DEVELOPMENT OF HIGH-STRENGTH REINFORCED CONCRETE COLUMN AND STEEL BEAM (NEW-RCS) STRUCTURAL SYSTEM

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ABSTRACT

Composite moment frame structures with Reinforced Concrete (RC) columns and Steel (S) beams are termed as RCS structures. RCS structures combine the inherent stiffness and economy of RC columns with the light-weight and long-spanning capability of steel beams to produce a structurally efficient and cost-effective structural system. The key to the development of RCS system is the design of beam-column joint details. Over the years, multiple innovative RCS joint details have been tested and incorporated in to the design guidelines. The existing design guidelines primarily deals with concentric RCS joint details developed for RC columns with square/rectangular cross-sections. However, architectural requirements often necessitate eccentric joints and joints with circular RC columns. Additionally, the joint details available in the existing design guidelines were developed for RC columns with conventional deformed bars with specified yield stress of 410-490 MPa. Hence, "New-RCS" project was initiated in Taiwan in 2020, to address the shortcomings of existing design guidelines. The term "New" refers to the use of high-strength deformed bars with specified yield stress of 690 MPa along with high-strength concrete in columns. As a part of New-RCS project, innovative through-beam and through-column type RCS joint details were developed for eccentric and concentric joints with columns having circular and square cross sections. Further, a re-evaluation of the existing analytical procedures to estimate joint strength, with focus on bearing strength estimation was also undertaken. Large-scale experimental testing of twenty-three beam-column subassemblies were carried out as a part of the project to evaluate the seismic behaviour and verify the adequacy of the newly proposed joint details. The joint details and design procedures developed as part of this study were crucial to the design and construction of a 27-storey office building with RCS structural system, which in nearing its competition in Taipei.

Keywords: RCS; Composite Structures; High-strength steel reinforcement; Beam-column joint; Moment frame.

1. INTRODUCTION

The New-RCS Project was initiated to tackle the limitations faced by conventional Reinforced Concrete-Steel (RCS) moment frame systems when used for high-rise buildings, especially in seismic regions. Traditional RCS systems, which utilize reinforced concrete (RC) columns and steel (S) beams, are effective for low-rise commercial buildings due to the combination of RC columns' stiffness and steel beams' capacity for long, lightweight spans. However, their use in high-rise construction is constrained by oversized columns, increased material usage, and reinforcement congestion. These issues arise from the reliance on conventional materials, including normal-strength concrete (compressive strengths below 60 MPa) and steel reinforcement with yield strengths between 410-490 MPa, leading to inefficient designs. Further, existing RCS beam-column joint designs, typically suited for concentrically framing beams and square RC columns, often fail to meet the architectural requirements. Architectural requirements, often necessitate RCS joint designs for eccentrically framing beams and RC columns with a variety of cross-sectional shapes (e.g. circular).

To address these challenges, the New-RCS Project was launched in 2020, building on the success of Taiwan's New-RC Project. Initiated in 2009 by the National Center for Research on Earthquake Engineering (NCREE), the New-RC Project has served as a flagship initiative that developed design provisions for reinforced concrete structural systems utilizing high-strength materials. In 2019, a comprehensive design draft for New-RC buildings was published (NCREE 2019). The term "New" in New-RC/RCS signifies the incorporation of high-strength materials—concrete with compressive strengths reaching up to 100 MPa and steel reinforcement with yield strengths up to 690 MPa. This innovation allows for the use of smaller RC columns with reduced steel reinforcement ratios, enhancing space efficiency and minimizing reinforcement congestion, ultimately improving constructability and cost-effectiveness.

The current New-RCS Project aims to develop versatile beam-column joint designs that incorporate these high-strength materials, making RCS systems feasible for high-rise construction. As shown in Figure 1, this marks a significant transition from conventional RCS systems, which are more suited for low-rise commercial buildings, to the proposed New-RCS systems designed for high-rise commercial buildings. This innovation is particularly relevant in high-density urban areas like Taipei, where high land values drive the demand for taller commercial buildings.

Low-rise commercial building — High-rise residential building — High-rise commercial building

Figure 1: Transition from RCS system to New RCS System.

2. NEW-RCS PROJECT BACKGROUND

The key to the development of New-RCS system is the design of beam-column joint detail. The design and detailing of the remaining elements of New-RCS systems (columns and beams) can be adopted from the well-developed research fields of high-strength reinforced concrete or New-RC (NCREE 2019) and steel structures (AISC-360 2022; AISC-341 2022). The RCS beam-column joint designs can be broadly categorized into two types:

1. Through-beam joints: The steel beam runs continuously through the joint. This design avoids the need for stringent detailing required for seismic steel beam-to-column connections, such as demand-critical welds, smoothening of welds to prevent notch effects, and the removal of backup bars. However, it requires complex fabrication, including drilling through the beam webs and flanges for passing the column reinforcement.
2. Through-column joints: The RC column runs continuously through the joint. This design simplifies fabrication by eliminating the need for joint confinement reinforcement, as steel cover plates are used to confine the joint. The steel beams are weld or bolt connected to the steel cover plates which confine the joint region. However, it requires careful design and detailing of bolted or welded connections at the column face, as these connections were found to be problematic during the 1994 Northridge and 1995 Kobe earthquakes.

At present, only the US and Japan have design standards dedicated for RCS beam-column joint designs. Japan's 2021 standard (AIJ 2021), issued by the Architectural Institute of Japan, covers both through-beam and through-column designs. In the US, there is no official national standard, but a detailed ASCE Pre-Standard (2015) exists, focusing on through-beam joints. An earlier ASCE guideline from 1994 was limited to low and moderate seismicity areas (ASCE 1994). Despite differences, both countries' standards align on key design principles. However, as can be seen from Table 1, both the US and Japanese design standards limit the maximum allowable yield strength of steel reinforcement to 410 MPa to 490 MPa, respectively. This limitation is due to the lack of large-scale testing of RCS joint designs with higher grade steel reinforcement. Hence, in the proposed New-RCS project, the test specimens were designed with high-strength grade SD 690 steel reinforcement along with high-strength concrete with compressive strengths in the range of 70 to 100 MPa to evaluate the performance of New-RCS joints.

Another drawback of the existing design codes is the lack of versatile beam-column joint details. Figures 2a and 2b depicts a conventional through-beam type RCS joint available in the existing literature. It can be seen that the longitudinal steel reinforcement of the RC column passes only through the corners (Figure 2b), which is not realistic for bottom storey columns of high-rise moment frame buildings in seismic zones, where longitudinal steel reinforcement ratio is typically around 3-4%. Providing a longitudinal reinforcement ratio of 3-4% often requires the flanges of the steel beam to be drilled as shown in Figure 2c. Further, the existing RCS joint details typically uses rectilinear ties for transverse reinforcement (Figure 2b). Presently, five-spiral transverse reinforcement layout

(Figures 2c and 2d) is becoming increasingly popular in Taiwan for RC columns because of its economy and superior seismic performance compared to the conventional rectilinear tie layout (Yin et al. 2011). Concrete columns with five-spiral layout is suitable for prefabrication and the manufacturing process can be automated with very little human intervention. Furthermore, the existing through-beam RCS joints (Figure 2a), were developed for joints with concentrically framing beams; architectural requirements often require eccentric joints as shown in Figure 2d.

Finally, another aspect regarding the behaviour of RCS joints which required a re-evaluation was the bearing strength estimation of joint. The existing design guidelines on RCS joint bearing strength prediction rely on equations (ASCE Pre-standard 2015) which were formulated based on tests performed with relatively low levels of axial load (0.0-0.2 $f_c'A_g$, A_g = gross-cross sectional area of the column) in the column (Kanno 1993). In real-life designs, the axial load in columns of high-rise moment frame buildings is typically in the range of 0.2-0.6 $f_c'A_g$. Additionally, as high-strength deformed bars ($f_y \leq$690 MPa) are used in place of conventional deformed bars ($f_y \leq$ 490 MPa) in New-RCS system, the existing minimum joint depth provision of RCS joint also required a revision, such that the joint depth is sufficient to prevent the slippage of longitudinal reinforcement.

Table 1: Maximum permissible material grade by international standards for RCS structures.

	ASCE Pre-standard (2015)	AIJ (2021)	New-RCS - Proposed
Steel reinforcement specified yield stress (MPa)	410	490	690
Steel beam specified yield stress (MPa)	345	355	350
Concrete grade (MPa)	100	60	100

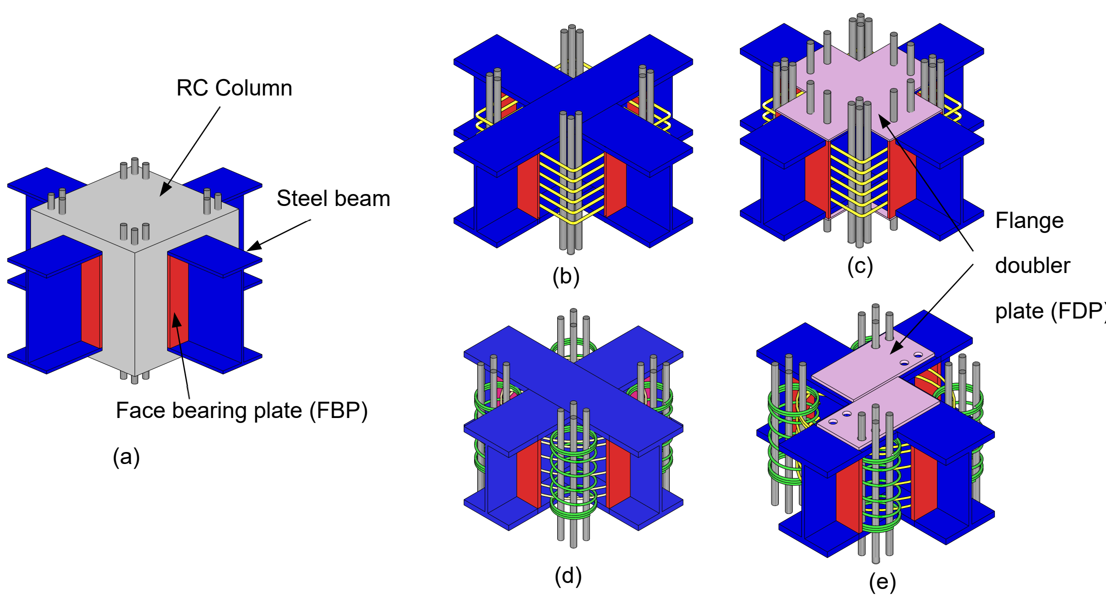


Figure 2: a) Conventional through-beam type RCS joint; b) Conventional joint with rectilinear ties; c) joint with realistic longitudinal reinforcement ratio; d) joint with five-spiral transverse reinforcement; e) eccentric joint.

3. SPECIFIC OBJECTIVES OF NEW-RCS PROJECT

Based on the identified research gaps in traditional RCS systems, the current New-RCS Project aimed to achieve the following specific objectives:

1. Design and develop beam-column joint details that incorporate high-strength materials, specifically 690 MPa steel reinforcement and high-strength concrete (70-100 MPa). This effort included the development of four distinct categories of joints that provided flexible design options for various architectural and structural requirements:
    a. Through-beam type joints for square New-RC columns,
        i. New-RC columns with conventional rectilinear ties, and
        ii. New-RC columns with five-spiral transverse reinforcement,
    b. Through-column type eccentric joints for square New-RC columns,
    c. Through-beam type joints for circular New-RC columns, and
    d. Through-column and through-diaphragm type joints for circular New-RC columns.
2. Evaluate the seismic performance of these joints through large-scale experimental testing.
3. Examine the bearing behavior of the New-RCS joints under varying axial load in the column and improve prediction models for joint bearing strength.
4. Create a robust design framework for the implementation of New-RCS systems in high-rise buildings, which can be seamlessly integrated into current international design standards.

4. SUMMARY AND KEY HIGHLIGHTS OF THE RESEARCH ACTIVITIES

The New-RCS project, outlined in Figures 3 and 4, comprised eight distinct phases focused on the design and development of test specimens. The strength design and proportioning of these specimens were based on the established design provisions for RCS structures as specified by AIJ (2021) and the ASCE Pre-Standard (2015). Modifications and enhancements were made to the existing guidelines to incorporate innovative features, such as high-strength steel, five-spiral reinforcement, flange doubler plates, and eccentric framing beams at the joints.

Large-scale beam-column subassembly specimens were subjected to cyclic loading under quasi-static displacement control, as illustrated in Figure 5, to evaluate their seismic response. This evaluation included an analysis of damage and failure mechanisms, hysteretic behavior, deformation responses of beam-column components (including beam flexure, column flexure, joint shear, and joint bearing), and the strain responses of the steel components.

The results indicated that most through-beam specimens exhibited desirable seismic responses characterized by ductility and stable energy dissipation mechanisms. However, certain through-column specimens demonstrated premature weld fractures at critical locations, specifically at the column face (Phase 5) and splice points (Phases 7 and 8). Notably, fractures of complete joint penetration (CJP) welds at the welded flange-bolted web splice detail were observed. This splice detail is commonly utilized in Taiwanese steel structures, raising concerns about its performance.

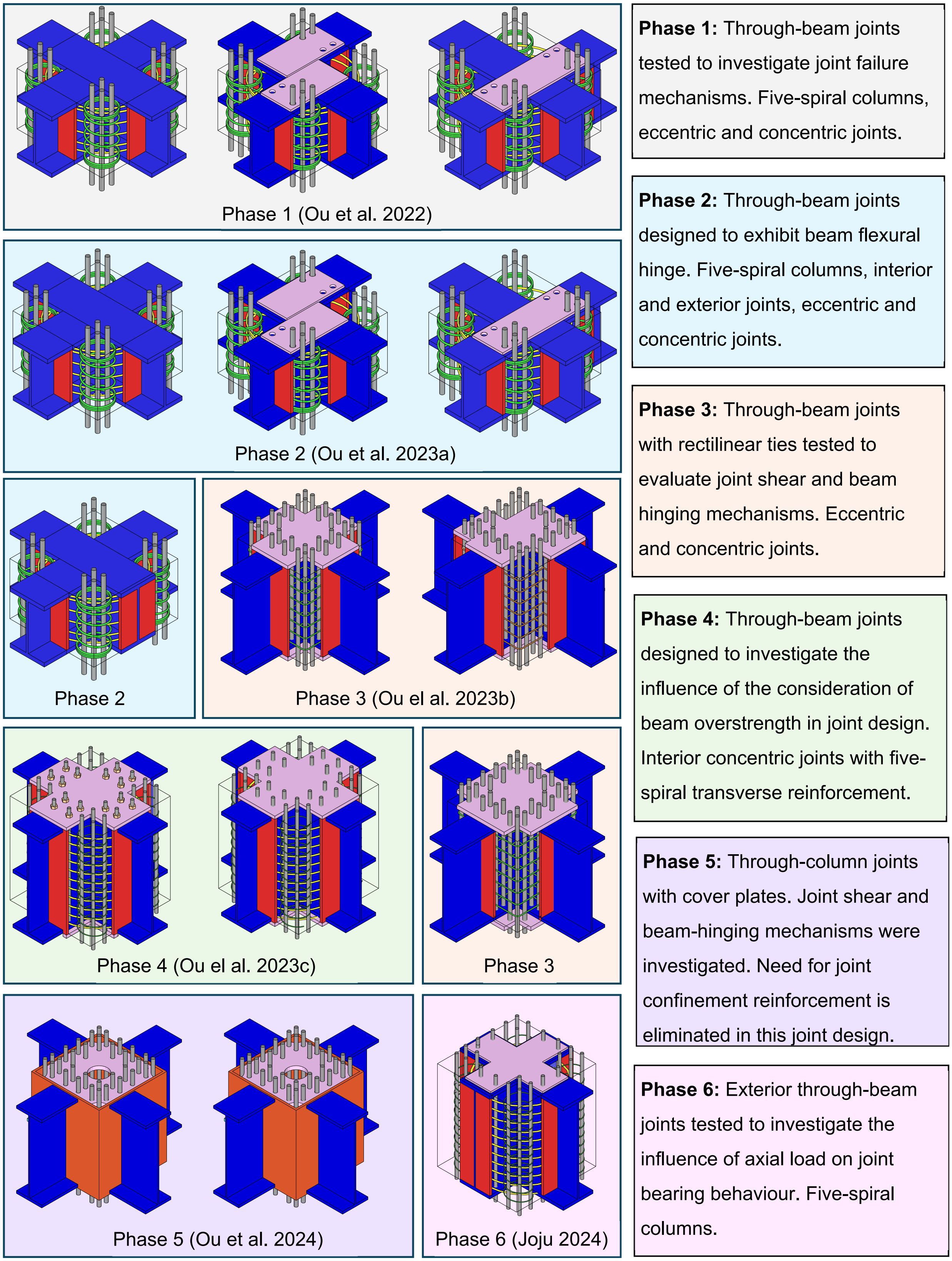
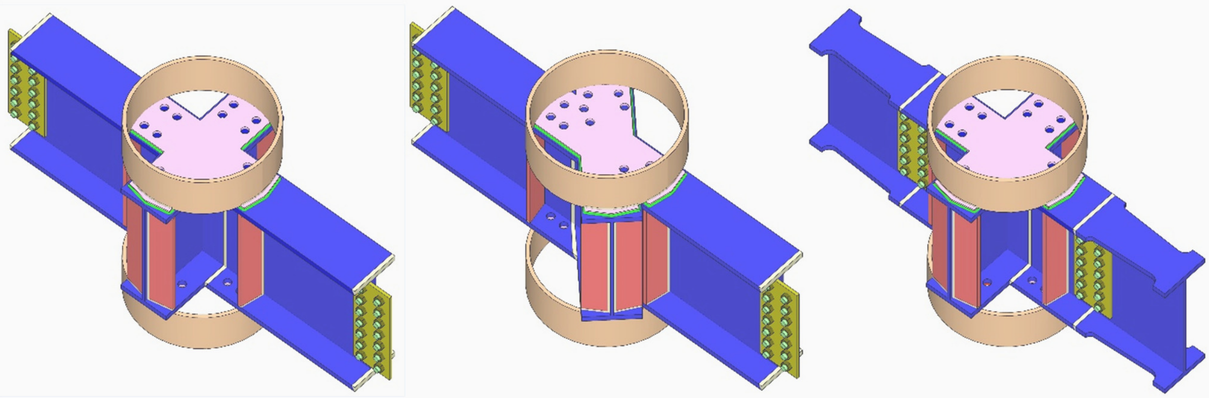


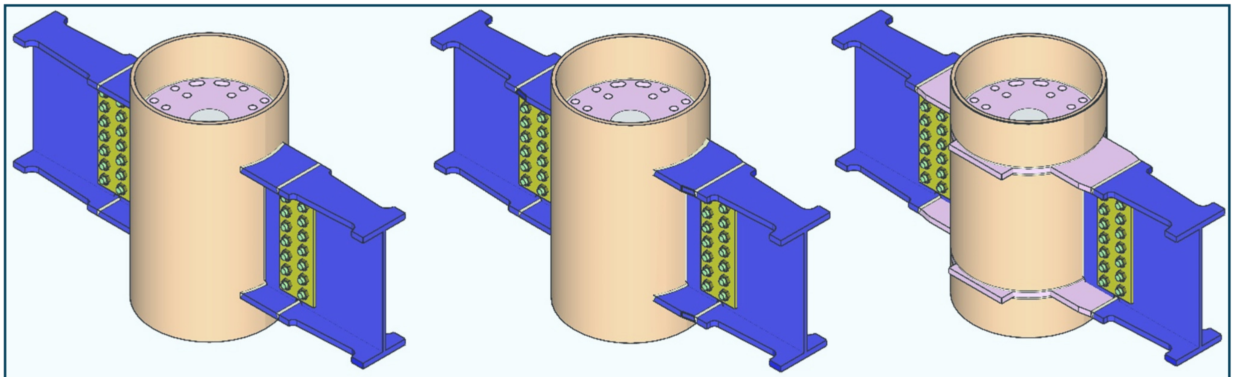
Figure 3: Isometric view of the joint region of the test specimens with square reinforced concrete columns tested during the phases 1 to 5 of the project.



Phase 7 (Joju 2024)

Phase 7: Through-beam type joints for circular columns.

Phase 8: Through-column type joints for circular columns



Phase 8 (Joju 2024)

Figure 4: Isometric view of the joint region of the test specimens with circular reinforced concrete columns tested during phase 7 and phase 8 of the project.

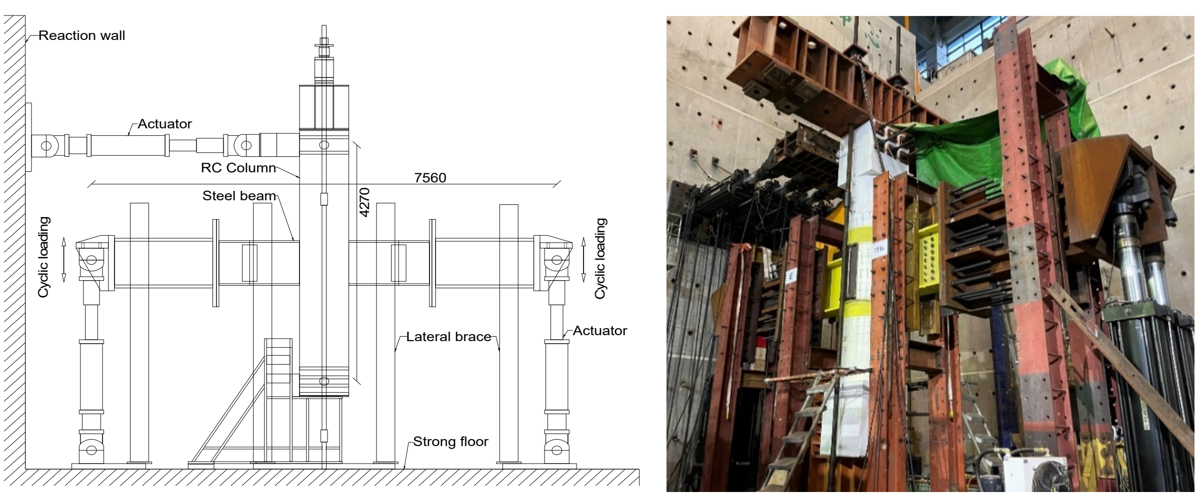


Figure 5: Typical Experimental Setup for Phases 1-5, 7 and 8

To prevent such premature fractures, minor modifications in connection detailing are recommended. For a comprehensive understanding of the specimen features, design provisions, experimental methodologies, and results, readers are encouraged to consult the references associated with Figures 3 and 4. Few highlights of the New-RCS project are listed below:

Use of high-strength steel reinforcement (SD 690): As high-strength steel (690 MPa) is being used in place of conventional steel (420 MPa), ensuring bond failure prevention is critical. Bond slippage is limited by providing adequate bond development length, i.e., to have a minimum joint depth (d_j) as shown in Figure 6. The minimum joint depth provisions in the ASCE pre-standard (2015) do not account for the improved bond behavior of high-strength concrete compared to normal-strength concrete, leading to impractically large joint depth requirements. Hence, the Taiwan New-RC draft (NCREE 2019) provision for minimum joint depth (see Figure 6), which is based on experimental studies involving high-strength materials, was adopted. Strain response of longitudinal reinforcement was monitored during experiment to estimate the bond efficiency parameter (Parra-Montesinos 2000). A positive slope of the bond efficiency parameter vs. drift response indicates an increase in average bond stress. While a negative slope indicates bond degradation. Bond efficiency of specimens (for example, specimens from Phase 6 is shown in Figure 6) nearly exhibited a positive slope till 4% drift, indicating excellent bond behavior. Hence, once the provisions of the New-RC draft (NCREE 2019) are used to estimate minimum joint depth, high-strength steels can be used for New-RCS joint designs.

Bearing behaviour of New-RCS Joints: An analytical model was developed to estimate the bearing strength of RCS joints under varying axial loads, providing reliable predictions when compared with the experimental results from Phase 6 (see Figure 7). The model revealed a reduction in bearing strength at low axial loads, explaining the premature failures observed in the RCS joints tested by Lee et al. (2019). In their study, Lee et al. (2019) used the ASCE pre-standard (2015) provisions, which do not explicitly account for axial load effects, and their test specimens were not subjected to axial load. Therefore, caution is advised when applying the ASCE pre-standard (2015) method under low axial load conditions. Further details on the model and comparison with experimental results can be found in Joju (2024).

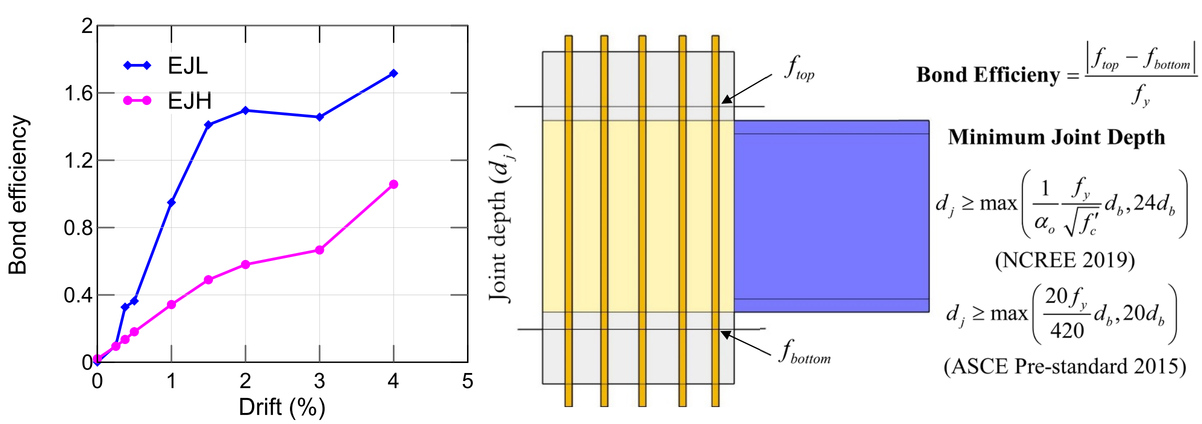


Figure 6: Variation of bond efficiency parameter with drift of specimens tested in Phase 6.

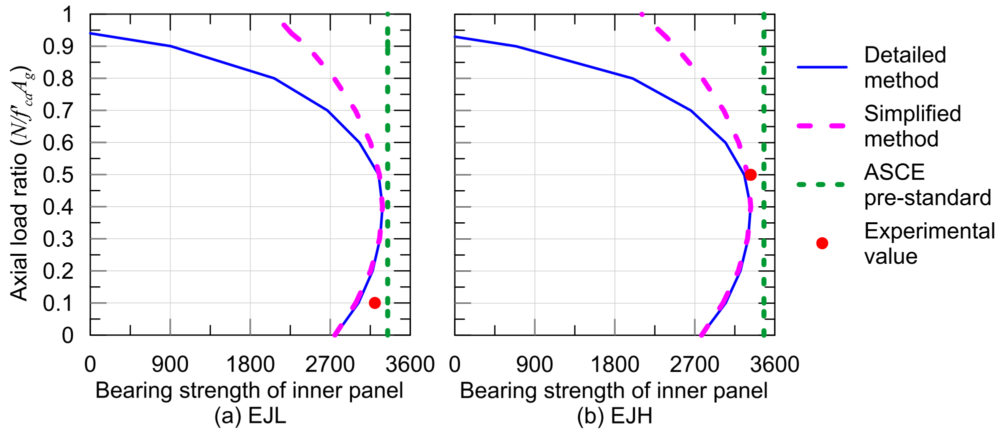


Figure 7: Bearing strength of specimens from Phase 6 (Joju 2024).

Figure 8: A 27-storey New RCS building in Nangang, Taipei by Ruentex Engineering and Construction Co., Ltd.

Practical Implementation: The Taiwan Land Management Agency has granted approval for New-RCS structural system. The design details developed as part of New-RCS project were used by the engineers at Ruentex Engineering and Construction Co., Ltd. in the construction of a 27-storey office building which is nearing its completion in Nangang, Taipei (see Figure 8). Additionally, five other high-rise New-RCS buildings are under construction in Taipei

5. CONCLUSIONS

This research advances the understanding of the seismic behavior of high-strength reinforced concrete and steel (New-RCS) joints, derived from extensive experimental testing and analytical modeling. Key findings include the safe extension of steel reinforcement yield stress to 690 MPa and concrete grade to 100 MPa for New RCS joints, exceeding current design limits. The proposed joint details, apart from those utilizing bolted web-welded flange splices, exhibited excellent seismic behavior with stable hysteretic responses and minimal joint damage. Analytical models developed were shown to provide accurate and conservative strength predictions, enhancing design reliability. Future research directions include broader validation of models, exploration of alternative splice details, and development of a comprehensive analytical model to improve design efficiency. These insights contribute to the advancement of safer, more resilient structures in seismic zones.

6. ACKNOWLEDGMENTS

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