Physical Modeling of Reinforced Concrete Structures with 3D-Printed Steel Cages at Centrifuge Scale

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ABSTRACT: Small-scale physical modeling of reinforced concrete (RC) structures offers a promising alternative to full-scale experimental testing for applications such as centrifuge modeling and the validation of numerical modeling assumptions. However, the credibility of such approaches depends on their ability to reproduce key aspects of prototype structural behavior. This paper presents a unified synthesis of two experimental campaigns on 1:30-scale RC beam–column joints and columns incorporating additively manufactured reinforcement cages and gypsum-based microconcrete. The small-scale test results are systematically compared with databases of full-scale quasi-static cyclic tests that exhibited comparable flexural failure modes. The comparison focuses on global response measures relevant to physical modeling, including normalized strength, stiffness, and ductility. The results show that the small-scale additively manufactured models follow the same response trends observed in full-scale tests for both joints and columns, despite unavoidable scale effects. These findings support the use of additively manufactured small-scale RC models as reliable tools for physical modeling applications and for providing experimental support to component- and system-level numerical model validation.

1 INTRODUCTION

Experimental testing remains a cornerstone of research in earthquake engineering and reinforced concrete (RC) structures. Full-scale cyclic and shake table tests provide the most reliable insight into the nonlinear behavior, damage mechanisms, and failure modes of RC components and systems. However, such tests are expensive, time-consuming, and often impractical when a large number of specimens or repeated testing under varying conditions is required. This is especially relevant in earthquake engineering as has been discussed by many researchers (Bachmann *et al.*, 2018; Vassiliou *et al.*, 2021; Elmorsy & Vassiliou, 2023a; 2023b; 2024; Zhong & Christopoulos, 2023; Zhang *et al.*, 2023; Bao *et al.*, 2022; Hassan & Elmorsy 2022a; 2022b; Elmorsy 2020; Elmorsy & Vamvatsikos 2025). These limitations have motivated the development of physical modeling approaches, in which reduced-scale specimens are used to study structural behavior under controlled laboratory conditions.

Small-scale physical models of RC structures are particularly attractive in the context of centrifuge testing and for the experimental validation of numerical models (Harris & Sabnis 1999). When appropriately designed, such models allow researchers to generate extensive experimental datasets while maintaining stress similitude and capturing essential aspects of nonlinear behavior. Nevertheless, modeling RC at scales on the order of 1:30–1:40 is challenging due to size effects, scaling of concrete mechanical properties, and difficulties associated with manufacturing and placing micro-reinforcement (Loli *et al.* 2014; Knappett *et al.* 2011). As a result, the credibility of small-scale RC testing critically depends on systematic comparisons with well-documented full-scale experimental evidence.

Recent advances in additive manufacturing (AM) have enabled the fabrication of submillimeter-diameter reinforcement cages with controlled geometry and material properties, opening new possibilities for physical modeling of RC structures at small scales (Del Giudice *et al.* 2020; 2022; Elmorsy *et al.* 2023; 2024b; 2025a; 2025b; Elmorsy 2025). Using metal 3D printing, reinforcement detailing that closely resembles prototype-scale layouts can be achieved, alleviating many of the practical limitations of traditional handcrafted micro-reinforcement. Several recent experimental campaigns have demonstrated the feasibility of this approach for individual RC components, including columns and beam–column joints, subjected to quasi-static cyclic loading (Del Giudice *et al.* 2022; Elmorsy *et al.* 2024b; 2025a; 2025b; Elmorsy 2025). It is important to emphasize here that this method can be used for the validation of system-level assumptions, for which a degree of distortion is acceptable, while large-scale component-level tests remain necessary for precise component behavior evaluation (Del Giudice *et al.*, 2020; Elmorsy *et al.* 2023; 2024a; 2026a; 2026b).

While these studies have shown promising results, a comparison with full-scale counterpart components is essential. In particular, there is a need to evaluate whether additively manufactured small-scale models can consistently reproduce the cyclic response characteristics observed in full-scale tests, including strength, stiffness, and ductility, across both flexural members and beam–column joints. This paper addresses this gap by synthesizing results from two experimental programs on 1:30-scale RC columns and beam–column joints incorporating additively manufactured reinforcement cages. The small-scale test results are systematically compared with databases of full-scale cyclic tests that exhibited comparable failure modes. The focus of the comparison is placed on global response measures relevant to physical modeling and numerical model validation, rather than on detailed material characterization.

2 OVERVIEW OF EXPERIMENTAL PROGRAMS

This section provides a concise overview of the experimental programs whose results are compared in this paper. Detailed descriptions of specimen design, material characterization, test setup, instrumentation, and loading protocols are available in the corresponding journal publications and are not repeated here (Elmorsy *et al.* 2025a; 2025b).

2.1 Small-Scale Beam–Column Joint Models

Quasi-static cyclic tests were conducted on 1:30-scale reinforced concrete exterior and knee beam–column joint specimens incorporating additively manufactured reinforcement cages (Elmorsy *et al.* 2025b). The specimens were designed to represent joints extracted from a prototype two-story RC frame designed according to modern seismic provisions. Additive manufacturing (Laser Powder Bed Fusion: LPBF) was used to fabricate submillimeter-diameter longitudinal and transverse reinforcement with controlled geometry and surface characteristics, enabling realistic detailing at the model scale. A stainless steel (316L) powder was used for printing the reinforcement cages of all models in this paper.

A gypsum-based microconcrete was adopted to better reproduce tensile strength and bond characteristics at small scale. The main test parameters were the joint geometry and the applied axial load ratio on the column. All specimens were subjected to displacement-controlled cyclic loading, targeting flexural-dominated response with damage concentrated in the beams, consistent with the intended seismic design philosophy. Representative reinforcement layouts for the joint specimens are shown in Fig. 1.

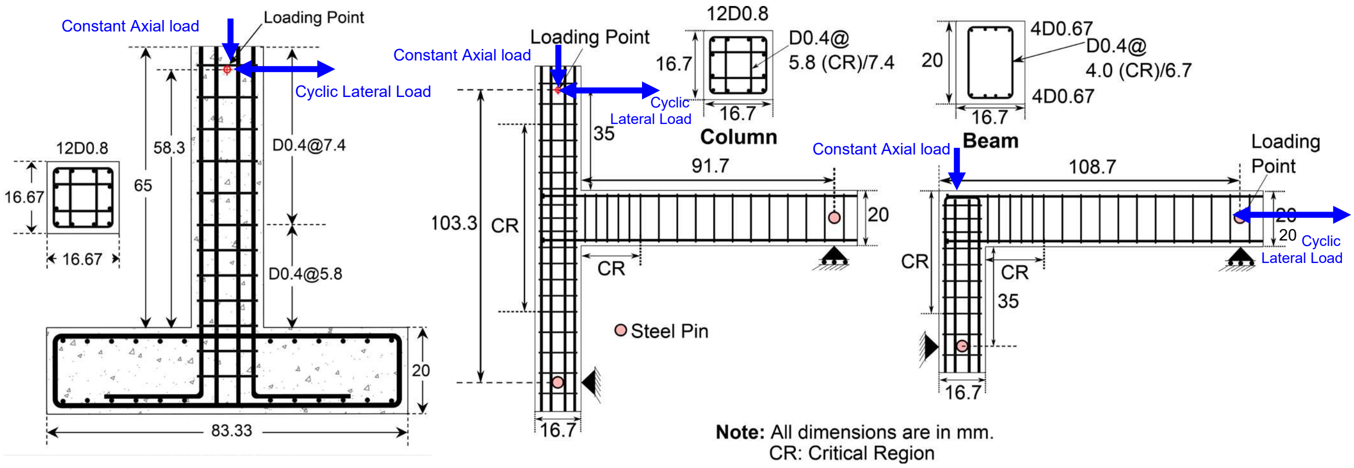

Figure 1. Specimen details: (left) Column, (middle) Exterior beam-column joint, and (right) Knee beam-column joint.

2.2 Small-Scale Column Models

The column test campaign (Elmorsy *et al.* 2025a) consisted of quasi-static cyclic tests on 1:30-scale RC column specimens with additively manufactured reinforcement cages. The specimens represented cantilever columns extracted from a prototype RC building and were designed to fail in flexure under combined axial load and lateral displacement demands.

As in the joint tests, gypsum-based microconcrete and metal 3D-printed reinforcement were used to address scaling challenges related to material behavior and reinforcement placement. The test variables included reinforcement ratio and axial load level. A representative reinforcement layout for the column specimens is shown in Fig. 1.

2.3 Scope of the Experimental Data Used in This Study

For the present paper, the results from the small-scale joint and column tests are compared with databases of full-scale cyclic tests that exhibited comparable failure modes, allowing an assessment of the degree to which additively manufactured small-scale RC models reproduce prototype behavior.

Full-Scale Reference TestsFull-scale specimens that exhibited failure modes and had reinforcement details comparable to those targeted in the small-scale tests are considered, ensuring that the comparison focuses on meaningful structural response rather than on differences driven by incompatible mechanisms.

For the beam–column joint comparison, databases consisting of seven knee joints from two studies (Wallace *et al.* 1998; Chun *et al.* 2007) and 59 exterior beam-column joints collected by Ghimire (2018) and Ghimire *et al.* (2021) were adopted. Full-scale exterior and knee joints that failed in beam flexure were selected. The comparison is conducted using normalized response measures, such as ratios of measured to nominal strength and drift-based deformation indices, which are commonly used to evaluate joint performance across different test programs.

For the column comparison, the ACI 369 (ACI 2023) rectangular column database (Sivaramakrishnan 2012; Ghannoum *et al.* 2015) was used. Full-scale rectangular RC columns failing in flexure under combined axial load and cyclic lateral displacement were used. The selected full-scale specimens span a range of reinforcement ratios and axial load levels comparable to those examined in the small-scale tests. Key response quantities extracted from the database include lateral strength, effective stiffness, and displacement ductility.

3 COMPARATIVE RESULTS AND DISCUSSION

3.1 Beam–Column Joints

Comparing the results of the small-scale tests with those of the full-scale counterparts is relevant only if they have comparable design and loading parameters. The small-scale joint tests had parameter ranges of 18.9–21.4 MPa concrete strength compared with 24–148 MPa in the full-scale database, 394.9–466.7 MPa yield strength of longitudinal reinforcement compared with 370–1,033 MPa in the full-scale database, and 0.0–0.20 column axial load ratio, exactly similar to the full-scale database. In addition, the longitudinal reinforcement ratio in the beam of the tested joints, which controlled the failure of the joint, was 0.84%, whereas it ranged from 0.47% to 2.88% in the full-scale database. According to Ghimire (2018), the behavior of beam-column joint specimens is to be considered satisfactory if the ratio of the peak to nominal flexural strength $M_p/M_n \geq 1.0$, and the reduction in the peak moment was not more than 20% at the end of the first complete cycle at 3.5% drift ratio. The peak moment M_p is calculated at the interface of the beam with the beam-column joint region, which is also the critical section for the headed bars in tension. Starting with the second criterion, all the specimens (exterior and knee joints) satisfied this requirement. The drift ratio at 15% strength loss was either not reached or more than 3.5%, and the maximum applied drift ratio was in all specimens more than 3.5%.

Figure 2 shows a comparison of the ratio of M_p/M_n for the tested beam column joints to the beam-column joint database discussed previously. The figure shows the trends of M_p/M_n with the ratio of the provided embedment length to the embedment length required to yield the headed bars l_{eh}/l_{ehy}. l_{ehy} is calculated according to (Ghimire *et al.* 2021). Figure 2 shows that all exterior joints satisfied the condition that $M_p/M_n \geq 1.0$, indicating satisfactory performance from this point of view. In addition, the beam-column joints tested in this paper agreed well with the clear trend observed in the database with l_{eh}/l_{ehy}. Most of the data points of this study's specimens fell within the 95% confidence interval of the full-scale test database, confirming that they behave similarly to the full-scale specimens. Most of the knee joints of the current tests did not satisfy that $M_p/M_n \geq 1.0$ (Fig. 2), but so did their full-scale counterparts. Similar to exterior joints, most of the data points of this study's specimens fell within the 95% confidence interval of the full-scale test database, also confirming that the small-scale specimens can be used for the physical modeling of the large-scale specimens.

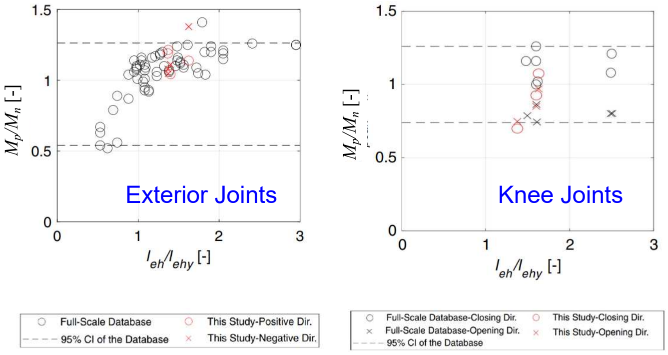

Figure 2. Comparison between the behavior of the tested beam-column joints and that of the large-scale database.

3.2 Columns

The stiffness comparison with full-scale tests is conducted using a secant-to-yield effective stiffness, as defined after Sezen and Moehle (2004). The Standard ACI 369-22 (ACI 2023) proposes constant factors to modify flexural rigidities for columns (E_cI_g) based on the effective stiffness proposed by Sezen and Moehle. Since it provides a suitable normalization, this factor is denoted α and is used as a basis for comparison between the tests performed in this study, the ACI 369 rectangular column database, and the ACI 369-22 code.

Figure 3 depicts a comparison (in terms of factor α) between the stiffness of the tested columns and the stiffness of the ACI 369 column database. It also shows the ACI 369-22 recommendation. It is evident from the figure that the stiffness of the tested columns was on the softer side (kind of a lower bound) of the ACI 369-22 model and the ACI 369 column database. The ACI 369-22 model can be considered as an average for the ACI 369 column database. The average of the test to model α *T/M* was 0.3534 in the positive loading direction and 0.4898 in the negative direction for the columns tested in this paper. The CoV of the *T/M* was 0.258 and 0.407 in the positive and negative loading directions, respectively. On the other hand, the average and CoV of the *T/M* for the database were 0.97 and 0.53, respectively. Notably, most of the points lied within or at least close to the 95% confidence interval (CI) (computed based on all the datapoints of the ACI 369 database), indicating that the small-scale columns with 3D-printed reinforcement can be considered a representation of full-scale columns despite being on the softer side and not matching the mean (or median) of the full-scale columns. One potential reason for the lower stiffness could be the fact that the 3D-printed rebars had a lower elastic modulus (~170–186 GPa) than typical prototype values (~200–210 GPa).

In order to compare the strength of the columns tested in this study and that of the database, the normalized strength (β) was used as a basis for comparison, and is defined as the ratio of the ultimate moment at the critical section at the interface with the foundation, normalized by (f_cbh^2). Figure 4 depicts a comparison (in terms of factor β) between the strengths of the tested columns and the ACI 369 column database. The figure shows that the current study test results well match the database trend in terms of strength. In the database, there is a clear trend of increasing normalized strength with increasing the mechanical reinforcement ratio $\rho_l f_{yl}/f_c$. A similar trend is also observed in the tested small-scale columns, despite being slightly on the weaker (lower) side of the linear regression shown by the black line in Fig. 4.

To assess the ductility of the tested columns, the ductility factor μ of the tested columns is compared with the ACI 369 database, as depicted in Fig. 5. Almost all test points reside within the 95% CI of the database, shown in dotted blue lines, well matching the ductility of full-scale columns. In addition, Fig. 5 shows a substantial effect of axial load ratio on the column ductility.

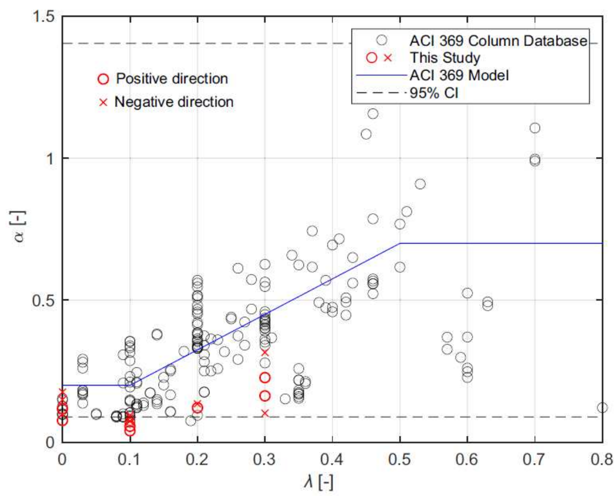

Figure 3. Comparison between the stiffness of the tested exterior columns and that of the large-scale column database.

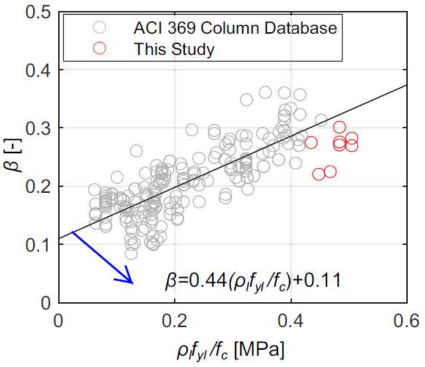

Figure 4. Comparison between the strength of the tested exterior columns and that of the large-scale column database.

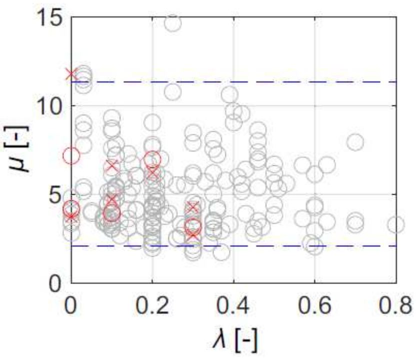

Figure 5. Comparison between the ductility of the tested exterior columns and that of the large-scale column database.

4 CONCLUSIONS

This paper presented a unified synthesis of two experimental campaigns on additively manufactured small-scale reinforced concrete beam–column joints and columns, with emphasis on their comparison against databases of full-scale cyclic tests. The objective was to assess the ability of such reduced-scale physical models to reproduce key aspects of prototype behavior relevant to physical modeling and numerical model validation.

The comparisons showed that the small-scale specimens capture the main trends observed in full-scale tests in terms of normalized strength, stiffness, and displacement ductility when flexural response is targeted. For both joints and columns, the use of additively manufactured reinforcement cages and gypsum-based microconcrete enabled realistic detailing and damage progression, provided that appropriate axial load levels were applied.

The results support the use of additively manufactured small-scale RC models as reliable tools for physical modeling applications, particularly in centrifuge testing and in the experimental support of system-level numerical modeling assumptions.

Future work should focus on extending this approach to system-level specimens and on further quantifying the limits of applicability of reduced-scale RC modeling for different failure mechanisms and structural typologies.

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