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PRECAST INFILLED FRAMES: CIRCULAR SOLUTION FOR SEISMIC-RESILIENT BUILDINGS

Summary: Within the ongoing EU-funded CIRC-BOOST project (call CL6-2022-CIRCBIO-02-01), Faculty of Civil Engineering in Belgrade, together with its partners, is developing the house concept that follows the core principles of circular economy and is designed to be functional, structurally stable, and seismic-resilient. An important structural component of this house is a frame composed of precast concrete columns made with recycled aggregate, reused steel beams, and masonry infill constructed from reused solid clay bricks, decoupled from the frame using recycled rubber strips of the INODIS system. The paper presents a setup and results of the first series of tests validating the concept for the described precast infilled frame. The tests results demonstrate that the precast frame with masonry infill simultaneously adheres to the circular approach and ensures structural resistance.

Keywords: precast infilled frames, circular economy, seismic resilience, INODIS system

PREFABRIKOVANI RAMOVI SA ISPUNOM: CIRKULARNO REŠENJE ZA SEIZMIČKI OTPORNE OBJEKTE

Rezime: U okviru aktuelnog projekta CIRC-BOOST (call CL6-2022-CIRCBIO-02-01), Građevinski fakultet u Beogradu, zajedno sa svojim partnerima, razvija koncept kuće koja prati osnovne principe cirkularne ekonomije, i koja se projektuje da bude funkcionalna, stabilna i seizmički otporna. Kao važan konstruktivni sklop ove kuće prisutan je ram izveden od prefabrikovanih stubova spravljenih od betona sa recikliranim agregatom, grede od ranije korišćenog čelika, kao i zidane ispune od ranije korišćene pune opeke. Ispuna je izolovana od rama korišćenjem recikliranih gumenih traka INODIS sistema. U radu su prikazane postavke i rezultati prve serije testova kojima se vrši validacija koncepta pomenutog rama sa zidanom ispunom. Rezultati testova pokazuju da prefabrikovani ram sa zidanom ispunom prati principe cirkularne ekonomije, istovremeno obezbeđujući i konstruktivnu otpornost.

Ključne reči: prefabrikovani ramovi sa ispunom, cirkularna ekonomija, seizmička otpornost, INODIS sistem

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1. INTRODUCTION

The construction industry has traditionally followed a linear economic model based on the "take–make–dispose" principle [1]. Under this approach, raw materials are extracted, converted into construction products, incorporated into buildings, and eventually disposed of at the end of their service life. Such an approach has significant environmental consequences, as the construction sector is responsible for a substantial share of global resource consumption, greenhouse-gas emissions, and solid waste generation [2].

To address these challenges, the concept of the circular economy (CE) has emerged as a sustainable alternative to the conventional linear model. The CE promotes the reuse, recycling, recovery, and extended service life of construction materials, thereby reducing the demand for virgin resources, lowering environmental impacts, and minimizing waste generation [2],[3]. In recent years, numerous studies and practical case studies have demonstrated the potential of circular design principles, reusable construction products, and reversible building systems for the development of more sustainable and resource-efficient buildings [4]–[7].

Although circularity and sustainability have become important drivers in contemporary construction, structural safety requirements must remain uncompromised. This is particularly important in seismically active regions, where buildings are expected not only to minimize their environmental impact but also to ensure adequate resistance and resilience under earthquake loading. Consequently, the development of structural systems capable of simultaneously satisfying circular economy principles and seismic performance requirements represents an important research challenge.

The practical implementation of circular construction solutions remains limited, particularly when structural safety and seismic performance must be ensured simultaneously. Within the ongoing EU-funded CIRC-BOOST project (call CL6-2022-CIRCBIO-02-01), Pilot 3 addresses this challenge through the development of the so-called 3R house, a single-storey demonstration building designed according to the principles of reduce, reuse, and recycle. The building is conceived as a fully demountable structure that incorporates recycled and reused construction materials while satisfying the required structural and serviceability criteria.

A key structural component of the 3R house is a precast infilled frame integrated into one of the façade walls. The system consists of precast reinforced concrete columns produced with recycled aggregate concrete, reused steel beams, and masonry infill constructed from reused solid clay bricks. The infill is isolated from the surrounding frame by recycled rubber strips of the INODIS system [8], which provide controlled interaction between the frame and the masonry, improve the seismic response of the infill, and enable dry and reversible connections that facilitate efficient assembly and disassembly.

The paper presents the first series of experimental tests aimed at assessing the behaviour of the proposed precast infilled frame concept. The experimental programme includes small-scale beam connection tests, column connection tests, and assembly/disassembly feasibility test, with a focus on connection behaviour and the applicability of the proposed circular system. The obtained results provide an initial experimental insight into the feasibility of integrating circular construction principles with seismic-resilient structural design.

2. PRECAST INFILLED FRAME IN 3R PILOT HOUSE: OVERVIEW

The precast infilled frame represents one of the key structural components of the 3R pilot house developed within the CIRC-BOOST project. The general appearance of the house, as well as the position and configuration of the considered frame, are presented in Figures 1, 2 and 3.

The frame consists of three bays and combines precast reinforced concrete columns produced with recycled aggregate concrete (RAC), reused steel beams, and decoupled masonry infills constructed from reused solid clay bricks. In accordance with the principles of circular construction, the system is designed as a prefabricated and demountable solution, enabling efficient assembly, disassembly, and potential reuse of structural components.

To ensure seismic performance while maintaining the reversibility of the system, the masonry infills are decoupled from the surrounding frame using the INODIS system [8]. The system is based on recycled rubber strips placed along the frame–infill interfaces, which allow controlled interaction between the masonry infill and the surrounding structural elements under seismic load. The main components and arrangement of the decoupling system within the proposed frame are shown in Figure 4.

Previous experimental and numerical studies have demonstrated the effectiveness of the INODIS system in improving the seismic behaviour of masonry infills in cast-in-situ RC frames under in-plane, out-of-plane, and combined loading conditions [8]–[11]. However, its implementation within a fully prefabricated frame composed of recycled and reused materials represents a further step towards integrating seismic resilience with circular construction principles.

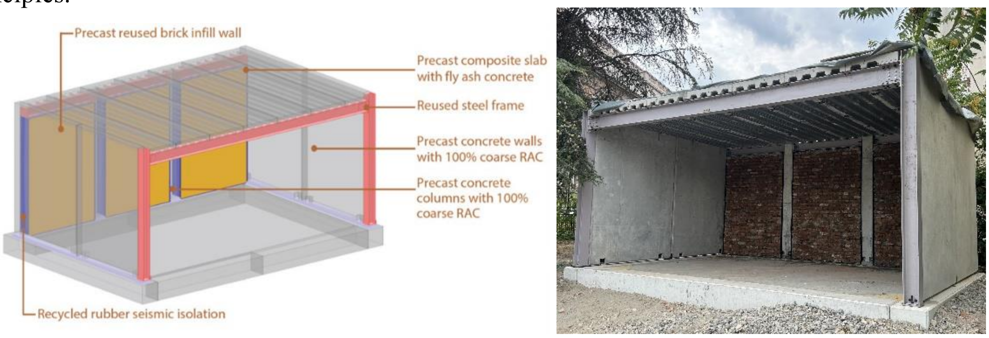


Figure 1: 3R pilot house: conceptual design and construction

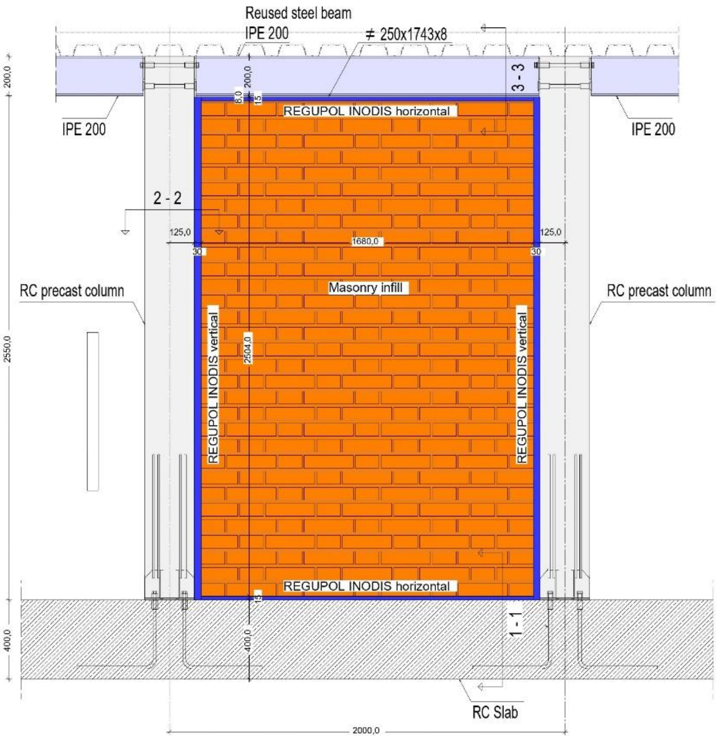


Figure 2: The central bay of the precast infilled frame (conceptual design)

Figure 3: Precast infilled frame in the 3R pilot house

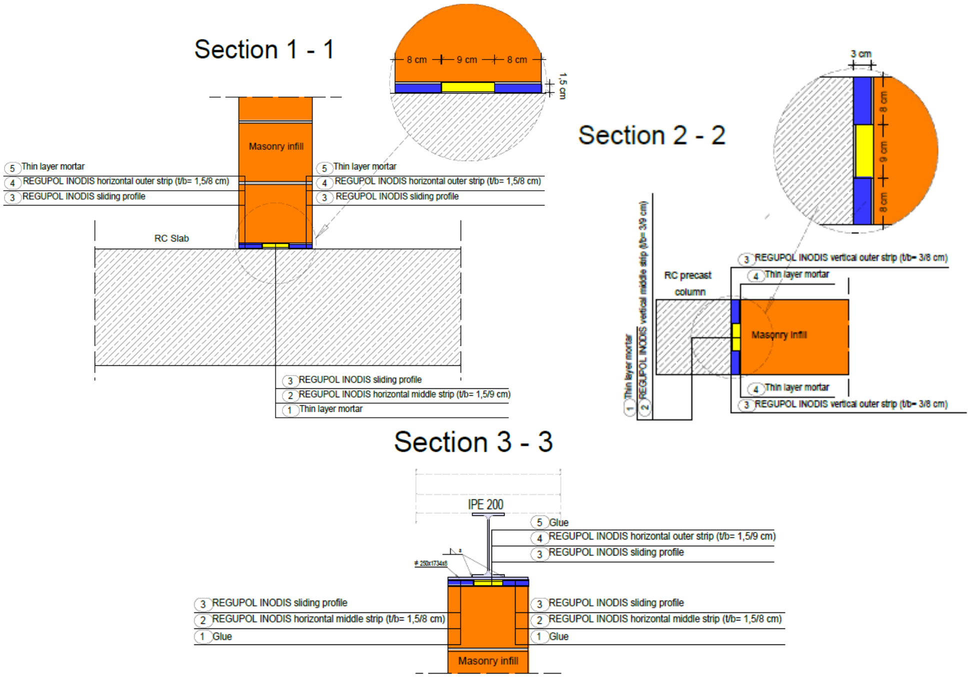


Figure 4: INODIS decoupling system within the precast infilled frame

3. CONNECTION TESTS

3.1. EXPERIMENTAL PROGRAMME

As an initial step in the experimental assessment of the proposed precast infilled frame, small-scale connection tests were performed on the two critical interfaces between the masonry infill and the surrounding frame, namely the beam–infill and column–infill connections. The specimens comprised a single masonry brick together with the steel or concrete element and the recycled rubber connection components forming the investigated interface. The objective of these tests was to characterize the mechanical behaviour and resistance of the proposed decoupled connection system, with particular emphasis on its ability to provide adequate out-of-plane restraint for the masonry infill and thus reduce the risk of its dislodgement during strong earthquakes. The beam connection tests investigate the proposed steel beam–rubber isolation–masonry interface, representing a connection configuration that, to the authors' knowledge, has not previously been experimentally investigated. In addition, the column connection tests examine the behaviour of the proposed connection system when used with recycled aggregate concrete (RAC) columns, thereby assessing the influence of RAC on the connection performance.

All tests were performed using a Shimadzu universal testing machine under displacement-controlled loading until failure. During testing, the applied load and the corresponding displacement were continuously recorded, while the peak load was adopted as the connection resistance. Since the connections were provided on both sides of the masonry specimen, the measured force represented the resistance of a double-sided connection, and the resistance of a single connection was therefore taken as one-half of the measured value.

A dedicated loading assembly was used for both experimental configurations to ensure stable support conditions and controlled load transfer. The specimens were stabilized by a steel support system without introducing significant horizontal confinement, while the load was applied through U-shaped steel sections connected by threaded rods and a reinforcing bar.

3.2. BEAM CONNECTION TEST

Five specimens (B1–B5) were tested to investigate the behaviour of the proposed beam–infill connection. Each specimen consisted of a reused solid clay brick, two reused steel profiles, and three recycled rubber strips on each side of the brick. The outer rubber strips were bonded to the brick using a thin-bed mortar, whereas the central rubber strip was adhesively bonded to the steel profiles. In this configuration, the brick represents the masonry infill, the steel profiles simulate the frame beam, and the recycled rubber strips reproduce the proposed decoupling layer. The specimen configuration and the experimental setup are presented in Figure 5.

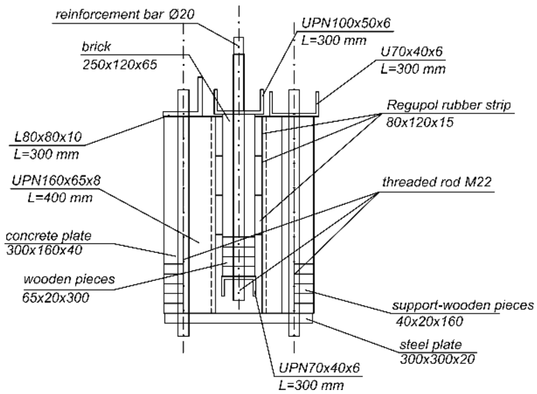


Figure 5: Beam connection test setup

The tests were conducted under displacement-controlled loading at a constant loading rate of 0.5 mm/min. Four specimens (B1–B4) were loaded in the upward direction, while specimen B5 was loaded downward to examine the possible influence of the loading direction on the response of the connection.

The force–displacement curves obtained for all tested specimens are shown in Figure 6. The corresponding peak loads are indicated alongside the specimen labels. All specimens exhibited a similar force–displacement response. The applied load generally increased with increasing displacement until the peak resistance was reached, after which a gradual decrease in load-carrying capacity was observed. Following the peak load, the specimens retained a significant portion of their load-carrying capacity over a relatively large displacement range, indicating stable post-peak behaviour of the proposed connection.

The average peak load of the double-sided connection, adopted as the mean shear resistance, was 3945 N. This value was statistically evaluated in accordance with Annex D of Eurocode 0 [12]. Assuming a Normal distribution of the test results, the characteristic resistance was determined as the 5% fractile and subsequently converted into the corresponding design resistance using the procedure prescribed in Equation D.1 of Clause D.7.2(1). The resulting design shear resistance amounted to 1708 N for the double-sided connection, corresponding to 854 N for a single connection.

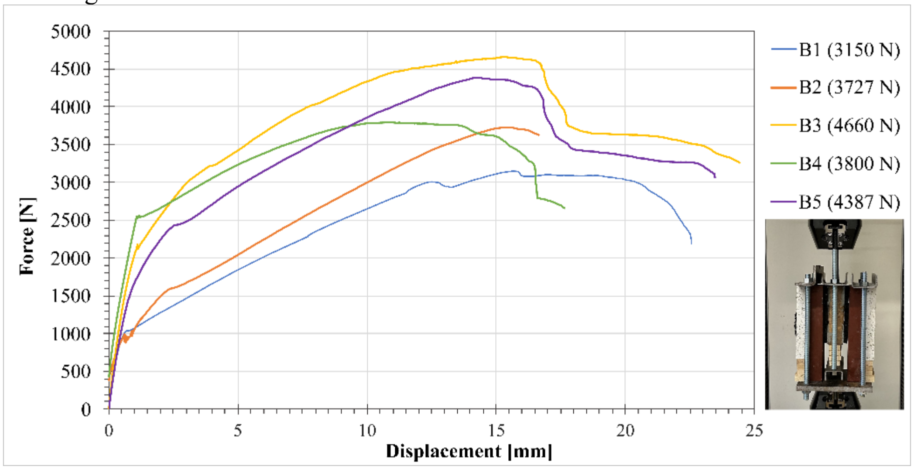


Figure 6: Force–displacement response of the beam–infill connection specimens

In all specimens, failure was consistently observed within the central rubber connection bonded to the steel profiles. The observed failure mechanisms included delamination of the thin factory-applied fleece layer from the central rubber strip, loss of adhesion between the rubber strip and the steel profile, or a combination of both. Despite these minor differences in the failure mechanism, all specimens exhibited comparable resistance and deformation capacity, confirming the robustness of the proposed beam–infill connection.

3.3. COLUMN CONNECTION TEST

Six specimens were tested to evaluate the behaviour of the column–infill connection. Each specimen consisted of a reused solid clay brick, two recycled aggregate concrete (RAC) plates, and three recycled rubber strips forming the connection. The outer rubber strips were bonded to the brick using a thin-bed mortar whereas the central rubber strip was bonded to the concrete plates using the same thin-bed mortar. In this configuration, the brick represents the masonry infill, the concrete plates simulate the reinforced concrete column, and the recycled rubber strips reproduce the proposed decoupling layer. The specimen configuration and the experimental setup are presented in Figure 7.

The specimens were divided into two groups. The first group comprised three reference specimens (C1–C3), while the second group consisted of three specimens (CG1–CG3) incorporating a 10 mm gap between the outer rubber strips and the concrete surface. The introduced gap was intended to simulate the separation that may occur between the masonry infill and the surrounding frame during in-plane seismic loading. Consequently, the second group represents the condition in which the connection has already experienced in-plane deformation before being subjected to out-of-plane loading, allowing the influence of combined seismic actions on the connection behaviour to be assessed.

The tests were performed using the same Shimadzu testing machine under displacement-controlled loading at a constant loading rate of 1 mm/min until failure. All specimens were loaded in the upward direction while the applied load and corresponding displacement were continuously recorded.

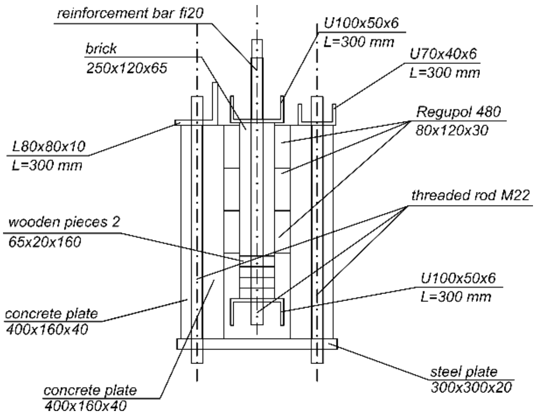


Figure 7: Column connection test setup

The force–displacement curves of all column connection specimens are presented in Figure 8, with the corresponding peak loads indicated alongside the specimen labels. A clear difference in behaviour was observed between the two specimen groups. The reference specimens (C1–C3) exhibited stable behaviour and consistent load-carrying capacity, reaching the peak load followed by a gradual reduction in resistance. In contrast, specimen CG1 experienced a rapid loss of resistance after reaching the peak load, accompanied by significantly larger displacements. Similar behaviour was observed for specimens CG2 and CG3. Owing to the exceptionally large displacements, while the load remained nearly constant, the tests were intentionally terminated to avoid damage to the testing equipment. The observed response indicates that once the gap is formed as a consequence of in-plane loading, the out-of-plane resistance of the connection is considerably reduced.

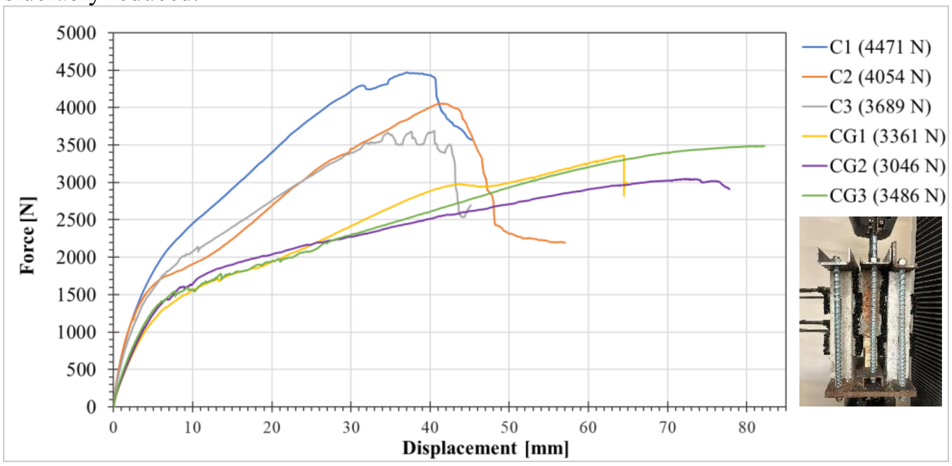


Figure 8: Force–displacement response of the column–infill connection specimens

For the reference specimens, the average peak load, adopted as the mean shear resistance of the double-sided connection, was 4071 N. Following the same statistical procedure as for the beam connection tests, the characteristic resistance was determined as the 5% fractile assuming a Normal distribution of the experimental results, while the corresponding design shear resistance amounted to 1835 N for the double-sided connection, corresponding to 918 N for a single connection. For the specimens with the introduced gap, the average peak load of the double-sided connection was 3298 N. The statistical evaluation yielded a design shear resistance of 1689 N, corresponding to 844 N for a single connection. Compared with the reference specimens, the design resistance was reduced by approximately 8%, demonstrating the adverse influence of prior in-plane deformation on the subsequent out-of-plane behaviour of the connection.

In all tested specimens, failure consistently occurred by debonding of the central rubber strip from the recycled aggregate concrete (RAC) plates, accompanied by partial debonding of the outer rubber strips from the masonry brick.

3.4. ASSESSMENT OF THE OUT-OF-PLANE RESISTANCE OF THE INFILL SYSTEM

The design shear resistances obtained from the beam and column connection tests were used to estimate the out-of-plane resistance of the complete infill restraint system. The tested specimens represent the connection associated with a single masonry unit. Consequently, the resistance of each full-scale frame–infill interface was obtained by multiplying the design resistance of a single connection by the corresponding number of masonry units along that interface. The considered masonry infill is 2.504 m high and 1.68 m wide. Based on the adopted masonry arrangement, nineteen masonry units contribute to each column–infill connection, while thirteen masonry units contribute to each beam–infill connection. For the vertical interfaces, the design resistance of 844 N obtained from the specimens with the introduced gap was adopted, representing the condition following prior in-plane deformation. For the horizontal interfaces, the design resistance obtained from the beam connection tests, amounting to 854 N per masonry unit, was used.

Accordingly, the design resistance of one column–infill connection amounted to 16.04 kN, whereas the resistance of one beam–infill connection was 11.10 kN. Considering the two column and two beam connections surrounding the masonry infill, the total design out-of-plane resistance of the complete connection system was determined as 54.28 kN.

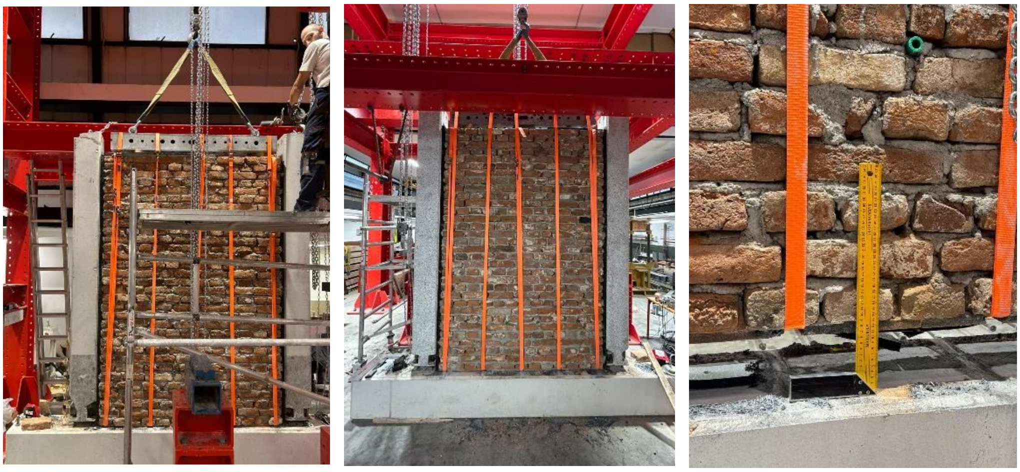
The out-of-plane seismic demand for the masonry infill, considered as a non-structural element, can be calculated according to Equations 4.24 and 4.25 of Clause 4.3.5.2 of Eurocode 8, Part 1 **Error! Reference source not found.**. To determine the seismic intensity corresponding to the calculated resistance of the complete connection system, the obtained resistance of 54.28 kN was introduced as the out-of-plane seismic demand in these equations. The corresponding design ground acceleration was then determined as 0.84g. This value represents the design ground acceleration at which the calculated out-of-plane resistance of the complete connection system is reached, initiating the out-of-plane dislodgement of the masonry infill from the surrounding precast frame.

4. ASSEMBLY/DISASSEMBLY FEASIBILITY TEST

To verify the practical feasibility of the proposed circular construction concept, an assembly/disassembly test was performed on the full-scale precast infilled frame. After removing the reused steel beam from the frame, a temporary lifting beam made of a hollow steel section was positioned on top of the masonry infill. Prior to the construction of the infill, openings had been intentionally provided at its base to facilitate future lifting and removal. Ratchet straps were threaded through these openings, wrapped around the temporary steel beam, and tightened to ensure a secure connection between the lifting system and the masonry panel. The test setup is shown in Figure 9 (a), (b).

The temporary lifting beam was subsequently connected to an overhead crane, and the masonry infill was gradually lifted from its original position. The panel was successfully raised by approximately 110 mm, demonstrating that the masonry infill can be safely detached from the surrounding frame and handled as an individual prefabricated element (Figure 9 (c)). The lifting operation was intentionally stopped at this stage because the available vertical clearance in the laboratory was insufficient to allow complete extraction of the panel.

Although the complete removal of the masonry infill could not be demonstrated due to the geometric limitations of the testing facility, the successful lifting confirmed the feasibility of the proposed assembly/disassembly concept. The test demonstrated that the masonry infill can be removed from the frame, transported, and reinstalled. Together with the demountable precast columns and the removable reused steel beam, this enables the entire structural system to be dismantled and reassembled at another location, fully supporting the principles of circular construction.



(a) (b) (c)

Figure 9: Assembly/disassembly feasibility test: (a),(b) installation of the temporary lifting system; (c) successful lifting of the masonry infill by approximately 110 mm.

5. CONCLUSIONS

The experimental programme presented in this study provides the first validation of the proposed precast infilled frame developed within the CIRC-BOOST project. The conducted small-scale beam–infill and column–infill connection tests provided an experimental assessment of the proposed connection details, while the assembly/disassembly feasibility test demonstrated the practical applicability of the developed circular construction concept. Together, these experimental investigations represent an important step towards the validation of the proposed structural system.

The experimentally determined design resistances of the beam and column connections were subsequently used to estimate the out-of-plane resistance of the complete infill restraint system. The calculated resistance of 54.28 kN corresponds to a design ground acceleration of approximately 0.84g, indicating that the proposed connection system is capable of preventing the out-of-plane dislodgement of the masonry infill even under seismic loading of very high intensity. These results demonstrate that the proposed solution successfully combines seismic decoupling with adequate out-of-plane resistance.

The assembly/disassembly feasibility test further confirmed the practical applicability of the proposed circular construction concept. The successful lifting of the masonry infill demonstrated that the panel can be safely removed, transported, and reinstalled. Together with the demountable precast columns and the removable reused steel beam, this enables the complete structural assembly to be dismantled and reconstructed at another location, thereby directly supporting the principles of circular economy.

Overall, the presented results demonstrate that the proposed precast infilled frame successfully combines circular construction principles with seismic resilience. The next phase of the research will include full-scale testing of the complete precast infilled frame under in-plane and combined in-plane and out-of-plane seismic loading, followed by the experimental validation of the complete 3R pilot house.

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