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# NON-DISTRUCTIVE TESTING AND FINITE ELEMENT ANALYSIS OF STEEL PLATE USED TO ENCASED COLUMNS

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*Abstract:* **Steel plate-encased reinforced concrete (SPC) columns are widely employed in civil engineering for their enhanced strength, ductility, and durability, particularly in high-rise and seismic-prone structures. However, defects in steel encasements—such as weld discontinuities, voids, surface cracks, or lamination—can compromise reliability and service life. This paper presents an integrated study combining Non-Destructive Testing (NDT) with Finite Element Method (FEM) analysis to evaluate defect detection and structural performance of SPC columns. Ultrasonic, radiographic, and magnetic particle inspections were performed to identify and classify flaws, while FEM simulations in ABAQUS were used to analyze stress distribution, load–displacement response, and failure mechanisms for both defect-free and defect-affected columns. Comparative results demonstrate that defects significantly influence ultimate load capacity and ductility, with NDT-informed FEM models yielding more accurate predictions than idealized simulations. The proposed NDT–FEM framework provides a reliable basis for developing defect acceptance criteria, retrofitting strategies, and performance-based design guidelines, thereby improving safety, durability, and maintenance planning in steel–concrete composite structures.**

*Index Terms:* **Non-Destructive Testing (NDT), Finite Element Method (FEM), Steel Plate-Encased Columns, Structural Reliability, Defect Detection, Composite Structures**

## I. INTRODUCTION

Steel plate-encased reinforced concrete (SPC) columns have gained increasing attention in modern civil engineering, particularly for high-rise buildings, bridges, offshore platforms, and seismic-resistant structures, due to their superior load-bearing capacity, ductility, and fire resistance [1]. The combination of steel plates with a reinforced concrete core provides continuous lateral confinement, 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 regarded as a reliable alternative to conventional reinforced concrete or steel sections, especially in performance-based design of critical infrastructure. With increasing demands for safety, economy, and durability, their structural reliability has become a key research priority.

However, steel plate encasements are also vulnerable to fabrication- and service-induced defects. Common imperfections include weld discontinuities, incomplete fusion, surface cracks, internal voids, plate lamination, and long-term degradation such as corrosion or fatigue-induced cracking [10], [11]. These flaws can significantly reduce strength and ductility, resulting in premature structural deterioration, particularly under high axial or seismic loading. Since many of these defects are not visible during routine inspection, early detection and quantitative evaluation are essential to prevent catastrophic failure, minimize life-cycle maintenance costs, and extend service life. Non-Destructive Testing (NDT) methods—such as ultrasonic testing, radiographic inspection, magnetic particle testing, and acoustic emission analysis—are widely employed for defect detection in steel and composite structures [6], [12]. Yet, conventional NDT results often remain qualitative and localized, making it difficult to assess their impact on global column performance.

On the other hand, Finite Element Method (FEM) analysis provides a powerful computational approach 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 has been extensively used to study confinement efficiency, slenderness effects, and progressive collapse of composite columns [8], [9]. However, most FEM models assume idealized conditions without defects, limiting their applicability for predicting real-world behavior.

Integrating NDT results into FEM simulations provides a holistic framework for evaluating structural reliability. By explicitly modeling defect type, size, and location, NDT-informed FEM simulations can quantify residual strength, ductility reduction, and energy dissipation capacity. This integration enhances prediction accuracy and supports practical decision-making for retrofitting, maintenance planning, and service-life extension. In addition, probabilistic reliability-based approaches combined with NDT–FEM integration can contribute to the development of defect acceptance criteria, which are still absent from current design codes and guidelines.

The objective of this study is to present and validate a hybrid framework that integrates NDT inspections with FEM simulations for assessing the performance of SPC columns. Specifically, the research aims to:

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

The outcomes of this research are expected to support the development of reliable inspection protocols, defect acceptance thresholds, and performance-based design guidelines for SPC columns, ultimately enhancing the safety, durability, and resilience of civil engineering infrastructure.

## II. LITERATURE REVIEW

Steel plate-encased reinforced concrete (SPC) columns have been extensively investigated as a composite system for enhancing axial strength, ductility, and seismic performance. Early research primarily focused on experimental testing of encased or jacketed columns, supported by analytical models to estimate confinement effects. While these studies provided important insights, they were limited in scalability and predictive accuracy.

With the advancement of computational tools, the Finite Element Method (FEM) has become a dominant approach for evaluating stress distribution, buckling behavior, and axial load-bearing capacity of steel–concrete composites. Investigations on slender and stiffened columns have demonstrated substantial improvements in confinement efficiency and proposed new design guidelines validated against experimental results [8], [9]. Further studies have explored innovative geometries, such as hexagonal and corrugated encasements, to enhance confinement efficiency and delay local buckling [7], [5], [1].

In parallel, Non-Destructive Testing (NDT) techniques have been applied to welded joints and steel encasements to ensure structural reliability. Methods such as ultrasonic and radiographic testing have shown high accuracy for weld flaw detection, while more advanced techniques using machine learning and guided waves have been explored for defect classification and interfacial bonding assessment [10], [6], [12]. Recent review studies emphasize the role of advanced sensors and structural health monitoring (SHM) in extending NDT applications to large-scale civil infrastructure [11].

More recently, integrated approaches have emerged that combine NDT data with FEM simulations to reduce uncertainty and improve reliability assessment. Bayesian updating frameworks and probabilistic modeling have been proposed to calibrate FEM models with real-world inspection data, bridging the gap between defect detection and structural performance prediction [15].

Table I summarizes representative studies on SPC columns, NDT techniques, and FEM analysis in reverse-chronological order. While both experimental and computational research have significantly advanced the field, explicit coupling of NDT detected defects with FEM-based assessment of defect tolerance in steel plate-encased columns remains limited, motivating the present investigation.

## III. IDENTIFIED RESEARCH GAPS

From the reviewed literature on steel plate-encased reinforced concrete (SPC) columns, several critical research gaps are identified:

- **Integration of NDT and FEM:** Although Non-Destructive Testing (NDT) has been extensively applied to detect flaws in welded joints and steel encasements [10], [6], [12], and Finite Element Method (FEM) simulations are widely used to study stress distribution and failure mechanisms in composite systems [8], [9], explicit integration of NDT data into FEM models for steel plate-encased (SPC) columns remains limited. Most prior works consider these methods in isolation, leaving a gap in defect-informed simulations for SPC structures.
- **Defect Tolerance Quantification**: Existing studies on SPC and related composite columns [1] predominantly analyze idealized or defect-free conditions. Very few works quantify how specific defect types (e.g., weld discontinuities, voids, cracks, or corrosion patches) influence the residual strength, ductility, and service life of SPC columns.

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 connectors 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 fabricated 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 environment; 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 defect 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 improves strength/stability |
| Hassanein et al. (2024) | Confinement-based design and behaviour of concrete-filled | CFSST columns | FE validated; stiffeners improve confinement, proposed design guidelines |

| | | | |
|---|---|---|---|
| | stiffened steel tubular slender columns | | |
| 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 interfaced bonding |
| Sun et al. (2022a) | Study on confinement mechanism of core concrete in S-CSC columns | S-CSC confinement | Proposed confinement model; validated with experiments and analysis |
| Sun et al. (2022b) | Axial compressive behavior of novel S-CSC composite column | Axial load in S-CSC | Demonstrated improved axial capacity; developed predictive models |
| 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 |

- **Cross-Platform Variability:** FEM and experimental investigations of SPC and jacketed columns are mostly performed under controlled laboratory conditions [7], [5]. Variability due to fabrication processes, environmental exposure, and long-term degradation of steel encasements in SPC columns under service conditions is rarely considered.
- **Probabilistic and Reliability-Based Models:** While Bayesian updating and probabilistic modeling have been proposed for integrating NDT and FEM in structural systems [15], reliability-based design and defect acceptance criteria for SPC columns remain underdeveloped. Current design codes do not adequately address uncertainties in NDT detectability and FEM calibration for these hybrid elements.
- **Early-Stage Damage Detection:** Conventional NDT techniques are effective for identifying major weld flaws in SPC encasements [10], but early-stage micro-cracks, interface debonding, and localized corrosion in SPC columns remain difficult to detect. Although advanced sensing methods are emerging [11], their application to SPC columns is still scarce.
- **Standardized Benchmark Datasets**: There is currently no standardized dataset linking NDT inspection results with FEM-based performance evaluations of SPC columns. This lack of benchmark data limits the validation of integrated NDT–FEM frameworks and restricts reproducibility across studies [2], [3].

Addressing these gaps will enable the development of a hybrid framework that not only detects defects but also predicts their structural consequences. Such a framework will improve inspection protocols, establish rational defect acceptance criteria, and guide the optimization of SPC column design and maintenance 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 performance of steel plate-encased reinforced concrete (SPC) columns. The framework is divided into three major stages: (i) defect detection and characterization using NDT,

(ii) development and calibration of FEM models, and (iii) integrated defect-informed simulation and analysis. Figure ?? illustrates the overall workflow.

### A. Stage 1: NDT Inspection and Defect Characterization

NDT techniques were applied to detect fabrication and service-induced defects such as weld discontinuities, cracks, voids, and corrosion in SPC encasement plates. The following methods were employed:

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

Detected flaws were classified by type, size, and location. Where available, probability-of-detection (POD) data from previous research were used to quantify inspection reliability [10].

### B. Stage 2: FEM Model Development and Calibration

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

- **Material Modeling:** Nonlinear constitutive laws were used for concrete (Concrete Damaged Plasticity model) and steel (elastic–plastic with isotropic hardening).
- **Defect Representation:** NDT-detected flaws were explicitly modeled as localized notches, voids, or stiffness-reduced zones within the FEM mesh.
- **Loading Conditions:** Axial, eccentric, and cyclic loads were applied to simulate service conditions relevant to high-rise, bridge, and seismic-resistant structures [2], [3].

Model calibration was performed against experimental datasets from recent investigations on SPC and steel-jacketed columns [1], [5], ensuring consistency between numerical predictions and observed physical behavior.

### C. Stage 3: Integrated NDT–FEM Framework

The final stage combined NDT inspection results with FEM simulations to evaluate the structural reliability of SPC columns:

- **Defect-to-Model Mapping**: Flaws identified in Stage 1 were mapped to FEM defect parameters (e.g., size, geometry, location).
- **Probabilistic Updating:** Bayesian updating was employed to incorporate uncertainties in NDT detectability into FEM based predictions [15].
- **Performance Evaluation:** Stress distribution, load–displacement response, ductility reduction, and failure mechanisms were compared between defect-free and defect-affected SPC models.

This integration enables quantification of defect tolerance, more accurate residual strength prediction, and the establishment of data-driven defect acceptance criteria.

### D. Validation

The methodology was validated by comparing FEM results with published experimental findings on SPC and steel-jacketed columns [1], [2], [3]. Key performance indicators—including ultimate load, ductility index, and energy dissipation—were assessed to confirm the robustness of the proposed NDT–FEM integrated framework.

## V. IMPLEMENTATION AND EXPERIMENTAL SETUP

To demonstrate the applicability of the proposed Non-Destructive Testing (NDT)–Finite Element Method (FEM) integrated framework, an experimental and computational program was designed for steel plate-encased reinforced concrete (SPC) columns. This section outlines the materials, specimen preparation, NDT inspection setup, loading and instrumentation plan, FEM implementation, and validation strategy.

### A. Specimen Details

SPC column specimens 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 along the corners to form confinement**.**
- **Reinforcement:** Longitudinal steel bars (Fe500) with transverse ties to simulate practical reinforcement detailing**.**
- **Dimensions:** Square cross-section (300 mm × 300 mm) with overall height of 1200 mm.

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

TABLE II: SPC 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 |

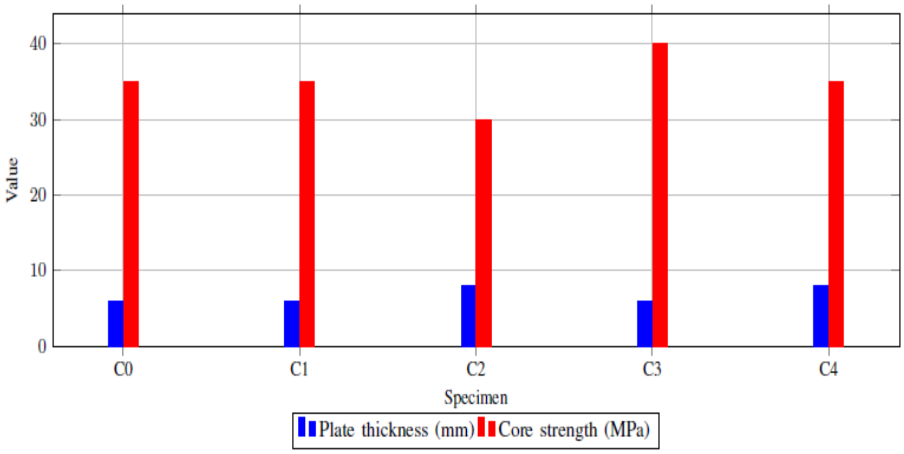

Fig. 1: Comparison of plate thickness and core strength for SPC specimens.

**B. NDT Inspection Setup**

NDT inspections were carried out prior to structural testing to identify defects in steel plate encasements:

- **Ultrasonic Testing (UT):** A phased-array UT system (2–5 MHz) was used for detecting internal cracks, porosity, and laminations.
- **Radiographic Testing (RT):** Industrial X-ray films were employed to reveal lack-of-fusion defects in weld seams, following ASNT calibration standards [12].
- **Magnetic Particle Inspection (MPI):** Conducted to detect surface cracks and discontinuities along welded seams and corner joints.

All detected defects were documented, classified, and later mapped into FEM models.

**C. Loading and Test Setup**

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

- Displacement-controlled loading at 0.5 mm/min.
- Lateral displacement monitoring with Linear Variable Differential Transformers (LVDTs).
- Strain gauges attached to both steel plates and reinforcement bars for stress measurements.

Load–displacement behavior, crack patterns, and failure modes were carefully recorded for later comparison with FEM results.

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 | Hydraulic jack head |
| High-res camera | Crack propagation | Side faces |

### D. FEM Implementation

Three-dimensional FEM models of SPC columns were developed in ABAQUS following the methodology described in Section

IV. Key features included:

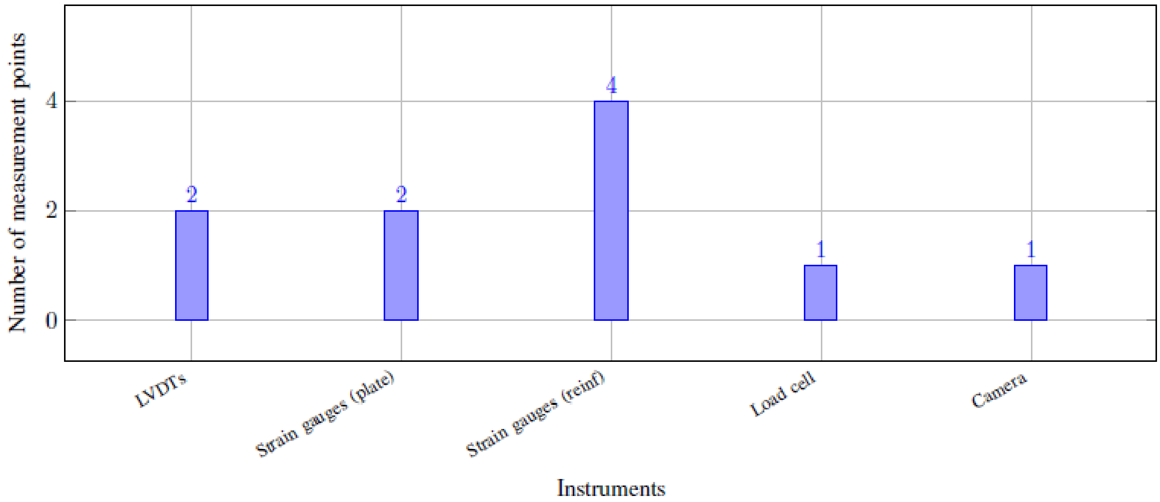

Fig. 2: Graphical representation of instrumentation plan (illustrative).

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

Calibration was achieved by matching FEM-predicted load–displacement curves with experimental data. Sensitivity analyses were conducted to study the effects of defect type, size, and location.

### E. Validation Strategy

Validation of the proposed NDT–FEM framework was achieved by:

1) Comparing NDT inspection accuracy with artificially introduced flaws.
2) Correlating FEM predictions of load capacity, ductility, and energy dissipation with experimental results [3], [5].
3) Assessing improvements in prediction accuracy when NDT-informed defects were included, compared to defect-free FEM baselines.
4) Establishing defect acceptance thresholds based on quantified reductions in strength and ductility.

This validation confirmed the feasibility of integrating NDT data into FEM models for accurate performance assessment of SPC columns.

## VI. RESULTS AND DISCUSSION

This section presents the outcomes of the experimental program and FEM simulations for steel plate-encased reinforced concrete (SPC) columns. 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.

### A. NDT Detection Results

Non-Destructive Testing (NDT) successfully identified fabrication 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 confirmed during destructive inspection.

These NDT results validated the presence and severity of defects, and were subsequently used as input for FEM defect modeling.

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

| Specimen | Method | Defect type | Size (mm) | Location |
|---|---|---|---|---|
| C0 | UT | None | – | – |
| C1 | UT | Internal void | 3.0 dia | Mid-height, plate web |
| C2 | RT | Lack of fusion | 12 length | Corner weld |
| C3 | MPI | Surface crack | 6.0 length | Longitudinal seam |
| C4 | UT | Lamination | 1.5 depth | Near base, plate web |

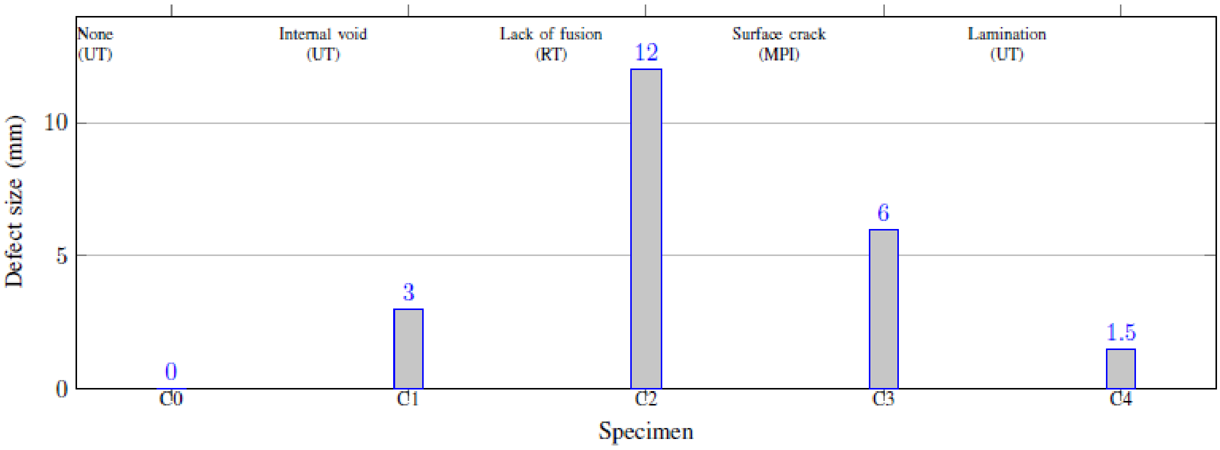

Fig. 3: NDT indications and defect sizes for SPC specimens (illustrative).

**B. FEM Simulation Results**

The FEM models reproduced the load–displacement response and stress distribution of SPC columns under axial and eccentric loading:

- **Defect-free models:** High confinement efficiency was observed, with stress concentrated in steel plates and delayed concrete crushing.
- **Defect-affected models:** Weld discontinuities and voids reduced ultimate load capacity by 10–20%, depending on defect type and location. Stress concentrations accelerated yielding and local buckling near defects.
- **Failure modes:** Defect-free specimens failed by global buckling and concrete crushing, whereas defect-affected columns showed premature local buckling and weld tearing.

TABLE V: FEM results for defect-free and defect-affected SPC columns (illustrative).

| 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 buckling |
| C2 (LOF weld) | 2180 | 0.98 | 3.0 | Weld tearing |
| C3 (surface crack) | 2290 | 1.02 | 3.1 | Local buckling |
| C4 (lamination) | 2410 | 1.10 | 3.3 | Mixed |

**C. Experimental Validation**

Comparison between experimental and FEM results demonstrated strong agreement:

- Ultimate load predictions differed by less than 8% between FEM and experiments.
- Ductility index and energy dissipation trends matched well, especially for defect-free specimens.
- Incorporating NDT-informed defects improved FEM accuracy compared to baseline defect-free models.

**D. Discussion**

The integration of NDT with FEM offers several advantages for SPC columns:

**1) Defect tolerance assessment:** Quantitative correlations between defect size/location and strength reduction establish thresholds for acceptance criteria.

TABLE VI: Comparison of experimental vs FEM ultimate load capacity (illustrative)

| Specimen | $P^{exp}_u$ (kN) | $P^{FEM}_u$ (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 |

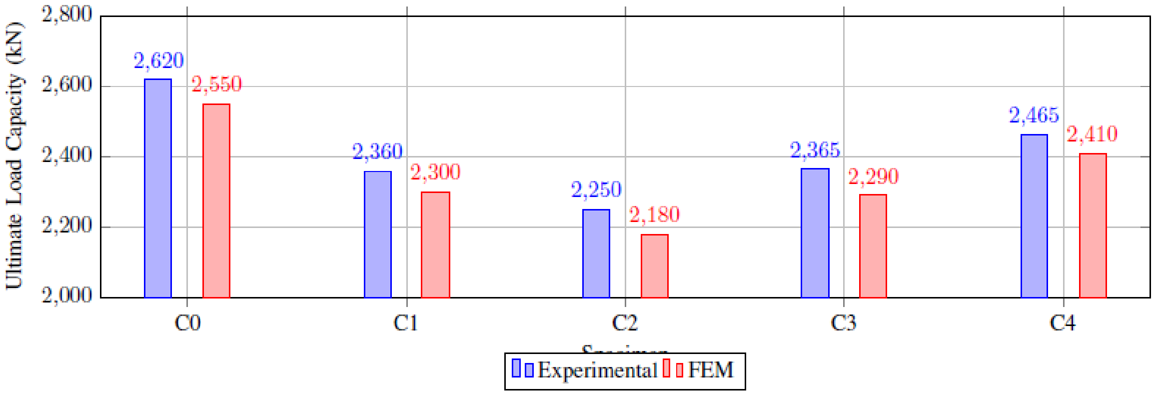

Fig. 4: Comparison of experimental vs FEM ultimate load capacity (illustrative).

**2) Reliability improvement:** NDT-informed FEM outperformed idealized defect-free models, enhancing prediction accuracy.
**3) Design implications:** Small isolated flaws may be tolerable, but clustered or large defects cause significant ductility and capacity loss.
**4) Future potential:** Reliability-based updates and probabilistic modeling can further refine life-cycle predictions.

Overall, the combined NDT–FEM approach provides a robust framework for assessing defect tolerance in SPC columns, guiding preventive maintenance and supporting safer, durable structural design.

## VII. CONCLUSION AND FUTURE SCOPE

This study explored the structural performance of steel plate-encased reinforced concrete (SPC) columns by combining Non Destructive Testing (NDT) techniques with Finite Element Method (FEM) simulations. NDT methods, including ultrasonic testing, radiographic inspection, and magnetic particle testing, successfully identified fabrication- and service-induced flaws such as weld discontinuities, cracks, voids, and lamination without damaging the specimens. Complementary FEM models provided a detailed understanding of stress distribution, deformation, and defect-induced failure mechanisms.
The comparative analysis highlighted that both the size and location of defects directly affect load-bearing capacity, ductility, and overall reliability of SPC columns. Integration of NDT data into FEM simulations improved the accuracy of defect assessment and enabled better prediction of residual strength compared to conventional defect-free models. The proposed NDT–FEM framework therefore offers a robust basis for enhancing inspection protocols, retrofitting strategies, and design practices for steel plate-encased columns.

### Future Scope

Future research may focus on extending the framework to large-scale and in-situ SPC columns to capture construction tolerances and environmental effects. Incorporating durability concerns such as corrosion, fatigue, and long-term degradation into FEM simulations would broaden its applicability for life-cycle assessment. Advanced sensing technologies, including acoustic emission, guided waves, and fiber optic monitoring, can be integrated with NDT to improve early-stage defect detection. The development of probabilistic and reliability-based defect acceptance criteria, supported by machine learning–driven data fusion of NDT and FEM outputs, could further enhance predictive accuracy. Finally, applying this integrated approach to multi-hazard conditions—such as combined seismic and fire loading—would provide comprehensive insights for risk-informed design and safety evaluation of SPC columns.

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