Shake Table Testing of Masonry-Infilled RC Frames with Flexible Joints for Seismic-Resilient Structural Performance

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Abstract. Masonry infills are critical components of reinforced concrete (RC) frame structures that often sustain significant damage, even during moderate earthquakes. Rubber joints have emerged as a promising solution to enhance their performance. However, further experimental and numerical investigations are required to assess their effectiveness under realistic seismic loading conditions. To address this gap, the H2020 EU-funded FLEJOI project (FLExible JOInts for seismic-resilient design of masonry-infilled RC frames) was conducted within the ERIES framework. As part of this initiative, two identical RC brick-infilled prototypes were constructed at the Dynamic Testing Laboratory of IZIIS in North Macedonia, each incorporating a distinct rubber joint system. One system was designed to reduce the infill stiffness while introducing damping capabilities, whereas the other aimed to fully decouple the infills from the frame. The prototypes underwent a series of shaking table tests to evaluate their seismic performance. A comprehensive set of sensors was installed to monitor key parameters influencing the seismic response of the structures, infills, and joints. This paper presents an overview of the experimental testing campaign and the data generated. These data will support the calibration and validation of numerical models and serve as a foundation for further studies on the seismic performance of RC frames with masonry infills and rubber joint systems.

Keywords: Shake table tests · Masonry infills · Rubber joints · RC frame

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1 Introduction

Reinforced concrete (RC) buildings are among the most common types of construction worldwide. These buildings typically include masonry infill walls, which provide a significant contribution to the building performance [1] and often represent the most vulnerable components of the structure. Infill walls can fail even under low-magnitude earthquakes, resulting in significant direct impacts (such as human casualties and repair costs) and indirect losses (such as downtime). The financial impact of damage to infill walls can be substantial, with studies showing that the cost of repairing infill damage often exceeds the cost of repairing structural components [2]. This underscores the critical need for innovative technologies that can enhance the seismic performance and resilience of buildings while minimizing the consequences of seismic events.

A considerable amount of research has focused on developing technologies to protect masonry infill walls from seismic damage. One common approach involves strengthening the infill walls using various techniques [3, 4]. However, these methods often require strengthening adjacent frame components, making them potentially cost-prohibitive. Recently, alternative strategies have emerged, focusing on the design of engineered infill walls with improved behavior, minimizing their interaction with the structural frame. Many of these strategies aim to increase the infill panel's flexibility and/or isolate it from the surrounding frame using flexible or sliding joints. Among the joint systems developed in the EU-funded INSYSME project [5], rubber joints have proven to be particularly effective due to their adaptable stiffness and energy dissipation properties, which can be customized through the selection of suitable materials and designs.

Experimental tests conducted mainly within the INSYSME project have demonstrated the feasibility of using rubber joints. However, further testing and numerical studies are needed to confirm their effectiveness under more realistic loading conditions and to advance the understanding of their design principles. To address this gap, the H2020 EU-funded project FLExible JOInts for seismic-resilient design of masonry-infilled RC frames (FLEJOI) was launched under the framework of Engineering Research Infrastructures for European Synergies (ERIES) [6, 7]. The goal of the ERIES-FLEJOI project is to evaluate the effectiveness of two different flexible rubber joint systems designed to protect masonry infills and improve the seismic performance of RC buildings.

The first system under investigation is a compliant joint system, consisting of horizontal joints (developed by TARRC - Tun Abdul Razak Research Centre) integrated into the panel, along with vertical rubber joints placed between the panel and the frame columns [8–11]. The second system, known as INODIS, is a decoupling system with sliding/flexible joints located at the interface between the infill panel and the frame [12–14]. The effectiveness of both systems for infill protection was previously demonstrated under quasi-static loading conditions. The primary objective of this study is to assess the performance of these systems under dynamic loading using shaking table tests.

To this end, two identical infilled RC frame prototypes were constructed at the Dynamic Testing Laboratory of IZIIS in North Macedonia, each equipped with a different rubber joint system. Both prototypes underwent a series of shaking table tests. This article outlines the experimental campaign, providing key information on the properties of the tested prototypes, their construction, instrumentation, testing procedures, and data collected from various sensors. The test results will be used to calibrate and validate numerical models and will support further research on the seismic performance of RC frames with infills and rubber joints.

2 Experimental Test Models

Two three-dimensional, single-story, one-bay RC frames with masonry infills and rubber joints were constructed and tested at IZIIS Dynamic testing laboratory. These RC frames are identical to those used in the INMASPOL Project, which evaluated the seismic performance of deformable polyurethane joints for infill protection [15]. Each frame measures 2.7 m × 2.7 m in both orthogonal directions, with extended footing beams and a cantilever slab, with a total height of 3.3 m, as shown in Fig. 1. The structural system consists of four square columns (20 cm × 20 cm) and 20 cm wide beams embedded in the 20 cm thick top slab. The columns are reinforced with eight longitudinal bars with 10 mm diameter and double stirrups with 8 mm diameter, while the beams are reinforced with eight longitudinal bars with 10 mm diameter and single stirrups with 8 mm diameter. Both have 5.5 cm concrete covers.

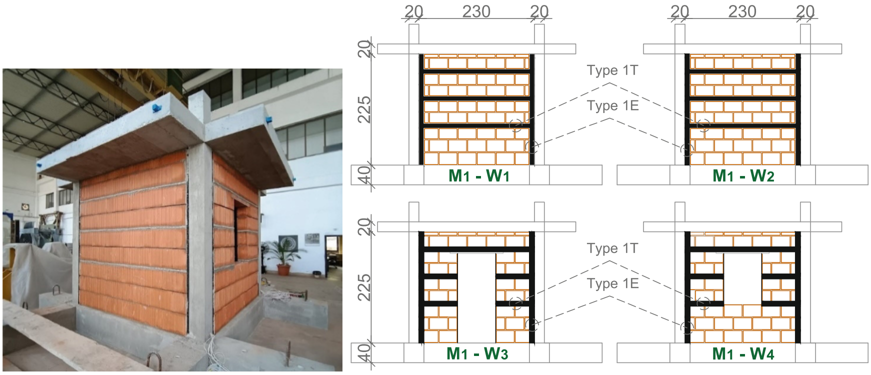

Fig. 1. Model 1 as built (left), wall properties (right).

The first model (Fig. 1) features horizontal rubber strips that divide the panel into four subpanels (Type 1T joints) and vertical rubber strips located between the masonry infill and the RC columns (Type 1E joints). This joint system is designed as a compliant and dissipative mechanism, enhancing the flexibility of the infill walls while also providing energy dissipation capacity. The second model (Fig. 2) incorporates sliding/flexible strips placed along all four sides of the masonry infill (Type 2 joints). This system fully decouples the infill from the RC frame in the in-plane direction while maintaining out-of-plane restraint. To simulate additional mass, both models were loaded with 18 400 kg steel ingots (total 7200 kg).

Figure 3 illustrates the Type 1 and Type 2 joint system. The horizontal joints (Type 1T) were developed by TARRC and consist of a special high-damping rubber compound tailored for this project. The vertical elastomeric joints (Type 1E) were made from recycled rubber provided by Isolgomma and placed at the interface between the masonry infill and the frame columns. The horizontal joints were positioned between two mortar layers, while the vertical joints were adhered to the columns using a silicone adhesive sealant. The Type 2 joint system, designed by Regupol, consists of rubber strips that isolate the infill from the frame, thereby enabling in-plane decoupling. The in-plane separation is achieved through rubber strips with low compressive and shear stiffness, while out-of-plane restraint is ensured by a specialized arrangement of the rubber strips. These strips are divided into three sections: the two outer parts are connected to the infill wall, and the central strip is adhered to the columns. The connection to the top beam (slab) and foundation beam is similarly divided into three segments, with the middle elastomer flanked by two outer elastomers separated by a plastic sheet profile (sliding surface), allowing unrestricted movement between the infill and the RC frame.

The masonry infills were built using Porotherm 20 bricks by Wienerberger, with dimensions 37.5 × 20 × 23.8 cm. The bricks were bonded with 1.5 cm-thick horizontal mortar layers, while the vertical joints remained dry.

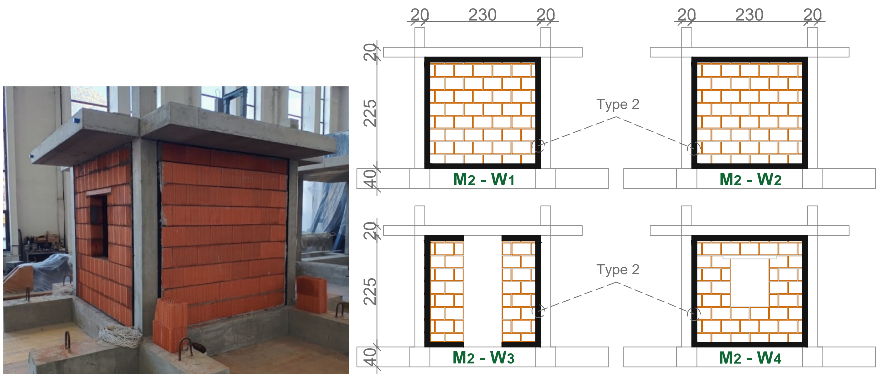

Fig. 2. Model 2 as built (left), wall properties (right).

Fig. 3. Joints Type 1T and 1E (left) and Type 2 (right).

3 Testing Methodology

The experimental test activities included characterization tests of the constituent materials and components and shake table tests of both models to evaluate their dynamic behavior and seismic response to specific earthquake time histories.

During the model construction phase, samples were collected for independent material and component characterization tests. Four concrete cubes (150 × 150 × 150 mm) were cast during the column construction for both models and tested following the EN 12390–3 standard [16]. The average 28-day compressive strength was 37.37 MPa. Similarly, three mortar cubes of the same dimensions, prepared from the ready-mix mortar used in the infill walls of Model 1, underwent compression tests. The average 28-day compressive strength was 20.5 MPa. For reinforcement, ten samples of 10 mm diameter longitudinal steel bars were tested as per the EN ISO 15630–1 standard [17]. The mean yield strength (f_y) was 578.3 MPa, while the ultimate tensile strength (f_u) averaged 667.3 MPa. Additionally, two brick samples were tested under compression along the rib direction, with thin mortar layers applied between them and the loading plates. Their ultimate load capacities were measured at 435.9 kN and 477.2 kN.

The shaking table tests were conducted in two phases for each model. The comprehensive list of all tests conducted on both models is provided in Table 1 and Table 2. In Phase 1, fully infilled walls were subjected to in-plane loading, aligned with the excitation direction, while walls with openings experienced out-of-plane loading, perpendicular to the excitation. In Phase 2, the models were rotated 90 degrees around the vertical axis, reversing the loading conditions—walls with openings were tested in-plane, whereas fully infilled walls were loaded out-of-plane. The testing program began with low-intensity white noise excitation on the shake table to determine the system's dynamic characteristics. Subsequently, ground motion excitations were applied with progressively increasing intensity levels.

For Model 1, the selected earthquake records included Adana 1998 (M_w 6.3), Erzincan 1992 (M_w 6.6), and Umbria 2016 (M_w 6.2). Model 2 was subjected to the Adana 1998 earthquake (M_w 6.3) and a synthetically generated earthquake based on the Eurocode 8 spectra for Soil Type C. The shaking table tests were performed with increasing intensities of such ground motion records (*e.g.,* 10%, 50%, 100%, as indicated in Table 1 and Table 2). White noise tests were performed at specific points during the seismic sequence to evaluate the variability of the change in dynamic properties. Additionally, modal hammer impact tests were performed before and after the shake table tests to assess changes in the out-of-plane dynamic characteristics of the infill walls using Experimental Modal Analysis (EMA). However, the results of the EMA are out of the scope of this paper.

Table 1. List of performed tests for Model 1 - Phase 1 and 2.

Model 1 – Phase 1			Model 1 – Phase 2	
Test	Type of test		Test	Type of test
1–6	EMA, Impact hammer - wall properties		1–3	EMA Impact hammer - wall properties
7	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g		4	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g
8	Seismic, Adana EQ 10% [0.055g]		5	Seismic, Adana EQ 10% [0.062g]
9	Seismic, Erzincan EQ 10% [0.065g]		6	Seismic, Erzincan EQ 10% [0.065g]
10	Seismic, Erzincan EQ 20% [0.128g]		7	Seismic, Erzincan EQ 20% [0.128g]
11	Seismic, Adana EQ 20% [0.123g]		8	Seismic, Adana EQ 20% [0.132g]
12	Seismic, Adana EQ 50% [0.332g]		9	Seismic, Adana EQ 50% [0.314g]
13	Seismic, Erzincan EQ 40% [0.268g]		10	Seismic, Erzincan EQ 40% [0.267g]
14	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g		11	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g
15–17	EMA, Impact hammer - wall properties		12–14	EMA, Impact hammer - wall properties
18	Seismic, Adana EQ 100% [0.675g]		15	Seismic, Adana EQ 100% [0.728g]
19	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g		16	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g
20	Seismic, Umbria EQ 100% [0.617g]		17	Seismic, Umbria EQ 80% [0.51g]
			18	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g
			19–21	EMA, Impact hammer - wall properties

Table 2. List of performed tests for Model 2 - Phase 1 and 2.

Model 2 – Phase 1			Model 2 – Phase 2	
Test	Type of test		Test	Type of test
1–3	EMA, Impact hammer - wall properties		1	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g
4	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g		2	Seismic, Adana EQ 10% [0.06g]
5	Seismic, Adana EQ 10% [0.065g]		3	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g
6	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g		4	Seismic, Adana EQ 30% [0.17g]
7	Seismic, Adana EQ 20% [0.122g]		5	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g
8	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g		6	Seismic, Adana EQ 40% [0.25g]
9	Seismic, Gener. EQ 30% [0.181g]		7	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g
10	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g		8	Seismic, Adana EQ 50% [0.3g]
11	Seismic, Gener. EQ 60% [0.322g]		9	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g
12	EMA, ST - wh. Noise 1 - 45 Hz, 0.01g		10–12	EMA, Impact hammer - wall properties
13–15	EMA, Impact hammer - wall properties			

3.1 Testing and Instrumentation Setup

The dynamic testing at IZIIS was conducted using a 5.0 m × 5.0 m shake table with five degrees of freedom, supported by two lateral and four vertical MTS hydraulic pistons, and controlled by an MTS Digital Controller 469D. The modal impact hammer used for these tests was the PCB Piezotronics model 086D20, equipped with the softest grey tip.

The instrumentation of the tested models included accelerometers (ACC) from PCB Piezotronics for measuring accelerations, linear potentiometers (LP) from Microepsilon WDS for recording total and relative displacements, linear variable differential transformers (LVDT) from MacroSensors DC750 for displacement measurements, and strain gauges (SG) from KYOWA KFG for capturing strain data. Their exact placement on each model is illustrated in Fig. 4 for Model 1 – Phase 1; Fig. 5 for Model 1 – Phase 2; Fig. 6 for Model 2 – Phase 1; and Fig. 7 for Model 2 – Phase 2. The data acquisition process was carried out using a National Instruments PXI modular system.

Additionally, a digital image correlation (DIC) system was utilized to measure displacement and strain fields on one side of each model, specifically the side subjected to in-plane loading. For Model 1, DIC measurements were taken during selected earthquake runs, whereas for Model 2, all runs were recorded (Fig. 8).

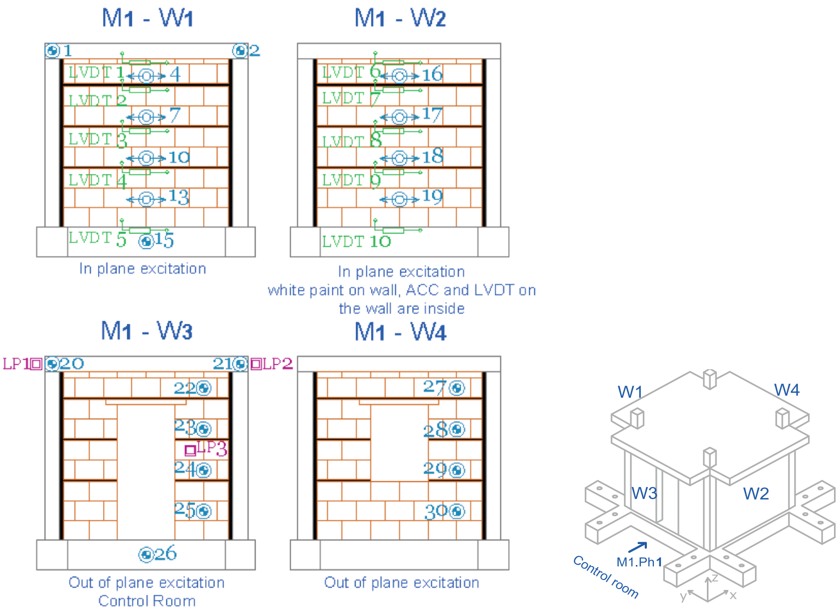

Fig. 4. Instrumentation setup Model 1 – Phase 1.

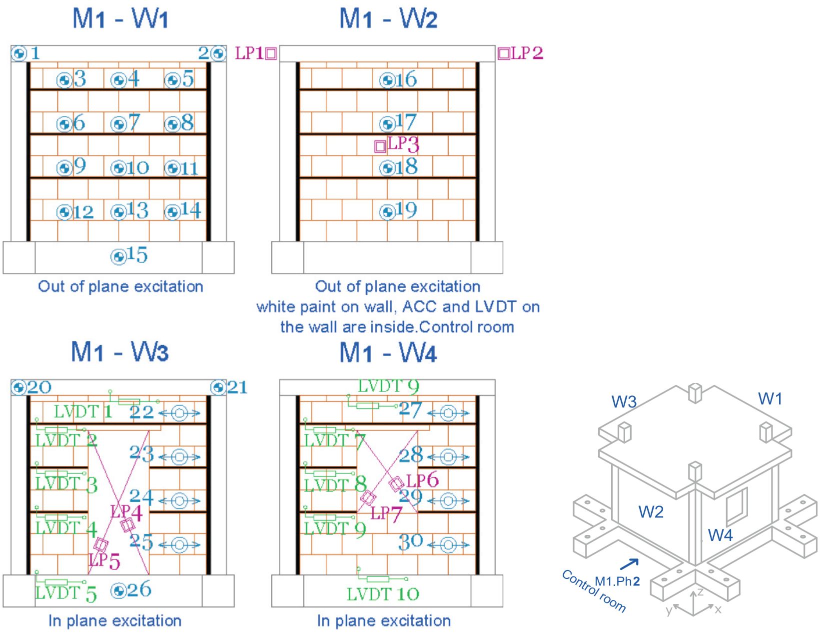

Fig. 5. Instrumentation setup Model 1 – Phase 2.

4 Results and Discussion

This section briefly illustrates the results of the shake table tests conducted on the two models. In particular, Figs. 9, 10, 11, 12 and 13 show the time histories of the accelerations recorded in correspondence of the shaking table and of the top slab under selected seismic inputs. Table 3 summarises the main results observed under the same seismic inputs in terms of peak inter-storey drift ratios (IDR) and top accelerations. It is noteworthy that both prototypes were able to sustain these inputs without experiencing any damage. The first prototype withstood very strong earthquake inputs, corresponding to peak ground accelerations (PGAs) up to 0.728g, without experiencing significant drifts and absolute accelerations, thanks to the stiffness and damping contribution of the Type 1 rubber joint system. A very low peak IDR of 0.69% was attained in phase 1 (full infills subjected to in-plane loading), and a larger one (1.98%) in phase 2, due to the reduced contribution of the infills with opening to the response.

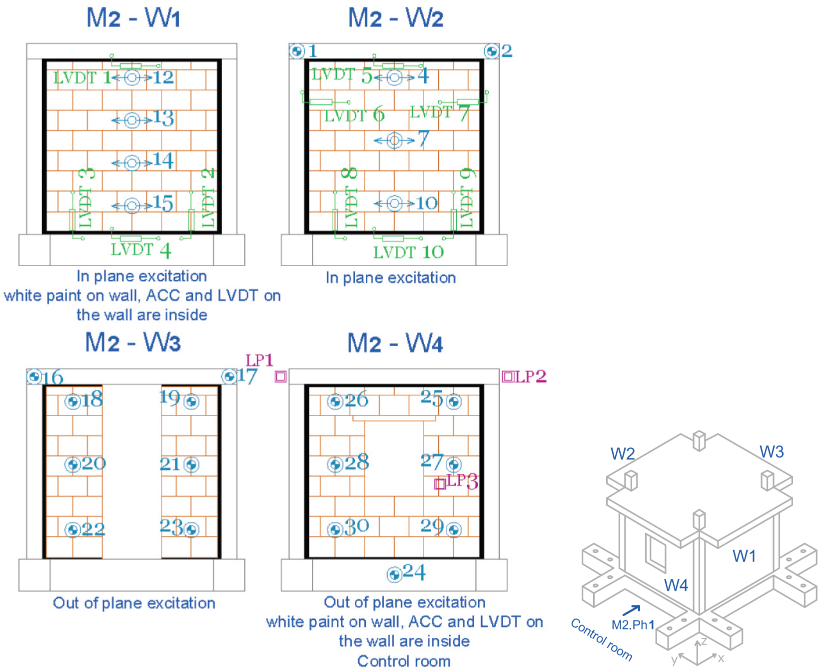

Fig. 6. Instrumentation setup Model 2 – Phase 1.

In testing the second prototype, seismic inputs only up to 0.322g were imposed, because stronger inputs would have resulted in significant damage to the RC frame (while still guaranteeing no damage in the isolated infill panel). The peak IDRs were respectively 2.20% and 2.91% in phase 1 and phase 2.

Figure 13 illustrates some of the results from the digital image correlation (DIC) analysis performed on the videos recorded during some tests. The localization of principal strains in the rubber joints (at the panel-frame interface and also between the masonry subpanels in Model 1) confirms that the joints performed as expected.

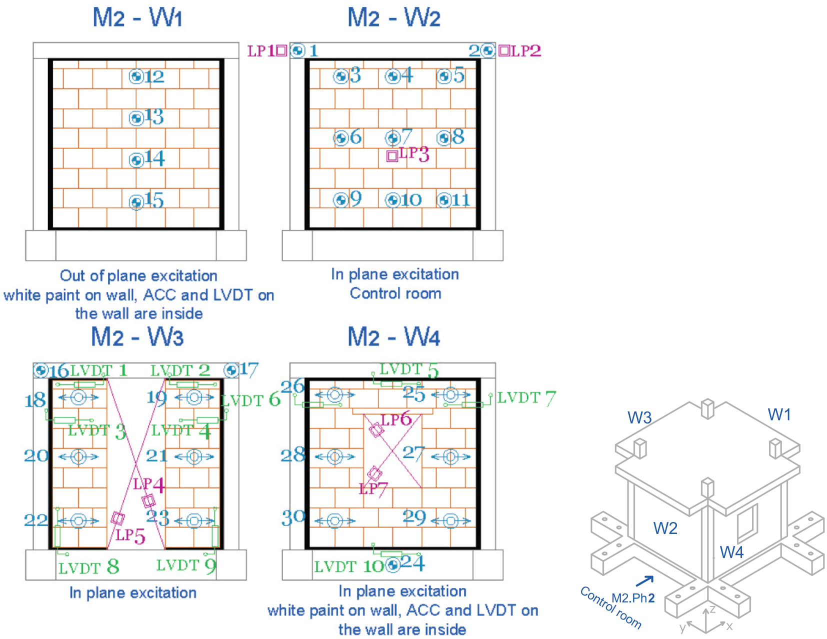

Fig. 7. Instrumentation setup Model 2 – Phase 2.

Fig. 8. DIC setup Model 1 and Model 2.

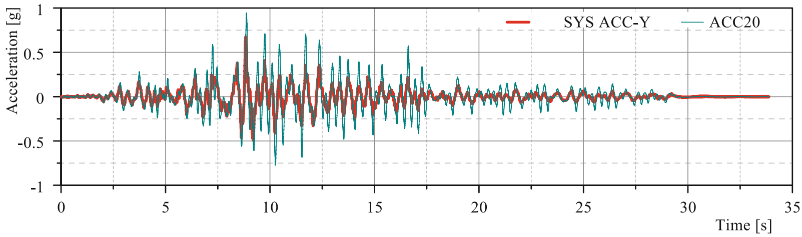

Fig. 9. Model 1 - Phase 1, Adana earthquake 100% [0.675g].

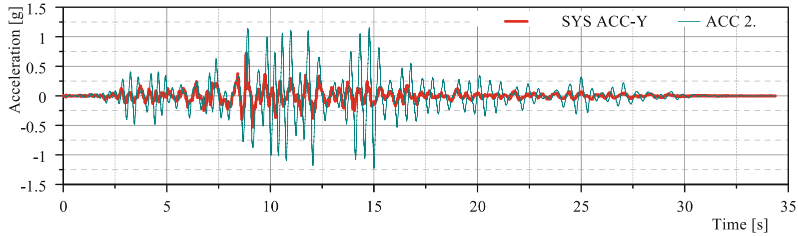

Fig. 10. Model 1 - Phase 2, Adana earthquake 100% [0.728g].

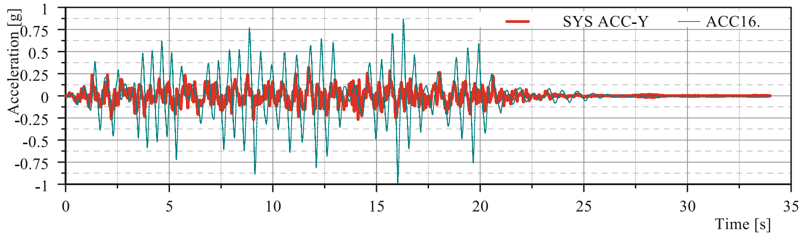

Fig. 11. Model 2 - Phase 1, Generated earthquake 60% [0.322g].

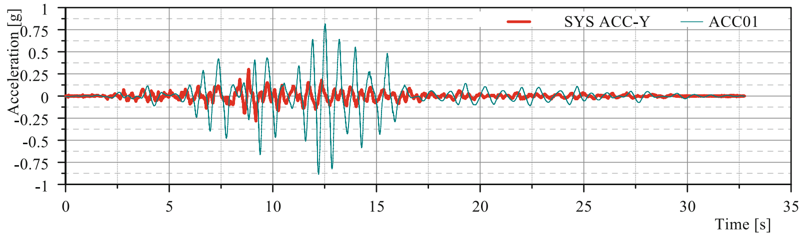

Fig. 12. Model 2 - Phase 2, Adana earthquake 50% [0.300g].

Table 3. Summary of main response parameters for Models 1 and 2 under selected record.

Input/output	Model 1 Phase 1	Model 1 Phase 2	Model 2 Phase 1	Model 2 Phase 2
Input record	Adana 100%	Adana 100%	Generated 60%	Adana 50%
PGA	0.675g	0.73g	0.32g	0.30g
Inter-storey drift	0.69%	1.98%	2.20%	2.91%
Top acceleration	0.93g	1.23g	0.98g	0.89g

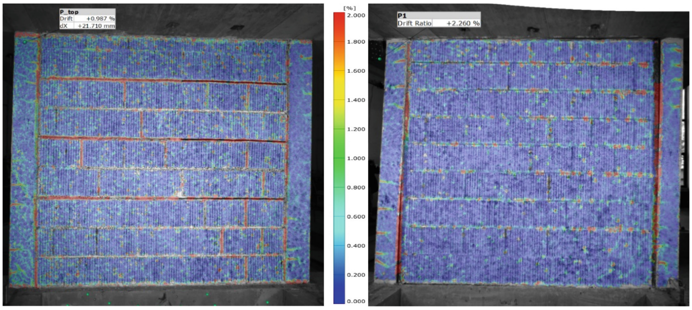

Fig. 13. Model 1 - Phase 1 - Umbria EQ 100%, left and Model 2 - Phase 1 Generated EQ 60%, right. Major strain plot by DIC. Red denotes higher strains, blue denotes lower strains.

5 Conclusions

This paper has presented the experimental campaign conducted as part of the ERIES-FLEJOI project and some of the preliminary results. The project's primary objective is to further validate the effectiveness of rubber joint technology in reducing the seismic vulnerability of masonry infills and enhancing the earthquake performance of masonry-infilled reinforced concrete (RC) frames. As part of this research, two full-scale RC frame prototypes were tested using the shaking table facility at IZIIS. The first prototype featured a 'compliant system,' incorporating horizontal and vertical rubber joints within the masonry infill to improve flexibility and energy dissipation. The second prototype utilized a 'decoupling system,' where rubber joints were placed only at the interface between the infill and the surrounding RC frame to minimise stress transfer and prevent damage concentration. The results from the shake table tests provided strong evidence of the effectiveness of rubber joint technology. The findings demonstrated that RC frames with these innovative joint systems exhibited significantly improved seismic resilience, with reduced damage and enhanced energy dissipation, even under severe earthquake excitations. These outcomes highlight the potential of rubber joint solutions in earthquake-resistant RC structures, offering a promising approach to mitigating seismic risks in masonry-infilled frames.

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