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NUMERICAL INVESTIGATION OF THE SEISMIC RESPONSE OF AN UNREINFORCED MASONRY RESIDENTIAL BUILDING HIT BY ZAGREB EARTHQUAKE IN 2020

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Abstract

Despite the moderate intensity, the series of earthquakes in Zagreb (2020) caused significant social and economic impacts and damage to the built environment. The city of Zagreb has a moderate seismic hazard, but it is highly exposed (densely populated) and the built environment is quite vulnerable (age of structures, low maintenance, illegal construction, and numerous reconstructions). The greatest damage was sustained by unreinforced masonry (URM) buildings for residential use in the historic downtown of Zagreb built in the late 19th and early 20th centuries. In addition to material deterioration, the transformations suffered by these buildings – often without being driven by anti-seismic standards - may increase their seismic vulnerability. Within this context, the main goal of the paper is to analyse the seismic response of an unreinforced masonry residential building selected to be representative of the existing historical masonry heritage in Zagreb downtown, built in the early twentieth century. The URM building has a rectangular floor plan and a 4-story elevation. Numerical investigations are carried out by using the equivalent frame method implemented in Tremuri software and by performing both nonlinear static and dynamic analyses. Since it is part of a typical residential block in the centre of Zagreb, the case study was analysed in two configurations: considering it isolated from the rest of the aggregate and sandwiched between two adjacent structural units. The results reported in this paper must be intended as a preliminary step for addressing future developments oriented to deepen the effects of interaction with adjacent buildings varying the position of the structure into the aggregate as well as those due to possible transformations and strengthening interventions.

Keywords: unreinforced masonry structures, equivalent frame model, nonlinear static and dynamic analyses, seismic vulnerability

1. Introduction

On 22 March 2020, at 6.24 a.m., the Zagreb city area was hit by an earthquake of magnitude 5.5 (ML) and intensity VII according to the EMS-98 scale (Figure 1). The epicentre was approximately 7 km north-east of the centre of Zagreb, in Podsljeme district, at a depth of 10 km. This seismic event caused significant damage to existing structures in the city of Zagreb, in fact approximately 25,000 buildings were damaged [1]. The city centre, known as Lower Town, is mainly composed of traditional masonry structures arranged in aggregate conditions. The potential high seismic vulnerability of masonry structures to both in-plane and out-of-plane actions has been already proved by many seismic events [2]–[4]. Moreover, when they are included in a building aggregate, the vulnerability factors may potentially increase because the structural units that compose it date back to different periods, present different construction techniques, different degrees of maintenance and different structural systems. All these factors contribute to a great structural variability that makes very difficult the behavioural analysis of this structural typology as well as to define at priori if the "aggregate effect" (meant as the effect played by the boundary conditions provided by adjacent structural unit with respect to the same structure analyses as "isolated") may be beneficial or detrimental. Following the earthquake that struck the city

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of Zagreb on 22 March 2020, numerous inspections were conducted to assess the damage. The assessment was carried out regarding the usability criteria to ensure the safety of the residents and to prevent further human casualties. Non structural damage in the form of local separation and decay of the plaster was registered very often. In plane mechanisms for bearing walls rarely appeared, mostly it was just for partition walls. On the other hand, out of plane mechanisms appeared most often due to the disconnection between the structures and the wooden beam floors. The damage in Zagreb is described in [5] and [6]. The database about buildings was obtained by collecting documentation from archives, performing visual inspections and gaining access to post-earthquake assessments.

In this paper, we chose to analyse a building in Zagreb's Lower Town, belonging to a building aggregate, of which we have information on mechanical and geometric parameters, but also information on post-earthquake damage. The examined building was modelled both by considering it isolated from the rest of the building aggregate and by modelling the two buildings adjacent to it. Two events were considered in order to conduct the non-linear dynamic analyses and thus obtain the damage level of the building: the Zagreb earthquake (22 March 2020), measured at a distance of 10 km from the case study, and the earthquake that struck the city of Petrinja (29 December 2020), 50 km from the city of Zagreb where the building is located (Figure 2). Numerical investigations are carried out by using the equivalent frame method implemented in Tremuri software and by performing both nonlinear static and dynamic analyses. Only the in-plane response is considered at this stage of the research, consistently also with the actual response of the examined building. Since the structure is part of a typical residential block, it was considered both as isolated and in aggregate through two adjacent structural units; however, in this paper, only a possible position within the aggregate has been considered and by assuming only one of possible interlocking conditions among adjacent units. In fact, the purpose of this study is preparatory research for a wider parametric evaluation of the seismic response of typical buildings in the city of Zagreb constructed in the late 19th and early 20th centuries.

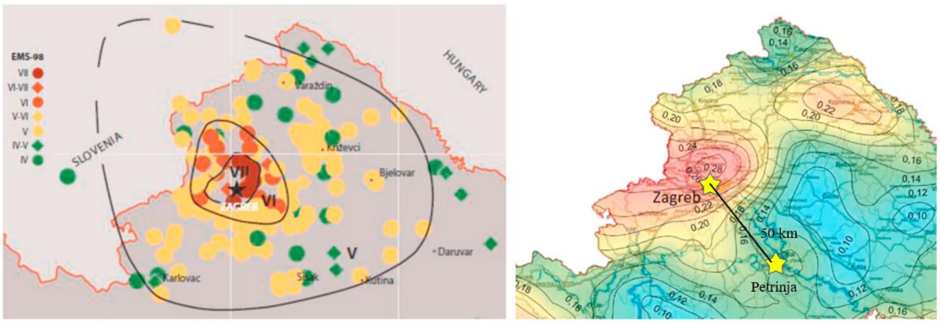

Figure 1. Preliminary Earthquake Intensity Map (left) from the 22nd of March 2020, at 6:24 (CET) compared with expected peak ground accelerations (right) for a return period of 475 years [7]

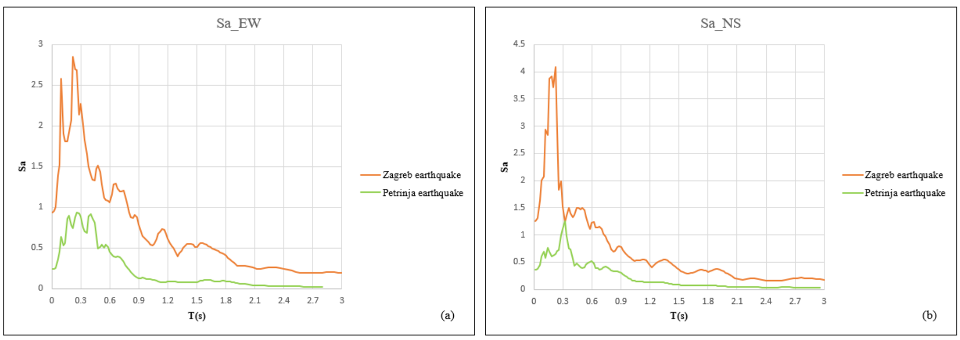

Figure 2. Response spectra of the Zagreb earthquake (22 March 2020) and the Petrinja earthquake (29 December 2020) in EW direction (a) and NS direction (b)

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2. Features of the building stock in Zagreb and selected case study

The case study presented here is a typical residential building in the city of Zagreb belonging to a building aggregate with a very recurring shape in the centre of Zagreb - Lower Town.

In the Zagreb Lower Town, most of the buildings are constructed in aggregates, built after the 1880 earthquake. These buildings of unreinforced masonry are built in relatively large aggregates or 'row aggregates' and were built until about 1920. There are at least 5 buildings on each side of the aggregate, and the side length of the aggregates ranges from 50 meters to as much as 150 meters. Although they do not have a common wall, they are built side by side without gaps or seismic dilation. It should be noted that the horizontal structures are mostly made of the timber joists with a rubble filling and rest on the longitudinal walls parallel to the street. Other horizontal structures used are shallow masonry vaults with steel beams or solid concrete slabs, usually used above the basement. The longitudinal direction is generally the stronger bearing direction for horizontal actions, while the weaker direction is the transverse direction, which usually includes only the staircase walls and perimeter transverse walls that are not adequately connected to the floor structures [8].

The case study building shown in Figure 3 was built in 1908 and is one of the representative examples of a building typology built in long row aggregates in the Lower Town in the centre of Zagreb. It has a basement, ground floor, 3 floors and an attic. The floor plan dimensions are 19.20 x 12.35 m, the height of the basement is 3 m, ground and upper floors are 3.85 m and the attic is 4.2 m, while the total height of the building is 22.70 m. The load- bearing walls are made of solid bricks with a thickness of 30, 45, 60 and 75 cm without any confinement RC elements. The thickness of the walls decreases with the height of the building. The basement floor structures are shallow vaults with steel beams and the upper floors are timber joists between planks with rubble material between the beams. The joist is oriented transversely and rest on the facade and the central longitudinal walls.

The building was modelled both in the configuration in which it is isolated from the rest of the aggregate and in the case in which the two adjacent buildings are also present Figure 3. For simplicity's sake, as we did not have detailed information, we chose to model the neighbouring buildings with the same footprint, geometric and mechanical characteristics as the building under study. The mechanical characteristics assumed in both models are as follows: $E = 1400$ Mpa, shear modulus $G = 462$ Mpa, compressive strength $f_m = 2.89$ Mpa, tensile strength $\tau_0 = 0.09$ Mpa and density of 18 kN/m^3.

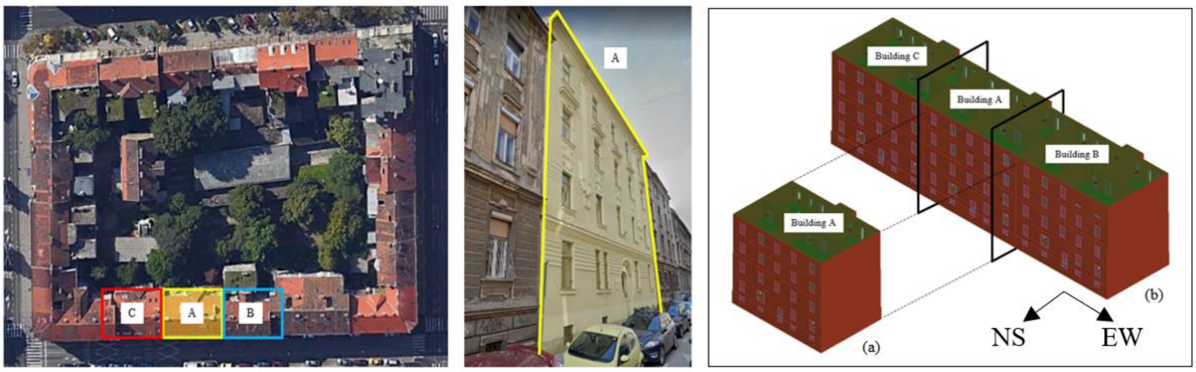

Figure 3. On the left - typical aggregate of the Lower Town of Zagreb to which the case study belongs; in the centre - elevation of the structural unit under study; a on the right - 3Muri model of the case study building in both isolated and aggregate configuration

In this paper, reference will be made to the east-west (EW) direction, i.e., the direction of development of the aggregate under consideration, and the north-south (NS) direction perpendicular to it.

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3. Modelling criteria

The structural model of both configurations was performed according to the equivalent frame (EF) modelling strategy implemented in Tremuri software [9], which considers masonry walls as a combination of piers (vertical elements) and spandrels (horizontal elements), connected by rigid areas (nodes).

The model of the isolated building and the model of the building connected to adjacent structures are shown in Figure 3. In the models, the non-linear response of the panels is described by a constitutive law based on a phenomenological approach and a piecewise-linear beam model (i.e. NLBEAM) proposed in Figure 4 [10]. The NLBEAM is characterised by a constitutive law describing the non-linear response up to very severe damage levels (DL, from 1 to 5) through the definition of a relationship between the drift value $\delta_{E,i}$ and the corresponding fraction of the residual shear strength $\beta_{E,i}$ upon reaching the *i*-th DL differentiated for piers, spandrels, bending and shear behaviour Table 1. Please refer to [11] and [12] for further details on the formulation of NLBEAM and its potential in executing NDA. Diaphragms are modelled as orthotropic membrane elements. The moduli of elasticity describe the connection degree between diaphragms and vertical wall parallel to its reference direction, whereas the shear modulus represents the shear stiffness of the floor and the horizontal force transfer among the walls.

Table 1. Main parameters adopted in the non linear analyses

	SHEAR								
	dirft Θ [%]			*residual strength β [%]*		*hysteretic response*			
	DL3	DL4	DL5	DL3	DL4	c1	c2	c3	
PIERS	0.47	0.73	0.94	0.6	0.2	0.8	0.8	0	
SPANDRELS	0	1	1.5	0.6	0.6	0.2	0	0.3	
	FLEXURAL								
	dirft Θ [%]			*residual strength β [%]*		*hysteretic response*			
	DL3	DL4	DL5	DL3	DL4	c1	c2	c3	c4
PIERS	0.6	0.9	1.2	1	0.85	0.9	0.8	0.6	0.5
SPANDRELS	0.6	1	1.5	1	0.6	0.2	0	0.3	0.8

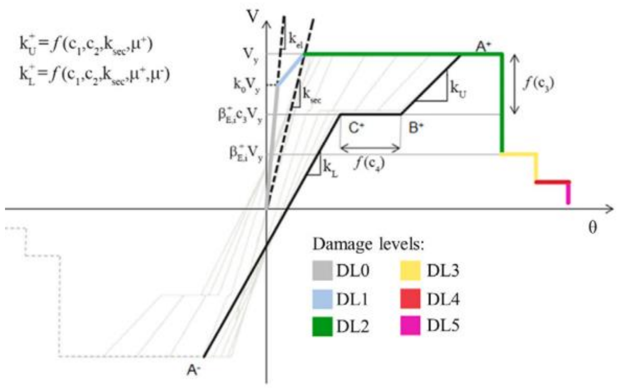

Figure 4. Piecewise-linear constitutive law and hysteretic response of the model

To explicitly account for the interaction effect between adjacent units, in the aggregate configuration, the procedure proposed in [12] has been implemented. Thus, the units were modelled separately to each other by introducing a finite-length gap represents the semi-length of the shared wall and, then, connected by elastic truss elements (sectional area of 0.00164 m2 and elastic modulus E of 210,000 MPa with null tensile behaviour) as well as orthotropic membranes (thickness of 0.05 m, E = 39,420 MPa, G = 13,112 MPa) to simulate possible transversal sliding between structural units (*Figure 5*).

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Struts, on the other hand, allow for the modelling of the ability of structural units to spread apart while avoiding the interpenetration of elements.

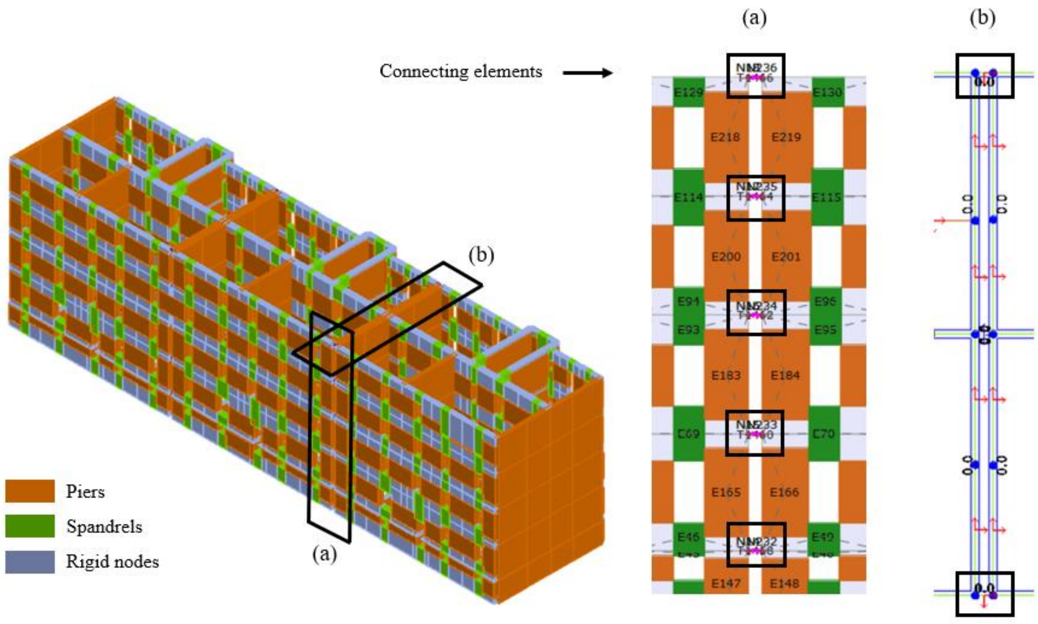

Figure 5. (a) Tremuri model of the aggregate configuration - (b) detail of the model elevation at the connection between two adjacent structural units and detail of the elastc truss elements with null tensile behavior and of the fictious floor connecting two adjacent units.

4. Main outcomes of numerical analyses

Modal analyses were conducted on the 3D equivalent frame model in order to obtain the dynamic behaviour of the building in the two configurations by identifying the main vibration modes, the corresponding periods and the participating mass.
Based on the results of the modal analysis for the isolated case (IB) and those for the aggregate case (AGG), it is possible to estimate the damping coefficients of the Rayleigh model needed for the NDAs [13]. These coefficients were found to be $\alpha = 0.364243\ s^{-1}$ and $\beta = 0.002196\ s^{-1}$ for the isolated configuration (IS) case and $\alpha = 0.377368\ s^{-1}$ e $\beta = 0.00212\ s^{-1}$ for the configuration in aggregate (AGG) case.

Table 2. Period, participant mass in x-direction (EW) and y-direction (NS) for both the isolated and aggregate case

	Isolated configuration			***Aggregate configuration***		
Mode	Period (T)	M_x [%]	M_y [%]	Period (T)	M_x [%]	M_y [%]
1	0.345	0.003	68.269	0.333	0.001	70.417
2	0.295	24.353	0.167	0.321	0.728	0.483
3	0.242	43.072	0.076	0.275	0.012	0.003
4	0.17	0.085	0.170	0.259	57.902	0.018

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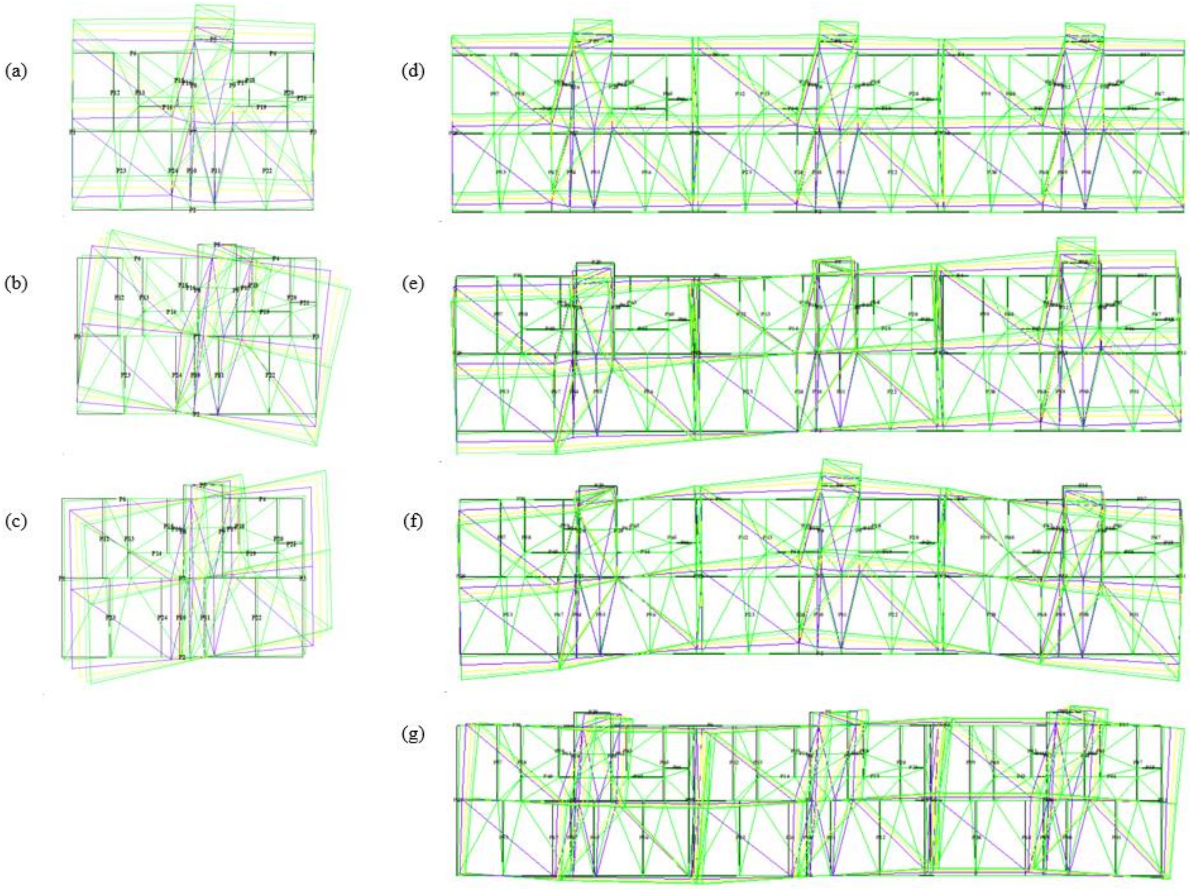

Figure 6. Modal forms. (a, b, c) first, second and third modal forms of the isolated configuration. (d, e, f, g) first, second, third and fourth modal forms of the configuration in aggregate.

Figure 7 and Figure 8 show the comparison between the pushover curves of the two configurations in terms of base shear-average last plane displacement (V-d). NSAs were performed for X and Y direction, both in the positive and negative directions, considering uniform load distributions proportional to the masses. NSAs were performed to estimate the capacity in terms of displacement in order to compare the results obtained from the NDAs. The NDAs were obtained by simultaneously applying the two components of the accelerogram along the X and Y direction. The Petrinja earthquake signal was reprocessed to take into account the variation of macroseismic intensity with distance from the epicentre [14]. The vertical component of the accelerograms was not considered.

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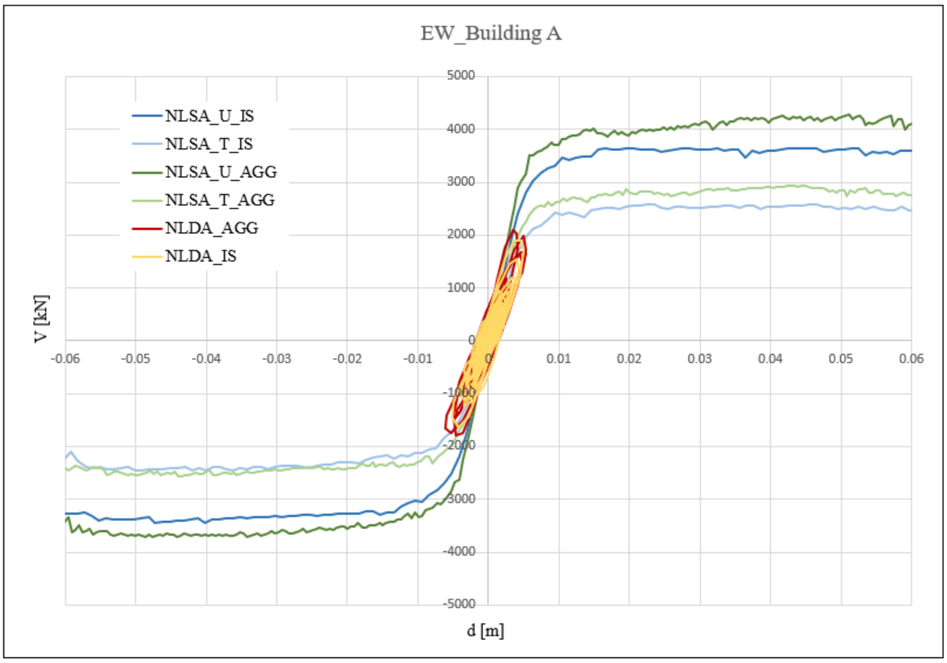

Figure 7. Overlapping of the non-linear static analyses (NLSAs) and non-linear dynamic analyses (NLDAs) of building A in both the isolated and aggregate case for the EW direction, i.e. that of the development of the aggregate.

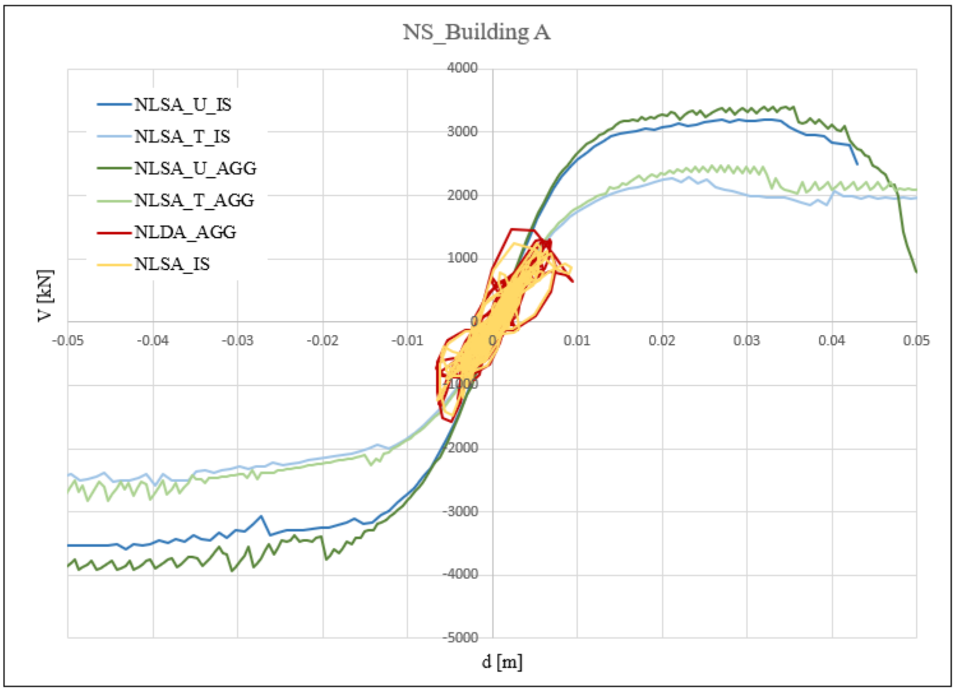

Figure 8. Overlapping of the non-linear static analyses (NLSAs) and non-linear dynamic analyses (NLDAs) of building A in both the isolated and aggregate case for the NS direction, i.e. the direction perpendicular to the development of the aggregate.

In order to synthetically interpret the data from the NLDAs, the multiscale approach originally proposed in [15], and then further developed in [16] and in [17] was adopted to assign a specitfic damage level to the building compatible with the EMS98 scale (i.e. from DL1 ti DL5) [18]. In particular, the adopted multiscale approach is associated to the wall scale. It is based on the extension of the "minimum DL"

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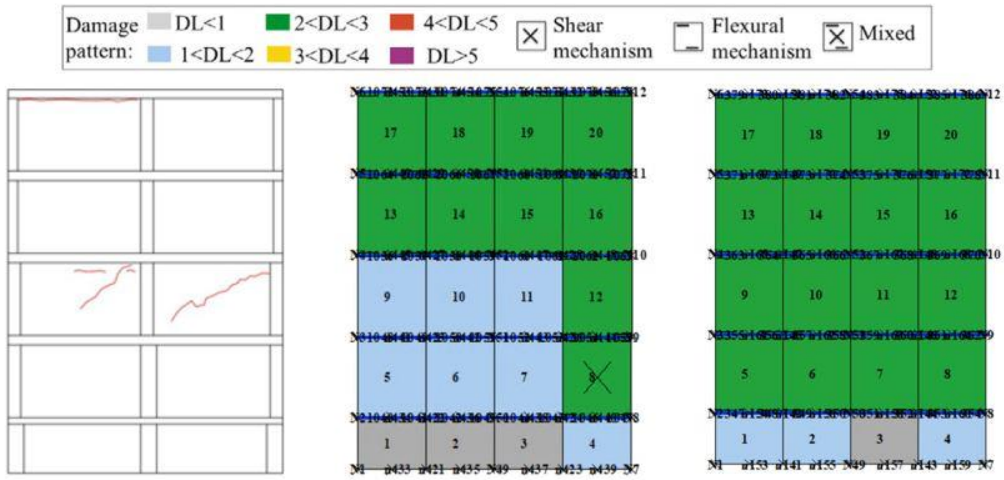
that occurred to piers ($DL_{min,P}$), weighted on their shear stress contribution. The concept of the "minimum DL" was originally proposed in [19] to replace the adoption of the interstorey drift thresholds at the wall scale, as previously adopted in [15]; in particular, such a proposal assigns a damage level to the wall based on the minimum damage level attained by all the elements of a certain floor [18].

Table 3. Average damage level of walls in both directions

	Event	***Isolated configuration***		***Aggregate configuration***	
		Dir X	**Dir Y**	**Dir X**	**Dir Y**
Level Damage	Zagreb earthquake	**0**	1	**0**	**1**
	Petrinja earthquake	**0**	**0**	**0**	**0**
Cum DL wall DL1	Zagreb earthquake	16.79	52.51	7.26	51.73
	Petrinja earthquake	2.71	1.56	7.26	5.81
Cum DL wall DL2	Zagreb earthquake	4.76	28.72	4.47	5.82
	Petrinja earthquake	0	0	0	5.81

As Table 2 shows, the Y component of the earthquake does not lead to changes in modal behaviour between the isolated and the aggregate configuration. In that direction, the participating mass remains more or less the same. What does vary is what happens in the X direction. The second mode is a mode in X with a participating mass of 24.35% in the isolated configuration and which is reduced to 1.73% in the aggregate configuration, so the earthquake does not excite this torsional mode in the aggregate configuration. In the isolated configuration the torsions are instead activated by the second and third modes of vibration. In the aggregate configuration, on the other hand, only the first and fourth modes do not torsionally operate. This explains what is shown in the table, i.e. the fact that in the Y direction, in the isolated configuration, the walls are damaged more than in the aggregate configuration, since they are more stressed by the torsional component.



(a) (b) (c)

Figure 9. Wall in NS direction of building A. (a) Schematisation of actual damage - (b) damage obtained with the NLDA considering the aggregate configuration - (c) damage obtained with the NLDA considering the isolated configuration

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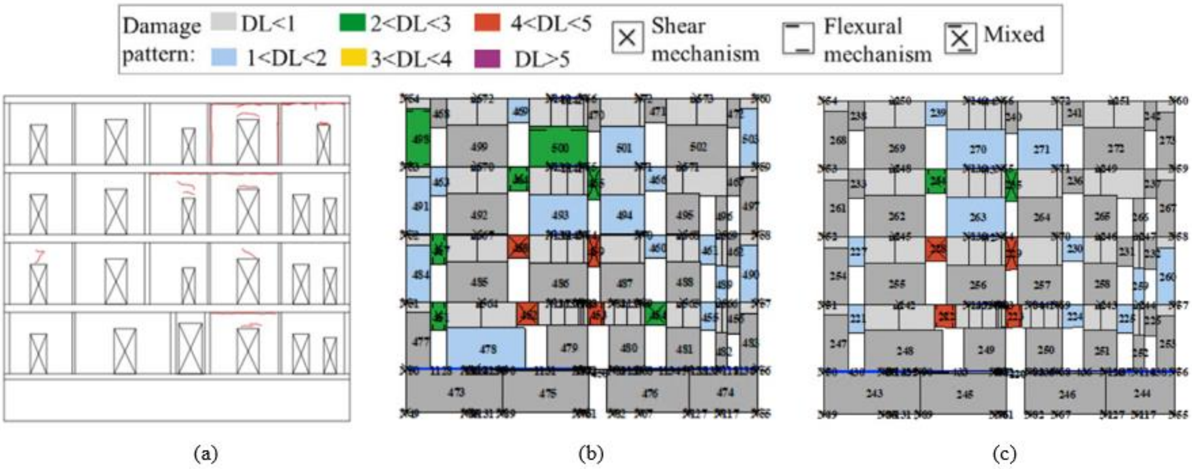

Figure 10. Wall in EW direction of building A. (a) Schematisation of actual damage - (b) damage obtained with the NLDA considering the aggregate configuration - (c) damage obtained with the NLDA considering the isolated configuration

The simulated damage in X direction appears more consistent with the actual one in the case of AGG configuration. Moreover, the overall damage level is substantially in agreement with that observed.

3. Conclusions

The study presented here proposes an evaluation of the seismic behaviour of an unreinforced masonry building located in an aggregate with a typical configuration in the historic centre of Zagreb Lower Town. The building in question was analysed both in the case in which it is considered isolated from the rest of the aggregate, and in the case in which it is included in the aggregate by considering the influence of the two buildings adjacent to it. The aggregate model showed a lower level than that of isolated building and generally gives a better description of the actual damage to the building.

This work is intended as a preparatory study for a broader analysis of the behaviour of the entire structural aggregate and the effect of different position of the structural units within it. In fact, it should be noted that buildings in a row aggregate during the Zagreb earthquake proved to be more resistant, as minor to moderate damage was found on these buildings. Buildings that are taller than the adjacent buildings proved to be more vulnerable, with significant damage occurring on the 'freestanding' floors above the adjacent buildings. On the other hand, it is common for a row unit to be interrupted for some reason (demolition of an adjacent building, opening of parking lots and access roads, etc.). Such buildings, which do not have an adjacent building on one side, sustained severe damage in some cases. Clearly, further research is needed on the properties of the connection between the buildings, as well as on the position within the aggregate and on the relative geometric and material properties of the adjacent buildings, to allow better calibration of the numerical models and realistic damage assessment. In fact, in the analysis presented here, the presence of orthotropic membranes of far from negligible stiffness has been assumed between the units. This assumption may not be always representative of reality, thus a future development will consist in carrying out sensitivity analyses on the various types of connections between adjacent units and also, if possible, performing in-situ dynamic identification investigations to validate assumptions made in numerical models.

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Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
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