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Seismic performance of 3D printed buildings: an overview of the world-first full-scale shaking table test

Valentino Sangiorgio[a,e]*, Enrico Spacone[a], Guido Camata[a], Raffaele De Risi[b], Tansu Gokce[b], Flavia De Luca[b], Matt Dietz[b], Adam Crewe[b], Dimitris Karamitros[b], George Mylonakis[b], Anastasios Sextos[b], André Furtado[c], José Melo[d], Humberto Varum[d]

[a] *Department of Engineering and Geology, "Gabriele d'Annunzio" University of Chieti-Pescara, Pescara, Italy*
[b] *School of Civil, Aerospace and Design Engineering, University of Bristol, Bristol, UK*
[c] *CERIS, Department of Civil Engineering, Instituto Superior Técnico, University of Lisbon, Portugal*
[d] *CONSTRUCT-LESE, Department of Civil Engineering and Georesources, Faculty of Engineering, University of Porto, Portugal*
[e] *Cadi Ayyad University. Department of Chemistry; Marrakesh, Morocco*

Abstract

Over the past decade, building construction has undergone a notable transformation with the advent of additive manufacturing. Indeed, several companies are developing 3D printing systems and buildings worldwide. However, the current literature lacks comprehensive studies, and a significant gap remains in understanding the seismic behaviour of monolithic 3D-printed structures. This paper aims to address this shortcoming by presenting a systematic experimental campaign, beginning with the characterisation of printed materials and culminating in a shake table test on a full-scale 3D-printed housing unit (3m x 4m). To the best of the authors' knowledge, this is the first seismic shake table test conducted on a 3D-printed building unit. The work proposes a methodological approach developed through a five-step procedure: i) conducting mechanical characterization through a series of preliminary tests, such as diagonal shear tests in 3D printed walls; ii) calibrating a numerical model using preliminary experimental tests to simulate the seismic response of the 3D-printed building unit; iii) designing and dimensioning the 3D-printed building unit, along with its connection to the shake table and the sensor system; iv) implementing the full-scale shake table test on the housing unit, printed directly on the shake table at the SOFSI Lab, University of Bristol; v) refining the numerical model based on the outcomes of the final dynamic test. Preliminary results indicate the potential for establishing foundational design guidelines to support engineers and industry stakeholders adopting this emerging technology. Ultimately, this study enhances seismic risk mitigation strategies and promotes technologically advanced construction solutions. This paper is part of the dissemination activities of the SAFE 3D PRINTED-CS project, funded under HORIZON-INFRA-2021-SERV-01-07, transnational access call 1.

Keywords: 3D construction printing; Shake Table Test; Construction Technology; Seismic Performance

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*Corresponding author. *E-mail address:* valentino.sangiorgio@unich.it

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Introduction

Additive manufacturing has become well established in various industrial sectors, with unprecedented growth in the building industry over the past decade (Loosemore 2015). In particular, 3D concrete printing is significantly impacting building technologies and construction processes (Hossain et al. 2020). Numerous applications by companies and a growing body of scientific literature highlight the importance and potential of this technology (Volpe et al. 2024).

The increasing interest in extrusion-based 3D concrete printing within the architecture, engineering, and construction (AEC) industry is largely due to its advantages: lower costs, reduced waste, shorter construction times, and a simplified supply chain (Bianchi et al. 2024). Furthermore, additive manufacturing is considered one of the most promising technologies for sustainable development in the AEC sector. The design freedom, ease of customization, and ability to create complex geometries (Sangiorgio et al. 2022) enable enhanced structural and thermal performance, as well as improved environmental sustainability (Sangiorgio et al. 2025).

However, there are still limitations and knowledge gaps that must be addressed before large-scale applications become feasible. Recent studies are focusing on the development of increasingly large-scale projects using advanced 3D printers to meet market demands for monolithic construction. In addition to printing technologies, another important research area involves the development of materials to accelerate the extrusion process and improve print quality (Volpe et al. 2021, Gebhard et al. 2020). One of the main concerns within the academic community is the effectiveness of reinforcement to improve structural performance. Various approaches have been proposed in the literature to incorporate reinforcement during the additive manufacturing process. However, most of these remain at the experimental stage, and no full-scale structural tests on printed walls have been carried out (Mechtcherine et al. 2021; Xiao et al. 2021; Souza et al. 2020).

Despite the growing number of 3D-printed buildings constructed worldwide, the actual seismic performance of such structures is still not well understood. Only a few studies and simulations have been conducted on simple, scaled-down walls or hollow structures with varying infill configurations (Wang et al. 2020; Mintsaev et al. 2018; Prakash & Basavangowda 2022). Notably, the research conducted by van den Heever et al. (2021), represents the first attempt at mechanical characterization for numerical simulation of extrusion-based 3D concrete printing, forming the basis of the proposed research project.

In conclusion, the literature review reveals a critical gap: the lack of thorough structural and seismic characterization of printed materials, walls, and building units through laboratory testing. As a result, a comprehensive investigation of the seismic performance of 3D construction printing is not just a research opportunity, but a fundamental requirement for the future widespread and large-scale adoption of this technology.

This study seeks to fill a significant research gap by presenting a structured experimental campaign, which starts with the mechanical characterization of 3D-printed materials and walls and culminates in a full-scale seismic shake table test on a 3m × 4m 3D-printed housing prototype. To the authors' knowledge, this represents the first known shake table test performed on a monolithic 3D-printed structural unit.

The proposed research is based on a five-phase methodological framework (Fig. 1):

- i) a preliminary experimental phase involving in-depth mechanical testing of materials, including diagonal shear tests on 3D-printed walls;
- ii) calibration of a numerical model using data from these preliminary tests, enabling the simulation and interpretation of the seismic performance of the 3D-printed unit across different geometrical setups;
- iii) the design and structural detailing of the housing prototype, including its connection system to the shake table and the dedicated sensor layout for seismic monitoring;
- iv) execution of the full-scale dynamic test on the printed structure, manufactured in situ on the shake table at the SOFSI Lab, University of Bristol;
- v) refinement and validation of the numerical model using the results from the shake table test.

The following sections are organized according to each operational phase of the proposed research. Specifically: Section 1 presents the preliminary tests carried out at FEUP; Section 2 discusses the calibration of the numerical model; Section 3 illustrates the design of the prototype; Section 4 details the execution of the full-scale test; and Section 5 provides final considerations useful for validating the developed model.

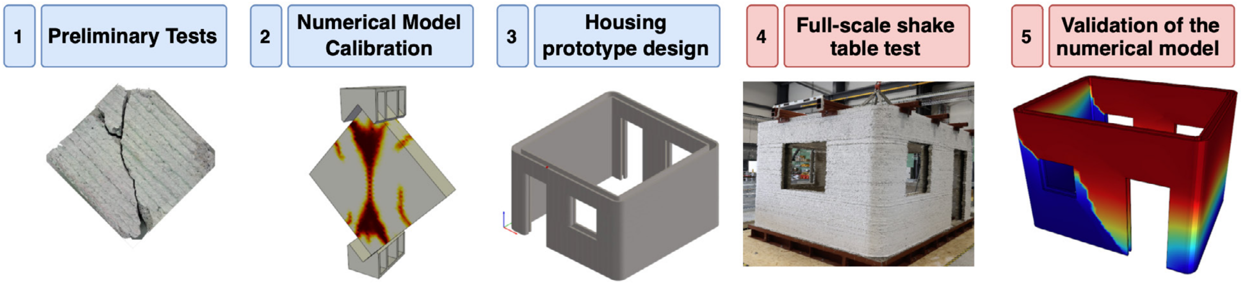


Fig. 1. The five steps of the proposed research.

1. Preliminary tests

The first step of the project involves preliminary laboratory tests on different materials and wall samples, to be carried out at FEUP. The main objective is to characterize the mechanical properties of the 3D-printed concrete material and walls.
The testing campaign includes:

- *Compression tests*: 6 cored cylindrical samples (70 mm × 140 mm) tested in orthotropic directions (perpendicular and parallel to the printing layers).
- *Young's Modulus tests*: 6 cored cylindrical samples (70 mm × 140 mm) tested in orthotropic directions.
- *Tensile tests*: 6 cored cylindrical samples (70 mm × 140 mm) tested in orthotropic directions.
- *Flexural (bending) tests*: 6 prismatic samples (80 mm × 150 mm × 500 mm), cut parallel to the printing layers, as shown in the Fig. 2.
- *Shear tests (diagonal compression)*: 6 panel samples (80 mm × 400 mm × 400 mm), prepared for diagonal compression testing.

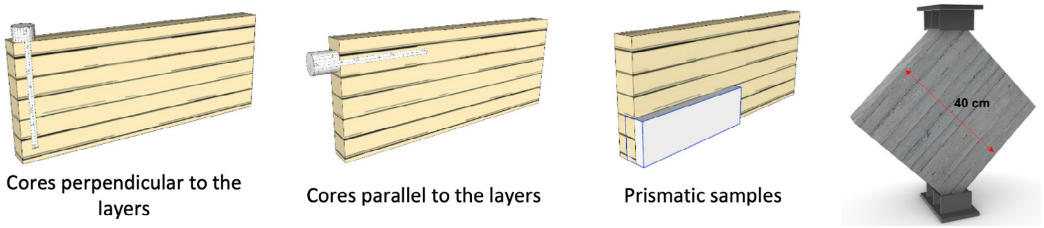
For most of the tests, cylindrical cores will be extracted in two directions: perpendicular and parallel to the printing layers. However, in the case of bending tests, samples will be cut only parallel to the printed layers. Fig. 2 shows the types and orientations of cores and samples extracted from the 3D-printed walls (left part) and the Shear tests (right part). The compressive strength of the 3D-printed concrete, based on the tested samples, was found to be 45 MPa, confirming good mechanical performance under axial load conditions. Regarding fracture energy, the compressive fracture energy was calculated as 27.06 N/mm. This value was derived using the empirical expression of equation (1):

$$Gfc = 15 + 0.43 \cdot fc - 0.0036 \cdot fc\text{^}2 \qquad (1)$$

This equation accounts for the nonlinear relationship between compressive strength and the corresponding energy dissipated during fracture. For tensile behaviour, the tensile fracture energy was estimated as 0.1 N/mm, using the following equation (2):

$$Gft = 0.025(2 \cdot ft)\text{^}0.7 \qquad (2)$$

This formulation is used to characterize the energy absorption capacity of the material in tension, which is particularly relevant for understanding crack propagation in 3D-printed elements.



Cores perpendicular to the layers

Cores parallel to the layers

Prismatic samples

Fig. 2 samples extracted from the 3D-printed walls and diagonal shear test.

2. Numerical model calibration

Numerical simulations are conducted within the OpenSees framework, leveraging the powerful modelling environment provided by the Scientific ToolKit for OpenSees (STKO), which is utilised both as a pre-processor for model definition and a post-processor for results visualisation and analysis. The simulations aim to reproduce the diagonal shear tests conducted in FEUP.

The calibration of model parameters is informed by the experimental material characterization presented in the previous Section 1. This dataset provides key mechanical properties of 3D-printed concrete, such as elastic modulus, tensile and compressive strengths, and fracture energies, which are essential for accurately defining the nonlinear behavior of the material in the numerical model. In particular, the numerical modeling focused on reproducing the diagonal shear test carried out during Step 1 of the experimental campaign. To achieve this, two distinct modeling strategies were developed. The first model explicitly defines each printed layer, including the interfaces between layers, in order to capture potential weak planes and interfacial behavior resulting from the 3D printing process.

The second model, by contrast, simplifies the geometry by modeling the wall as a homogenized anisotropic material, where the directional dependence of the mechanical properties—caused by the printing process—is incorporated directly into the material definition. This dual-model approach allows for a comparative analysis to evaluate the effectiveness and accuracy of modeling interlayer effects versus applying anisotropic constitutive behavior in reproducing the shear response of 3D-printed walls. At the end of the evaluation process, the second model—based on a homogenized anisotropic material—was selected to proceed with the subsequent phases of the project. This choice was made because it proved to be equally effective in reproducing the experimental results, while requiring significantly lower computational effort and reduced modeling complexity compared to the layered model. This makes it more suitable for full-scale simulations and parametric studies. Fig. 3 illustrates the results of different numerical modelling approaches developed to replicate the diagonal shear test: (a) a layered model with interfaces, (b) a homogenized model using anisotropic material, and (c) the actual cracking observed in the experimental setup.

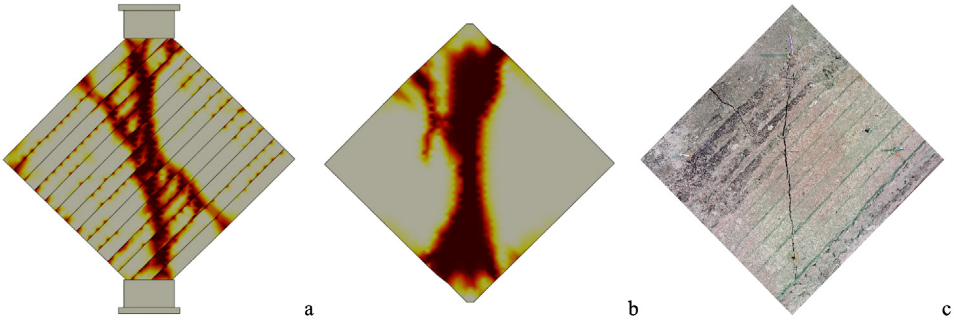


Fig. 3. (a) Layered model with explicit representation of printing layers and interfaces; (b) Homogenized model using anisotropic material properties; (c) Experimental setup of the real diagonal shear test.

3. Housing prototype desing

The prototyping phase of the project involved several key steps:

- *Planning and setup of the on-site 3D printing process* at SOFSI Lab (foundation pads, printer configuration);
- *Structural analysis* and housing geometry optimization based on shake table constraints (mass, acceleration);
- *Design of the foundation system*, including a steel frame to connect the prototype to the shake table;
- *Design of construction details* based on real 3D printing practices;
- *Instrumentation Setup*, including load cells, LVDTs, gyroscopes, accelerometers, and data acquisition units.

3.1. Planning and setup of the on-site 3D printing process

One of the initial challenges was determining how to configure a 3D printer within the SOFSI Lab in Bristol in such a way that it could successfully print a full-scale housing unit directly onto the shake table. This required careful planning in terms of space, printer dimensions, and 3D printer foundation setup to ensure both printing feasibility and structural stability during dynamic testing. In particular, it was decided to place the concrete mixing equipment outside the SOFSI Lab, using aggregates with a maximum diameter of 2 mm (same material of the preliminary tests) to ensure compatibility with the extrusion system. A dedicated pumping system was then installed to deliver the concrete mix from the external preparation area to the BOD2 printer (COBOD), which was positioned directly on the shake table. The chosen printer setup consists of four vertical columns. To support the printer structure without interfering with the movement of the shake table, 4 foundation pads were designed and placed around the table, without being in direct contact with it.

3.2. Structural analysis

The structural analysis was based on an iterative approach that integrates parametric modeling with numerical simulations. The parametric model was developed using Grasshopper, a visual programming environment embedded within Rhinoceros 3D software. This environment allows real-time manipulation of a wide range of geometric parameters, such as wall thickness, curvature, number, size, and position of openings. The parametric model enables the user to modify input parameters dynamically and generate an updated 3D geometry instantly, streamlining the design process. This flexibility is crucial for optimizing the structural layout of the 3D-printed housing unit. The structural analysis was performed using OpenSees, through the STKO platform, and was calibrated based on the preliminary experimental characterization of the printed materials. The proposed workflow allowed for an efficient iteration between geometry and performance, with the goal of identifying the most suitable configuration for full-scale testing. The final configuration (Fig. 4a) selected consists of a housing unit measuring 3 × 4 m, with an approximate height of 3 meters. The structure features double printed walls, each with a thickness of 6 mm, corresponding to the 6 mm nozzle used in the printing process. The layout includes one door opening measuring 2.2 × 1 m and one window of 1 × 1.1 m, symmetrically positioned on both the long sides. On each short side, a 1.2 × 1.1 m window is placed, resulting in a balanced and realistic architectural configuration suitable for testing. Finally, a rigid top element was properly connected to the walls to simulate a two-way slab system, and represent realistic floor-to-wall interaction.

3.3. Design of the foundation system

Once the housing geometry was defined, attention shifted to the design of the foundation system. A steel base frame was engineered and dimensioned to ensure a rigid and safe connection between the 3D-printed structure and the shake table. The design deliberately aimed to ensure that any failure would occur within the printed structure itself, and not at the foundation–structure interface, which is a critical aspect for a valid structural test. Fig. 4b shows how the U-shaped steel foundation profile is connected to the shake table. The initial extrusion phase fills the steel profile before the actual printing of the double-wall layers of the housing unit begins. This ensures proper anchorage and continuity between the printed structure and the foundation system. Fig. 5a shows the first printed layers of the housing unit, marking the beginning of the 3D printing process directly on the shake table surface at SOFSI Lab.

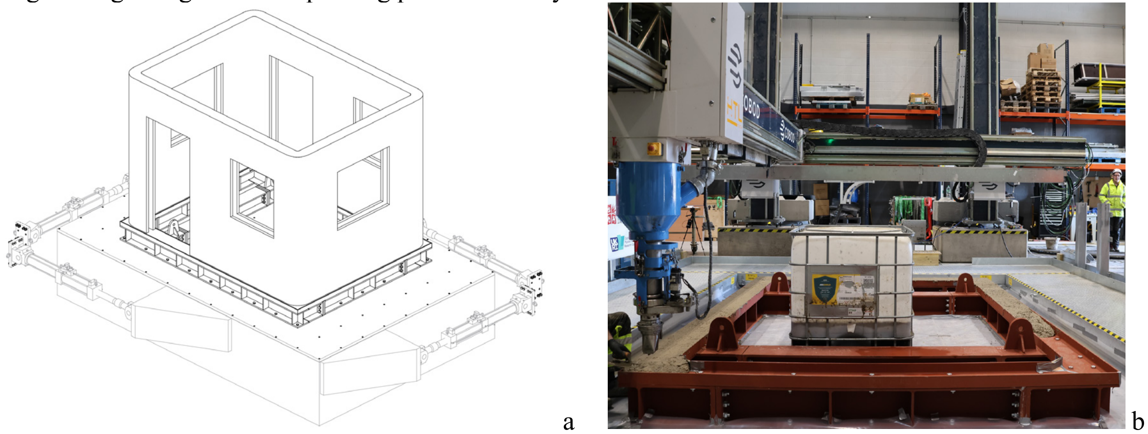


Fig. 4. (a) Axonometric view of the final configuration of the building unit, as defined following the iterative structural analysis process; (b) Extrusion in the U-shaped steel foundation profile connected to the shake table.

3.4. 3D-printed housing construction details

Following the foundation system, the team focused on developing the construction details of the prototype, taking into account current practices observed in innovative construction sites that employ 3D printing technology. These included aspects such as joint design, openings, and transitions between elements, to replicate realistic construction scenarios. Fig. 5b shows the prefabricated elements used as lintels to allow continuous 3D printing of the housing unit at the SOFSI Lab while creating window and door openings. This solution enables the printing process to proceed across openings, and it reflects a common practice in on-site 3D printing construction, where prefabricated components are integrated to ensure structural continuity and printing efficiency. It is worth noting that dry joints, which may represent potential critical elements, are not avoided as in traditional construction techniques. In the 3D printing process, interruptions often occur due to the insertion of elements such as lintels, or because of overnight pauses in printing from one day to the next.

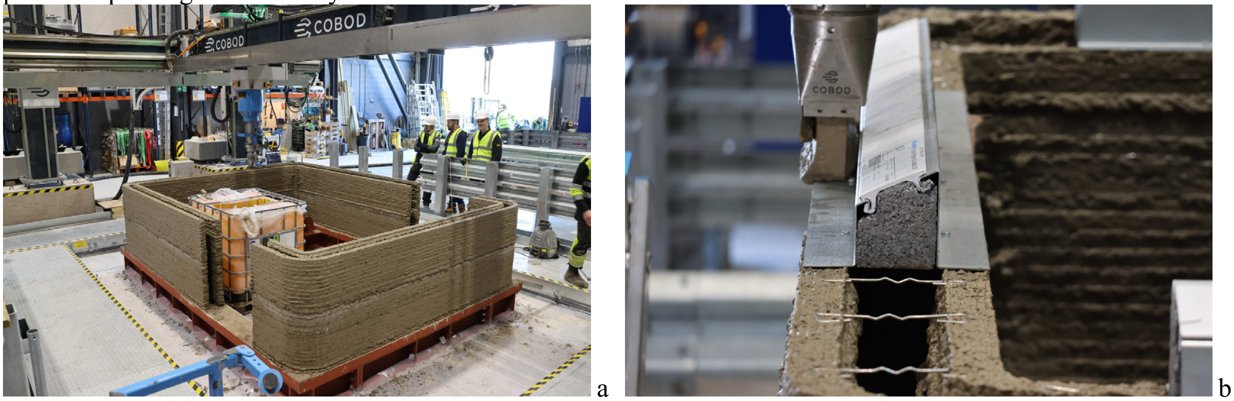


Fig 5. (a) first printed layers of the housing unit; (b) Use of lintels in the 3D-printed walls of the housing unit at SOFSI Lab.

3.5. Instrumentation and Monitoring Setup

An additional and fundamental phase of the project involved the planning and implementation of a comprehensive monitoring system, which is essential both for the validation of the numerical models and for the accurate interpretation of the structural response during dynamic loading. To meet these requirements, the experimental setup made use of the advanced instrumentation available at the SOFSI Lab. The monitoring system is centered around a 64-channel data acquisition system, based on HBM MX1601B units, which provide voltage input channels with high flexibility. For strain measurements, the setup includes 20 channels with strain-to-voltage converters, and full-bridge configurations, and optimized for 120-ohm sensors. Displacement measurements are covered by a range of LVDTs (Linear Variable Displacement Transducers) and laser distance sensors with ranges of 50 mm, 100 mm, and 200 mm. These sensors process signals digitally and are designed for relative displacement measurements. For applications requiring absolute reference-based displacement tracking, the lab utilizes the Imetrum Video Gauge system, a digital image correlation (DIC) solution with 12MP cameras operating at 10 Hz (or up to 50 Hz at reduced resolution). The system allows simultaneous or independent use of two cameras, ideal for capturing complex deformation fields across multiple areas of the experiment. The shake table controller includes voltage output channels that provide real-time data on X and Y axis accelerations, positions, and synchronization signals. Standard practice includes recording X, Y, and yaw motions using three voltage input channels. A wide range of accelerometers is also available, including: 20 units of Setra Model 141 single-channel accelerometers (2g).

4. Full scale shake table on 3D printed housing prototype

The seismic test campaign consisted of a total of 72 shake table excitations, performed over multiple sessions to evaluate the dynamic response and damage progression of the 3D-printed housing prototype. During the initial phase, the structure was subjected to 40 shakings using a recorded natural accelerogram. The intensity of the input motion was progressively increased, reaching up to 200% of the original signal amplitude. Despite the high excitation levels, no visible damage was observed at the end of the first day. However, a careful analysis of the recorded signals revealed a reduction in the natural frequency, indicating a slight shift in the structural period due to incipient internal damage not yet visible on the surface. On the second day test, the team switched to a synthetic accelerogram, commonly used for seismic qualification procedures. This signal is characterized by a long duration, a high number of cycles, and a broad frequency content, making it well-suited to test the structure under a wide range of dynamic demands. The synthetic signal was applied in incremental steps, starting from 10% and reaching up to 70% intensity, with each excitation level interspersed by white noise signals to assess system dynamics and allow frequency tracking between seismic pulses. Throughout the tests, the structure exhibited rigid body motion with no apparent damage, and the unit behaved essentially as a box undergoing uniform displacement. Significant structural damage was observed only during the final test (70% synthetic accelerogram intensity) in the longitudinal (X) direction. Damage localization aligned with the structural model, confirming structural weaknesses at expected locations:

- A major failure occurred at the dry joint located at the top of the wall, in correspondence with the prefabricated lintel elements (architraves).
- Additional cracking was observed below a window opening, also at a known dry joint location, indicating concentration of stress in areas lacking full continuity.
- Diagonal cracks emanated from the corners of the window openings, a typical damage pattern under in-plane shear action.

The Fig. 6a highlights the damage at the dry joints near the lintels and below the window openings, while Fig. 6b shows a view of the crack from the interior of the 3D-printed housing.

5. Validation of the numerical model

The results of the full-scale seismic test provided a robust experimental benchmark for the validation of the numerical model developed during the design phase. The model, created in the OpenSees framework and calibrated using material properties obtained from preliminary testing, was able to accurately reproduce the global behavior of the 3D-printed housing unit under increasing seismic demand.

In particular, the numerical simulations successfully predicted the rigid body motion observed during low- to moderate-intensity shaking, as well as the onset and location of damage at higher excitation levels. The concentration of damage at structurally weak zones—specifically at dry joints near lintel elements and below window openings—matched the failure patterns captured both in the experimental recordings and in the model outputs. Early findings suggest the potential to develop essential design criteria that could guide engineers and practitioners in adopting 3D printing technologies in seismically active regions. The broader goal of the research is to contribute to improved seismic resilience and to foster sustainable innovation in the construction sector.

Fig. 6. (a) Cracking mechanism observed in the 3D-printed housing unit during the final seismic test; (b) an interior view of the crack in the dry joint at the top of the opening.

Conclusions

This work presented a sneak peek at the first shake table test of a full-scale 3D-printed housing unit. The study covered all phases of the investigation: from preliminary material and wall characterization, to parametric modelling and building uniut optimisation, to the execution of a large-scale shake table test at the SOFSI Lab. The experimental campaign confirmed the ability of 3D-printed structures to withstand a significant number of dynamic excitations with limited damage, while also revealing critical failure mechanisms associated with dry joints and prefabricated elements such as lintels. The recorded data enabled the validation of a numerical model developed in OpenSees, which accurately reproduced both global response and localized damage. This outcome confirms the reliability of the proposed digital workflow combining parametric design and performance-based simulation. Most importantly, this test campaign lays the foundation for future research in the field of seismic design of 3D-printed buildings. The large quantity of high-quality experimental data collected will be further analyzed to define new seismic design criteria tailored specifically to the unique features of additive manufacturing, such as anisotropy, interface behavior, and print-layer geometry. These results represent a significant step toward the development of dedicated design guidelines and code provisions for 3D-printed construction. The knowledge generated through this project will serve as a reference for engineers, researchers, and regulatory bodies involved in shaping the future of construction in seismic regions.

Acknowledgements

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