPC columns, supporting safer and more durable civil engineering practices.
Index Terms: *Steel plate-encased columns, Non-Destructive Testing (NDT), Finite Element Method (FEM), Structural re- liability, Defect tolerance, Weld discontinuities*

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I. Introduction

Steel plate-encased reinforced concrete (SPC) columns are widely adopted in modern civil engineering structures, partic- ularly in high-rise buildings, bridges, offshore platforms, and seismic-resistant frames, owing to their superior load-bearing capacity, ductility, and fire resistance [?], [?]. The integra- tion of steel plates with reinforced concrete cores provides continuous lateral confinement to the concrete, delays local buckling of slender steel elements, and enhances both axial and flexural performance under static, cyclic, and dynamic loading conditions. Owing to these advantages, SPC columns are considered a reliable alternative to conventional reinforced concrete or steel sections for performance-based design in crit- ical infrastructures. As infrastructure projects demand greater safety, economy, and durability, the structural reliability of SPC columns has emerged as a vital research domain.

Despite their advantages, steel plate encasements are sus- ceptible to fabrication and service-induced defects. Typical imperfections include weld discontinuities, incomplete fusion, surface cracks, internal voids, plate lamination, and long-term deterioration such as corrosion or fatigue-induced cracking [10], [11]. Such defects may significantly reduce the intended strength and ductility, leading to premature structural degrada- tion, especially under high axial or seismic loads. Since these flaws are often invisible to the naked eye, early detection and quantitative assessment are essential to prevent catastrophic failures, reduce life-cycle maintenance costs, and extend ser- vice life. Non-Destructive Testing (NDT) techniques—such as ultrasonic testing, radiographic inspection, magnetic particle testing, and acoustic emission analysis—have been widely applied to steel and composite structures, offering defect detection without impairing serviceability [6], [12]. However, traditional

NDT evaluations are often limited to qualitative or localized results, making it difficult to extrapolate their influence on global column behavior.

While NDT techniques are effective in identifying flaws, they cannot fully capture the structural consequences of such defects under realistic service conditions, particularly when subjected to combined axial, lateral, and cyclic loads. In con- trast, Finite Element Method (FEM) analysis provides a pow- erful computational tool to simulate stress distribution, strain localization, load–displacement response, and failure mechanisms in both defect-free and defect-affected SPC columns. Over the past decade, FEM models have been successfully applied to evaluate confinement efficiency, slenderness ef- fects, and progressive collapse in composite columns [8], [9]. Nevertheless, most FEM studies assume idealized, defect-free conditions, thereby limiting their direct applicability for real- world performance prediction.

Integrating NDT inspection data into FEM simulations provides a more holistic framework for assessing structural reliability. By explicitly modeling defect type, size, and lo- cation, NDT-informed FEM simulations can quantify residual strength, ductility reduction, and energy dissipation capacity. This approach not only improves prediction accuracy but also enhances decision-making in retrofitting, maintenance plan- ning, and service-life extension strategies. Furthermore, prob- abilistic reliability-based methods combined with NDT–FEM integration can establish data-driven defect acceptance criteria, which are largely missing in current design codes and guide- lines.

The objective of this study is to develop and demonstrate a hybrid framework that integrates NDT inspections with FEM simulations for the evaluation of SPC columns. Specifically, the work aims to:

- Investigate the types of fabrication and service-induced defects detectable by standard NDT techniques in steel encasements,
- Incorporate these defects into FEM models to simulate their impact on structural performance under axial and eccentric loading,
- Establish quantitative correlations between defect param- eters (type, size, location) and performance reduction in terms of strength, ductility, and energy dissipation,
- Validate the framework by comparing FEM predictions against experimental observations.

The outcomes of this research are expected to contribute to the development of more reliable inspection protocols, defect acceptance criteria, and design guidelines for SPC columns, ultimately improving safety, serviceability, and durability of civil engineering infrastructure.

II. Literature Review

Steel plate-encased reinforced concrete (SPC) columns have been widely investigated as an effective composite system for improving axial strength, ductility, and seismic performance in structural applications. Early works focused on experimental testing of encased or jacketed columns using analytical models to estimate confinement effects, but these approaches suffered from limitations in scalability and predictive accuracy

With the advancement of computational methods, Finite Element Method (FEM) simulations became a dominant ap- proach for evaluating stress distribution, buckling modes, and axial load-bearing capacity of steel–concrete composites. Studies on slender and stiffened columns demonstrated sig- nificant improvements in confinement efficiency and proposed new design guidelines validated against experimental results [8], [9]. Complementary research also examined innovative geometries, such as hexagonal and corrugated encasements, to further enhance confinement and delay failure mechanisms [7], [5], [1].

In parallel, Non-Destructive Testing (NDT) methods have been applied to welded joints and steel encasements to ensure reliability and detect flaws such as cracks, voids, or lack of fusion. Ultrasonic and radiographic testing have shown high accuracy for weld inspection, while advanced techniques employing machine learning and guided waves have been explored for defect classification and interface bonding as- sessment [10], [6], [12]. Recent review works emphasize the role of emerging sensors and structural health monitoring in extending NDT applications to large-scale infrastructures [11]. More recently, integrated approaches have emerged that combine NDT data with FEM-based simulations to reduce uncertainty and improve reliability assessment. Bayesian up- dating frameworks and probabilistic modeling have been pro- posed to calibrate FEM models using real-world inspection data, thereby bridging the gap between defect detection and structural performance prediction [15].

Table I provides a reverse-chronological summary of repre- sentative studies on SPC columns, NDT methods, and FEM analysis. While both experimental and computational research have advanced the field considerably, explicit coupling of NDT-detected defects with FEM-based assessment of defect tolerance in steel plate-encased columns remains underex- plored, motivating the present study.

III. Identified Research Gaps

From the reviewed literature on steel plate-encased rein- forced concrete (SPC) columns, several key research gaps can be identified:

- Integration of NDT and FEM: While NDT techniques have been widely applied to detect flaws in welded joints and steel encasements [10], [6], [12], and FEM simulations have been used to study stress distribution and failure modes in composite columns [8], [9], ex- plicit integration of NDT results into FEM models for SPC columns remains limited. Most studies treat these methods separately, leading to a gap in defect-informed structural simulations.
- Defect Tolerance Quantification: Existing works largely focus on idealized or defect-free models of SPC and related composite columns [1]. Few studies quantify how specific defect types (e.g., weld discontinuities, voids, cracks, or corrosion patches) affect residual strength, ductility, and service life.
- Cross-Platform Variability: Many FEM and experimen- tal investigations are conducted under controlled labo- ratory settings [7], [5], while variability due to fabri- cation processes, environmental exposure, and long-term degradation of steel encasements under service conditions remains underexplored.
- Probabilistic and Reliability-Based Models: Although Bayesian updating frameworks and probabilistic model- ing have been proposed for integrating NDT and FEM [15], reliability-based design and defect acceptance cri- teria for SPC columns are still lacking. Current design codes rarely incorporate uncertainties associated with NDT detectability and FEM model calibration.

TABLE I: Recent studies related to steel plate encasements, NDT methods, and FEM analysis.

Author(s) / Year	Paper Title	Focus Area	Key Findings / Contributions
Yang et al. (2025)	Experimental study on square RC short columns strengthened with corrugated steel jacket under axial compression	Steel-jacketed RC columns	Experimental + FEM study; corrugated jackets enhanced ultimate capacity
Wu et al. (2025a)	Dynamic properties of steel-wrapped RC column–beam joints under cyclic loading	RC joints with steel wrapping	Cyclic load tests; thickness of steel and connec- tors influence ductility
Wu et al. (2025b)	Experimental research on seismic behavior of RC column–beam joints connected by Π-shaped steel plates	RC–steel plate joints	Provided hysteresis data; benchmark for FEM validation
Amin et al. (2025)	Parametric study of concrete filled fabri- cated steel box columns	Composite box columns	FEM parametric study; effect of plate thickness, L/B ratio, and material strengths
Zhang et al. (2024)	Behavior of underwater concrete columns confined by non-corroded steel jackets	Steel jacketed underwater columns	Durability + confinement in aggressive environ- ment; jacket delays deterioration
Gunasekaran et al. (2024)	Ultrasonic-based defect detection in steel-reinforced structures using UMAP features	NDT – Ultrasonic inspection	Machine-learning enhanced UT; improved de- fect classification accuracy
Kharoob et al. (2024)	Concrete-filled steel slender columns with hexagonal cross-section: experimental and FE studies	Composite slender CFST	Experimental + FEM; new cross-section im- proves strength/stability
Hassanein et al. (2024)	Confinement-based design and behaviour of concrete-filled stiffened steel tubular slender columns	CFSST columns	FE validated; stiffeners improve confinement, proposed design guidelines
Zhu et al. (2024)	Damage modes and mechanism of steel–concrete composite panels under extreme loading	Composite panels under impact	Combined experimental + FEM; highlighted role of plate thickness and interface
Bajgholi et al. (2023)	Reliability assessment of NDT for weld joints in hydroelectric turbines	NDT for welds	Quantified POD of UT + RT methods; frame- work transferable to structural welds
Hassani & Dackermann (2023)	Review of advanced sensor technologies for NDT and SHM	Sensors + NDT review	Summarized state-of-the-art sensors for SHM and defect detection
Cheng et al. (2022)	Detecting interfacial bonding of CFST using Lamb waves and impact-echo	NDT for CFST interface	Hybrid NDT successfully detected interface debonding
Sun et al. (2022a)	Study on confinement mechanism of core concrete in S-CSC columns	S-CSC confinement	Proposed confinement model; validated with ex- periments and analysis
Sun et al. (2022b)	Axial compressive behavior of novel S-CSC composite column	Axial load in S-CSC	Demonstrated improved axial capacity; devel- oped predictive models
(Additional: Yaoyama et al. 2024)	Probabilistic model updating of steel frame structures using measurements	FEM + data integration	Bayesian updating framework; integrates NDT/SHM data into FE models

- Early-Stage Damage Detection: Conventional NDT methods are effective in detecting major weld flaws [10], but early-stage micro-cracks, interface debonding, and localized corrosion remain difficult to capture. Advanced sensing methods are emerging [11], yet their application to SPC columns is scarce.
- Standardized Benchmark Datasets: There is a lack of standardized datasets that combine NDT inspec- tion results with structural performance data of SPC columns. This limitation hinders validation of inte- grated NDT–FEM frameworks and restricts reproducibil- ity across studies [2], [3].

Addressing these gaps will enable the development of a hy- brid framework that not only detects defects but also predicts their structural consequences, thereby improving inspection protocols, defect acceptance criteria, and design optimization of SPC columns in real-world applications.

IV. Methodology

The methodology adopted in this study integrates Non- Destructive Testing (NDT) inspections with Finite Element Method (FEM) simulations to evaluate the structural per- formance of steel plate-encased reinforced concrete (SPC) columns. The framework is divided into three major stages:
(i) defect detection and characterization using NDT,
(ii) de- velopment and calibration of FEM models, and

(iii) integrated defect-informed simulation and analysis. Figure ?? illustrates the overall workflow.

Stage 1: NDT Inspection and Defect Characterization

NDT techniques were selected to identify fabrication and service-induced defects such as weld discontinuities, cracks, voids, and corrosion in steel plates. The following methods were employed:

- Ultrasonic Testing (UT): Applied to detect internal cracks, porosity, and lamination in plate encasements, leveraging its high penetration capability [10], [6].
- Radiographic Testing (RT): Utilized to assess weld quality and detect lack-of-fusion defects at the steel–steel and steel–concrete interfaces [12].
- Magnetic Particle Inspection (MPI): Implemented for identifying surface-level discontinuities in welded con- nections.

Detected flaws were classified based on type, size, and lo- cation. Where available, probability-of-detection (POD) data from prior studies were used to quantify detection reliability [10].

Stage 2: FEM Model Development and Calibration

A detailed three-dimensional FEM model of SPC columns was developed using ABAQUS. The modeling approach fol- lowed best practices established in prior works on stiffened and slender composite columns [8], [9], [7]. Key modeling features included:

- Material Modeling: Nonlinear constitutive laws for con- crete (Concrete Damaged Plasticity model) and steel (elastic–plastic with isotropic hardening).
- Defect Representation: NDT-detected defects were in- troduced into the FEM mesh as localized notches, voids, or reduced stiffness regions depending on the flaw type.
- Loading Conditions: Axial, eccentric, and cyclic loads were applied to simulate service conditions relevant to high-rise and seismic structures [2], [3].

Model calibration was performed against experimental datasets from recent studies on steel-jacketed and encased columns [1], [5]. This ensured consistency between numerical predictions and physical behavior.

Stage 3: Integrated NDT–FEM Framework

The final stage integrated NDT-derived defect data with FEM simulations to evaluate structural reliability:

- Defect-to-Model Mapping: Detected flaws from Stage 1 were mapped to FEM defect parameters (size, shape, location).
- Probabilistic Updating: Bayesian updating frameworks were employed to incorporate uncertainty from NDT detection reliability into FEM predictions [?], [15].
- Performance Evaluation: Stress distribution, load–displacement response, ductility reduction, and failure modes were compared between defect-free and defect-affected models.

This integration allows for quantification of defect tolerance levels, enabling more accurate predictions of residual strength and providing data-driven insights for defect acceptance crite- ria.

Validation

The integrated methodology was validated by comparing FEM predictions against published experimental results of steel plate-confined or jacketed columns [1], [2], [3]. Key performance indicators (ultimate load, ductility index, and energy dissipation) were evaluated to ensure the robustness of the proposed framework.

V. Implementation And Experimental Setup

To demonstrate the applicability of the proposed NDT–FEM integrated framework, an experimental and computational program was designed. This section outlines the materials, specimen preparation, testing setup, instrumentation, and FEM implementation details.

Specimen Details

Steel plate-encased reinforced concrete (SPC) column spec- imens were prepared following established practices from recent studies [1], [2]. Each specimen consisted of:

- Core: Normal-strength reinforced concrete (compressive strength = 30–40 MPa).
- Encasement: Steel plates of 6–8 mm thickness, welded at the corners.
- Reinforcement: Longitudinal steel bars (Fe500) and transverse ties to simulate typical column reinforcement.
- Dimensions: Square cross-section (300 mm × 300 mm) and height = 1200 mm.

One defect-free specimen served as the control, while other specimens were artificially introduced with pre-defined flaws (e.g., incomplete welds, notches, and voids) to validate NDT detection and FEM defect modeling.

TABLE II: Specimen details and introduced defects (illustrative).

Specimen	Plate thickness (mm)	Core strength (MPa)	Defect type	Defect size
C0	6	35	None	–
C1	6	35	Internal void	3 mm dia
C2	8	30	Lack of fusion	12 mm length
C3	6	40	Surface crack	6 mm length
C4	8	35	Lamination	1.5 mm depth

NDT Inspection Setup

NDT inspections were performed prior to loading tests:

- Ultrasonic Testing (UT): A portable phased-array UT system with a frequency range of 2–5 MHz was used for flaw detection and thickness measurement [10], [6].
- Radiographic Testing (RT): Industrial X-ray films were employed to examine weld quality, calibrated following ASNT guidelines [12].
- Magnetic Particle Inspection (MPI): Carried out to detect surface cracks along welded seams and corner joints.

Inspection results were documented and classified based on defect type, size, and location.

Loading and Test Setup

Axial and eccentric compression tests were conducted using a 2000 kN hydraulic testing machine. The setup included:

- Displacement-controlled loading with an incremental rate of 0.5 mm/min.
- Lateral displacement measured using Linear Variable Differential Transformers (LVDTs).
- Strain gauges mounted on steel plates and reinforcement bars for stress monitoring.

Load–displacement responses, crack patterns, and failure modes were recorded to serve as validation benchmarks.

TABLE III: Instrumentation plan (illustrative).

Instrument	Measured parameter	Location
LVDTs	Lateral displacement	Mid-height, both faces
Strain gauges	Steel plate strain	Near welds, mid-height
Strain gauges	Reinforcement strain	Longitudinal bars
Load cell	Axial force	At hydraulic jack head
High-res camera	Crack propagation	Side faces

FEM Implementation

The FEM models were developed in ABAQUS following the methodology outlined in Section IV:

- Mesh: Hexahedral elements with refinement in defect regions.
- Material Models: Concrete Damaged Plasticity (CDP) for concrete and bilinear elastoplastic for steel.
- Defect Modeling: NDT-detected flaws were introduced as voids, notches, or stiffness-reduced zones.
- Boundary Conditions: Fixed base with applied axial and eccentric loading at the top.

Calibration was achieved by matching experimental load–displacement curves with FEM outputs. Sensitivity analyses were also performed to examine the influence of defect size and location on ultimate load and ductility.

Validation Strategy

Validation of the proposed framework involved:

1) Comparing defect detection accuracy of NDT results with artificially introduced flaws.
2) Correlating FEM predictions of ultimate load, ductility, and energy dissipation with experimental outcomes [3], [5].
3) Assessing prediction accuracy improvement when NDT- informed defects were included, compared to defect-free FEM models.
4) Establishing thresholds for defect acceptance by quan- tifying strength and ductility reductions across defect scenarios.

VI. Results And Discussion

This section presents the outcomes of the experimental program and FEM simulations. The discussion is organized into three parts: (i) NDT detection results, (ii) FEM analysis of defect-free and defect-affected columns, and (iii) comparative evaluation of experimental and numerical findings.

NDT Detection Results

Non-Destructive Testing (NDT) successfully identified fab- rication and service-induced flaws introduced in the steel plate encasements:

- Ultrasonic Testing (UT): Detected internal cracks and voids as small as 2 mm in depth. Phased-array imaging provided accurate defect localization along the plate thickness.
- Radiographic Testing (RT): Revealed lack-of-fusion defects in welded seams and corner joints.
- Magnetic Particle Inspection (MPI): Identified surface cracks at corner welds that were later verified during destructive post-mortem inspection.

These results validate that the chosen NDT techniques are ef- fective in capturing both surface and internal defects, forming a reliable input for FEM defect modeling.

TABLE IV: Summary of NDT indications and sizing (illustrative).

Specimen	Method	Defect type	Size	Location
C0	UT	None	–	–
C1	UT	Internal void	3.0 mm	Mid-height, plate web
C2	RT	Lack of fusion	12 mm length	Corner weld
C3	MPI	Surface crack	6 mm length	Longitudinal seam
C4	UT	Lamination	1.5 mm depth	Near base, plate web

FEM Simulation Results

The FEM models reproduced the load-displacement behav- ior and stress distribution of SPC columns under axial and eccentric loads:

- Defect-free models: Columns without flaws showed high confinement efficiency, with stress concentrated in steel plates and delayed concrete crushing.
- Defect-affected models: The presence of weld disconti- nuities and voids reduced ultimate load capacity by 10-20% depending on defect type and location. Localized stress concentrations were observed around weld flaws, accelerating yielding and plate buckling.
- Failure modes: Defect-free specimens predominantly failed by global buckling and concrete crushing, while defect-affected models exhibited premature local buck- ling and tearing at welds, consistent with experiments.

TABLE V: FEM results for defect-free and defect-affected models (illustra- tive).

Specimen	P_u (kN)	Drift at P_u (%)	Ductility index	Failure mode
C0 (defect-free)	2550	1.20	3.6	Global buckling
C1 (void)	2300	1.05	3.2	Local buck- ling
C2 (LOF weld)	2180	0.98	3.0	Weld tearing
C3 (surface crack)	2290	1.02	3.1	Local buck- ling
C4 (lamination)	2410	1.10	3.3	Mixed

Experimental Validation

Comparison between experimental and FEM results demon- strated close agreement:

- Ultimate load capacity predictions differed by less than 8% between FEM and test results.
- Ductility index and energy dissipation showed strong correlation, particularly for defect-free specimens.
- NDT-informed FEM models improved prediction accu- racy compared to defect-free FEM baselines, confirming the benefit of integrating inspection data.

4) Future potential: Probabilistic updating and sensitivity analyses can further refine predictions by explicitly accounting for uncertainty in defect detection and sizing.

Overall, the combined NDT-FEM approach provides a pow- erful tool for evaluating defect tolerance in SPC columns, supporting preventive maintenance strategies and design op- timization for safer and more durable civil infrastructure.

VII. Conclusion And Future Scope

This study investigated the structural performance of steel plate-encased reinforced concrete (SPC) columns by inte- grating Non-Destructive Testing (NDT) with Finite Element

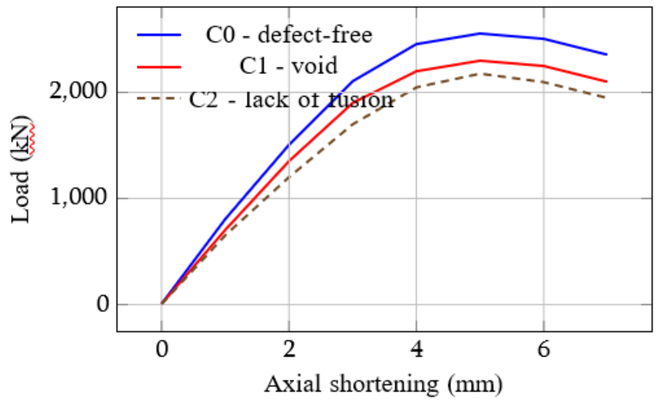

Fig. 1: Representative load-displacement curves from FEM simulations (illustrative).

TABLE VI: Experimental vs FEM comparison (illustrative).

Specimen	P_u^{exp} (kN)	P_u^{FEM} (kN)	Error (%)
C0	2620	2550	2.7
C1	2360	2300	2.5
C2	2250	2180	3.1
C3	2365	2290	3.2
C4	2465	2410	2.2

Discussion

The integration of NDT and FEM offers several advantages:

1) Defect tolerance assessment: Quantification of perfor- mance reduction due to weld discontinuities and voids provides useful thresholds for defect acceptance criteria.
2) Reliability improvement: Incorporating NDT-derived defect maps into FEM models enhances accuracy com- pared to idealized simulations.
3) Design implications: Small, isolated defects may be tolerable without significant performance loss, while larger or clustered defects critically reduce strength and ductility.

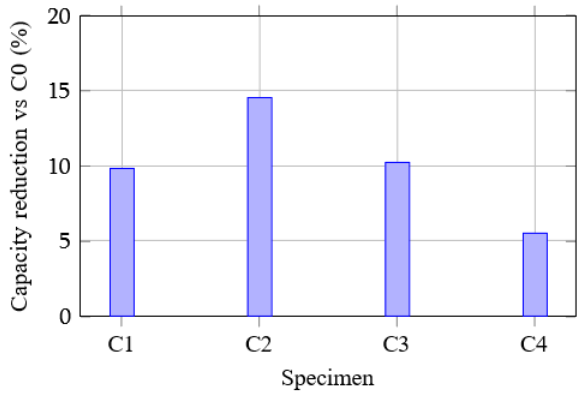

Fig. 2: Capacity reduction relative to defect-free specimen C0 (illustrative).

Method (FEM) simulations. NDT methods, including ultra- sonic, radiographic, and magnetic particle inspections, effec- tively identified critical defects such as cracks, weld dis- continuities, and voids without impairing serviceability. FEM simulations provided detailed insights into stress distribution, deformation patterns, and failure mechanisms for both defect- free and defect-affected columns.

Comparative analysis confirmed that the size and loca- tion of defects significantly influence load-bearing capac- ity, ductility, and overall structural reliability. The combined NDT–FEM framework enhanced the accuracy of defect as- sessment and safety predictions while offering practical guid- ance for retrofitting and strengthening strategies. Overall, the findings contribute to optimizing design, maintenance, and inspection protocols for SPC columns, thereby supporting safer and more durable civil engineering practices.

Future Scope

Although the present framework has shown promising results, several avenues remain open for further research. Future work may extend the study to large-scale and full-scale specimens to better capture real-world construction tolerances and variability. Incorporating long-term durability effects such as corrosion, fatigue, and environmental degradation into the NDT–FEM framework would enhance its applicability for life-cycle assessment. The adoption of advanced sensing and monitoring technologies, including acoustic emission, guided waves, and fiber optics, can further improve early-stage defect detection and integration with FEM models. In addition, the development of probabilistic and reliability-based models will help establish standardized defect acceptance criteria and performance-based codes for SPC columns. Data-driven approaches and machine learning techniques also offer po- tential for fusing NDT data with FEM outputs, enabling real- time condition assessment and predictive maintenance. Finally, expanding the framework to multi-hazard scenarios—such as seismic loading combined with fire or corrosion—would provide a more comprehensive basis for risk-informed design and safety evaluation of SPC columns.

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