SIMULATING TO EVALUATE, MANAGE AND IMPROVE EARTHQUAKE RESILIENCE IN HISTORICAL CITY CENTERS: APPLICATION TO AN EMERGENCY SIMULATION-BASED METHOD TO THE HISTORIC CENTRE OF COIMBRA

G. Bernardini [1], T. M. Ferreira [2, *]

[1] Department of Construction, Civil Engineering and Architecture, Università Politecnica delle Marche, via di Brecce Bianche 60131 Ancona, Italy - g.bernardini@univpm.it
[2] ISISE, Institute of Science and Innovation for Bio-Sustainability (IB-S), Department of Civil Engineering, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal - tmferreira@civil.uminho.pt

Commission II - WG II/8

KEY WORDS: Evacuation simulation, Earthquake risk assessment, Behavioural design, Earthquake mitigation solutions

ABSTRACT:

Earthquake resilience in historical centres is significantly affected by interactions between the built environment, defined as the network of building heritage and surrounding open spaces, and hosted population. Building vulnerability, earthquake-induced effects and population's exposure mainly influence the first emergency phases. In the immediate post-earthquake evacuation conditions, people should leave their position to gather in assembly points where first responders can rescue them. Thus, joint analyses of building damage and evacuation flows along the evacuation paths become essential to determine the risk levels for the urban scenario and to provide risk-mitigation solutions. This paper tries to reach this goal by adopting a holistic simulation-based approach. A simplified vulnerability assessment method is used to evaluate the seismic performance of masonry façade walls and to estimate debris depth on outdoor spaces. An existing earthquake pedestrians' evacuation simulator is used to evaluate the probable pedestrians' choices in such evacuation post-earthquake damage scenarios. Then, risk indexes, combining damage assessment and evacuation results, are provided to quantify evacuation safety and to outline critical conditions in the urban layout. Finally, the impact resulting from the consideration of a series of resilience-increasing strategies is simulated and discussed from the proposed risk indexes. A part of the historic centre of Coimbra, Portugal, one of the oldest and most relevant Portuguese cities, is used in this work as a pilot case study. Results show how the method could be used by Local Authorities and Civil Protection Bodies to outline, analyse and coordinate resilience-increasing strategies at the urban scale.

1. INTRODUCTION

Urban resilience is generally understood as the ability of an exposed urban area to prepare, respond and recover from the effects of multi-hazard threats, being directly connected to mitigation, preparedness, disaster, response, recovery and reconstruction disaster risk management phases (Coaffee, 2008).

Increasing the urban resilience in case of Sudden Onset Disasters means improving the possibility to face unpredictable and quick-arising conditions by limiting the threads for the exposed population. In this context, disasters like earthquake are one of the most critical ones. According to previous researches (Gavarini, 2001; Indirli, 2009), one of the most influencing elements in urban resilience while considering the hosted inhabitants' safety is represented by the interactions between people and post-event environment in urban scenarios. In fact, the streets networks and open spaces (Bernardini et al., 2020; French et al., 2019) play a crucial role in earthquake emergency planning. During the evacuation phase, some urban areas can become wholly or partially inaccessible due to the deposition of debris resulting from collapsed or heavily damaged buildings (Aguado et al., 2019), hindering the evacuation process of residents, as well as the possibility of first responders to properly access the damaged area (Italian technical commission for seismic micro-zoning, 2014).

This is a paramount issue in historical city centres, where the configuration of urban fabric (i.e. spatial complexity and compactness) is combined with a significant built environment vulnerability (Aguado et al., 2018; Santarelli et al., 2018) and a potentially high density of residents and tourists (who are not familiar with the urban spaces, with the evacuation procedure and the emergency plan) (Sato et al., 2014).

In this sense, understanding urban and buildings vulnerabilities is a crucial step towards the development of more efficient and effective risk mitigation strategies (Bernardini et al., 2020; French et al., 2019). Such strategies can be mainly related to interventions on buildings that are significant since they can limit the effects of damages on the urban paths, thus improving the rescuers' access actions as well as the movement of people towards the assembly areas. However, the effort to implement such strategies should be coordinated and widespread by involving the collaboration of public and private stakeholders. As a complementary strategy, the definition of emergency plans (e.g. assembly areas location) is essential to face the problems connected to the damage state in the historical urban fabric.

To this end, replicating the human behaviours and the evacuation flows along the urban paths, and towards the assembly areas, can evidence how the hosted population can safely react in evacuation conditions because of the surrounding Built Environment and its damage (Bernardini et al., 2019; Lin et al., 2020).

---

* Corresponding author

Simulation-based approaches can be used to evaluate such aspects from an urban resilience-increasing perspective, and then to improve safety by proposing risk-mitigation interventions on Building Heritage (i.e. those interfering with the emergency and evacuation processes) and on the planning of emergency management actions by first responders (D'Orazio et al., 2014). Such methods should adopt a holistic perspective, so as to jointly consider both the building damage on the street/open spaces (to take into account the effects due to the building heritage vulnerability and the earthquake severity) and the human motion over the urban spaces, and results should describe the effective system conditions through quantitative risk indexes. This paper aims at applying such perspective to earthquake emergency planning, by using a holistic simulation-based approach to compare the effectiveness of risk-mitigation strategies based on different levels of building interventions and emergency plan actions in respect to the current probable disaster conditions. The application to a significant case study allows demonstrating the capabilities of the proposed approach and the related tools.

2. METHODOLOGY

The holistic methodology proposed in this work is composed of three main parts: (i) a vulnerability assessment of the buildings, based on an index-based method (Aguado et al., 2018), as described in Section 2.1; (ii) a building debris estimation based on (Santarelli et al., 2018), as described in Section 2.2; and (iii) an evacuation assessment through the use of a microscopic simulation model (D'Orazio et al., 2014) and by combining vulnerability-related and exposure-related factors into risk indexes, as described in Section 2.3.

The methodology is applied to a significant case study, that is a part of the historic centre of Coimbra, Portugal, as described in Section 2.4.

The effectiveness of two risk-reduction strategies has been compared with respect to the current state condition of the historical centre by using the proposed risk indexes.

2.1 Building vulnerability assessment

The seismic vulnerability assessment method used in this work – usually classified as a hybrid technique (Ferreira et al., 2019) - is inspired in the original vulnerability index formulation proposed by Benedetti and Petrini (1984).

In Ferreira, Vicente, and Varum (2014), the authors present an adaptation of the original formulation in order to assess masonry façade walls. More recently, further calibration of the method was proposed and discussed by the same author in Ferreira et al. (2017).

According to this method, individual vulnerability is measured using an index obtained as the weighted sum of 13 evaluation parameters (presented in Table 1), each one of which related to 4 classes, C_{vi}, of increasing vulnerability: A, B, C, and D. The relative importance of each parameter is also taken into account through the weighting factor p_i, as in Equation 1.

$$I_{vf}^* = \sum_{i=1}^{13} C_{vi} p_i \qquad (1)$$

For ease of use, the vulnerability index is usually normalized to range between 0 and 100; the lower its value, the lower the seismic vulnerability of the façade wall.

Parameters	Class, C_{vi}				Weight
	A	B	C	D	p_i
Geometry of the façade	0	5	20	50	0.50
Maximum slenderness	0	5	20	50	0.50
Area of openings	0	5	20	50	0.50
Misalignment of openings	0	5	20	50	0.50
Interaction between contiguous façades	0	5	20	50	0.25
Quality of materials	0	5	20	50	2.00
State of conservation	0	5	20	50	2.00
Replacement of original flooring system	0	5	20	50	0.25
Connection to orthogonal walls	0	5	20	50	2.00
Connection to horizontal diaphragms	0	5	20	50	0.50
Impulsive nature of the roofing system	0	5	20	50	2.00
Elements connected to the façade	0	5	20	50	0.50
Improving elements	0	5	20	50	-2.00

Table 1. Vulnerability index, associated classes and weights.

2.2 Building debris estimation

An experimental method to define the debris depths on streets and open spaces due to building heritage (i.e. masonry structures) damage is adopted (Santarelli et al., 2018). For each building, the debris depth d [m] on a facing space with a given width w [m] is calculated according to Equation 2. It depends on the building vulnerability I_{vf}^* (Section 2.1), the ratio R_M between the earthquake Moment Magnitude and the maximum expected value according to the World seismic history (9.5), the ratio R_S between the building height and facing space. In case $d>w$, the facing space is considered as obstructed by debris.

$$V^* = I_{vf}^* \cdot R_M \cdot R_s ; d = \min(2.131 \cdot V^* \cdot w; w) \qquad (2)$$

2.3 Evacuation assessment and risk indexes

The adopted evacuation simulation model used is the experimental-based microscopic one developed and validated by D'Orazio et al. (2014). According to Agent-Based Modelling criteria, it assigns damage rules to the Built Environment and evacuation rules to each simulated individual. The damage rules are those described in Section 2.2.

The evacuation rules are mainly characterized by three tasks: (i) the individuals try to move towards assembly areas (pre-defined in the emergency plan) (Italian technical commission for seismic micro-zoning, 2014); (ii) in case an assembly area cannot be reached (e.g. because of path blockage), they spontaneously gather in the nearest visible, widest and less damaged area of the urban fabric (e.g. crossroads, squares); and (iii) the local velocity depends on attractive (i.e. attraction between individuals in the same group) and repulsive (i.e. repulsion to avoid collision with debris and other evacuees) forces according to the Social Force Model, by trying to maximizing the speed at 2.1±0.5m/s (Gaussian distribution from experimental analysis of real earthquakes). Additional variations in standard behaviours can be represented (e.g. individuals' speed or path choice) according to a random force parameter in the model. The complete discussion of the model is offered by D'Orazio et al. (2014).

Risk indexes are defined to match behavioural simulation and damage assessment results so as to mainly evidence the related interactions in reference to fundamental evacuation rules (Points 1 and 2). In particular, the attention is focused on the risk evaluation of gathering areas defined in the emergency management plan since their system plays a pivotal role in the evacuation process, by guaranteeing the possibility to host the evacuees in safe conditions and to reach the rescuers' support in the immediate aftermath.

For such areas, and each considered scenario, the following risk indexes are discussed:

1. evacuation curve (evacuees [pp] reaching an assembly area over the time [s]);
2. the overall evacuation flow at the assembly area F [pp], the percentage value in respect to the whole simulated population J [%];
3. the absolute occupancy rate O_r [-] of the assembly area. The value is calculated as the ratio between the critical area per person a_i leading to physical contacts between evacuees (which is about $0.3m^2$ (Klüpfel and Meyer-König, 2014)) and the division between the free-of-debris assembly area by F. This value is capped by 1. When $O_r = 1$, overcrowding conditions can appear (Klüpfel, Meyer-König, 2014);
4. the path tortuosity T [-] which expresses the difference between the minimum linear path length and the average evacuees' path length ($T \geq 1$);
5. the risk index for the paths leading to the assembly areas P [-], as expressed in Equation 3, as a function of the average evacuation flows F_{path} along the path [pp], the debris area A_d and the overall area of each path A_{path} [m^2].

$$P = \sum_{paths}\left[\min\left(\frac{A_{d,path} + F_{path} \cdot a_i}{A_{path}};1\right) \cdot \left(\frac{F_{path}}{F}\right)\right] \qquad (3)$$

Finally, Equation 4 expresses the risk index for each assembly area R, which depends on the variables above. R can vary from 0 to 1.73 since all the factors in Equation 4 are variables from 0 to 1 (critical conditions).

O_r highlights criticalities inside the assembly area: the higher O_r, the higher the possibility of physical contacts between the evacuees while waiting for rescuers. T and P evidence the criticalities along the path on two different layers, both leading the possible evacuation time increase. T expresses microscopic interactions between the evacuees and the surrounding built environment: the higher T, the higher the possibility for evacuees to suffer from interactions in local motion due to other individuals and debris. P points out the overall effects on debris and path dimension together with the evacuees' flows.

$$R = \sqrt{O_r{}^2 + (T-1)^2 + P^2} \qquad (4)$$

Additional analysis of the position of individuals who spontaneously gather out of the assembly areas are performed to evidence:

1. how the open spaces can be used in the evacuation process;
2. the possibility that some assembly areas can be removed;
3. if some spontaneous gathering area can be introduced in the pre-defined emergency plan to rescue people where they are placed;
4. after the application of risk mitigation strategies, if some similarities appear in the different considered scenarios.
5.

2.4 Case study description and considered scenarios

The historic centre of Coimbra, in Portugal, is used in this work as a case study. Coimbra is one of the oldest Portuguese cities and is the home of the University of Coimbra, one of the world's first universities. Besides the University of Coimbra-Alta and Sofia zone, classified in 2013 as a UNESCO World Heritage Site (Vicente et al., 2015), the historical city centre of Coimbra is also a remarkable cultural and touristic point of

the city. The historic centre of Coimbra is characterised by a complex and irregular urban fabric, with historic unreinforced masonry buildings that face narrow streets and winding alleys, thus being representative of many European historical city centres (Figure 1). The majority of the buildings do not actually possess any seismic design or detailing and are therefore extremely vulnerable to a seismic event, even of a low to moderate intensity (Aguado et al., 2018).

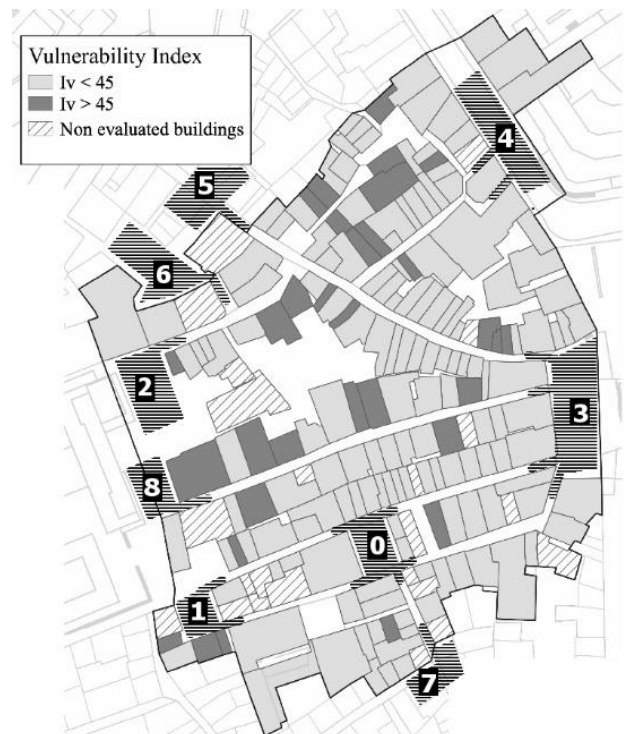Figure 1. View to a typological inner street of the historic centre of Coimbra.

Figure 2. Urban layout involved in the simulation, by outlining the building vulnerability and the position of assembly areas and related main accesses (dashed areas) defined in the emergency plan of the SCENARIO A.

All the considered scenarios involve: (1) an earthquake magnitude of 5.6 Mw, which is the maximum historical local magnitude; (2) total simulated population of 1200 individuals, homogeneously distributed, according to an in-situ survey. In all the cases, the simulation time was posed to 350s, which is the time to go across the overall urban layout (maximum path length 350m) by moving at 1m/s ('not-emergency' walking conditions).

Three scenarios are compared according to the risk indexes defined in Section 2.3. The SCENARIO A considers the current scenario, in which the evacuees try to gather in the considered assembly areas identified according to general guidelines on emergency planning for earthquakes (Italian technical commission for seismic micro-zoning, 2014). In particular, Figure 2 shows how they are selected between the widest squares in the urban layout (so as to reduce the possible interferences with the building debris), and the areas that are directly placed outside of the borders of the historical centre part, being directly accessible by the main urban streets. The SCENARIO B involved the re-organization of the assembly areas (in number and position in the urban layout) so as to consider only those that effectively attracts evacuees and the areas in which the evacuees spontaneously gather according to the SCENARIO A. In particular, the assembly areas gathering less than 10% of the arrived evacuees are either deleted or merged together (if located nearby). In SCENARIO C, the re-organization of assembly areas from the SCENARIO B is combined with vulnerability-reduction interventions in critical building heritage (in respect to the main evacuees' flows towards the assembly areas), thus reducing the impact of damages on the open facing spaces.

3. RESULTS

The section firstly offers an overview of the simulations related to the current conditions of the historical city centres (SCENARIO A), which results are used to trace the risk-mitigation strategies for SCENARIO B and SCENARIO C. The second part of the section involves the comparisons of the three conditions to evidence how the proposed strategies can mitigate the overall risk.

3.1 Results and criticalities for risk-mitigation strategies definition

SCENARIO A is characterized by the arrival of 766 individuals to an assembly area, which is about 64% of the overall hosted population. About 95% of the individuals arrive at the assembly areas in around 200s, as shown in Figure 6. The last part of the evacuation time is mainly characterized by latecomers, which speed is reduced by the presence of debris or significant evacuation flows over the path. In general terms, the related phenomena can be considered as marginal for the whole evacuation process, i.e. because of subtleties in behavioural simulations (Shiwakoti et al., 2008) which does not affect the overall trend.

Figure 3 evidences how the evacuees underuse some assembly areas pre-defined in the emergency plan. The numerical values for J are shown in Table 1. This phenomenon is mainly due to the damages caused by buildings on the open spaces can hinder the evacuation motion towards them (also compare to P values in Table 1). As a result, the evacuees spontaneously gather towards nearest widest and free-of-debris areas such as crossroads and squares inside the urban fabric, as well as in front of less vulnerable buildings, as shown by full black areas in Figure 3. According to such general results, it is important to evidence how some assembly areas:

1. placed nearby could be merged to collect the gathering individuals jointly and to support the first responders' actions by concentrating their intervention in the urban fabric (i.e. compare assembly areas 2 and 8);
2. are underused because placed at the border of the urban fabric and neighbouring areas in which people spontaneously gather (i.e. compare to assembly areas 5). In this case, a new assembly area can be positioned inside the urban fabric nearby;

3. placed at the border of the urban fabric can be suppressed because of their proximity with other areas (i.e. compare assembly area 7 close to 0, and 6 close to 2).
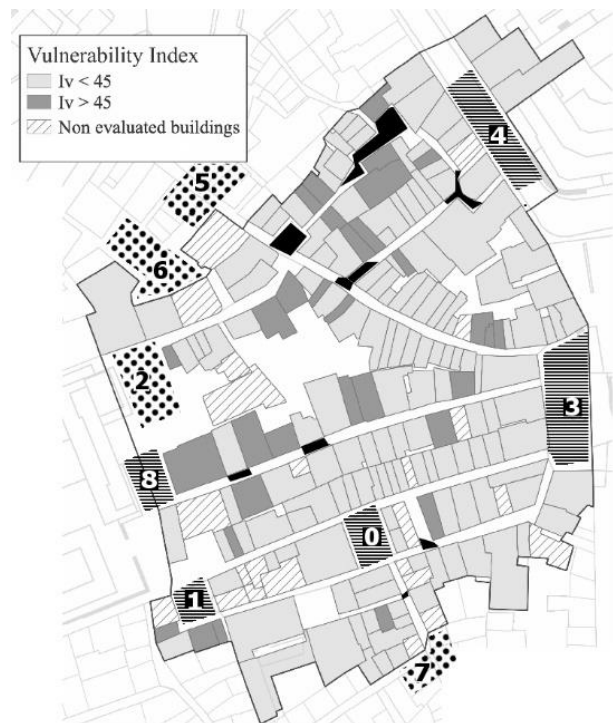

Figure 3. Open spaces usage at the end of the simulation in the SCENARIO A, by evidencing: assembly areas used by more than the 10% of arrived evacuees (dashed areas) and less than the 10% (dotted areas); main areas of spontaneous gathering (full black areas).
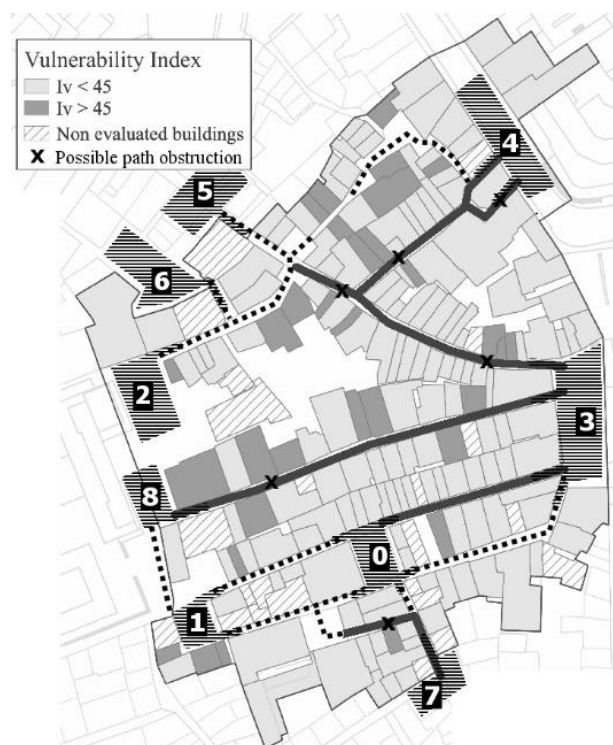

Figure 4. Debris state along the paths (dashed line: Apath free-of-debris >50%; full grey lines: Apath free-of-debris <50%) and possible path obstruction due to debris.

Furthermore, the most critical areas in terms of building damage and debris along the open spaces seem to be the longest road, e.g. those connecting areas 5 to 3, 8 to 3, and 5 to 4. Along these paths, the paths can be significantly reduced or even obstructed by debris, as shown by Figure 4.

On such bases, Figure 5 shows the implementation of the new assembly areas in SCENARIO B. The new placement of the assembly areas ensures a homogenous position of them in respect to the urban fabric, especially in consideration of the longest paths in the historical centre. The risk-mitigation along the path connecting assembly areas 2 and 3 could be increased by the seismic retrofit interventions of the facing buildings, in the SCENARIO C. From this point of view, Figure 4 also shows the buildings retrofitted in SCENARIO C. In particular, the building retrofit actions can involve the improvement of the: (i) wall-to-wall connections through effectively tying walls together with steel tie-rods; (ii) wall-to-floor connections employing steel angle brackets anchored to walls through steel connectors and anchor plates; (iii) structural performance of the roofing system by introducing steel tie-rods underneath the ceiling joists.
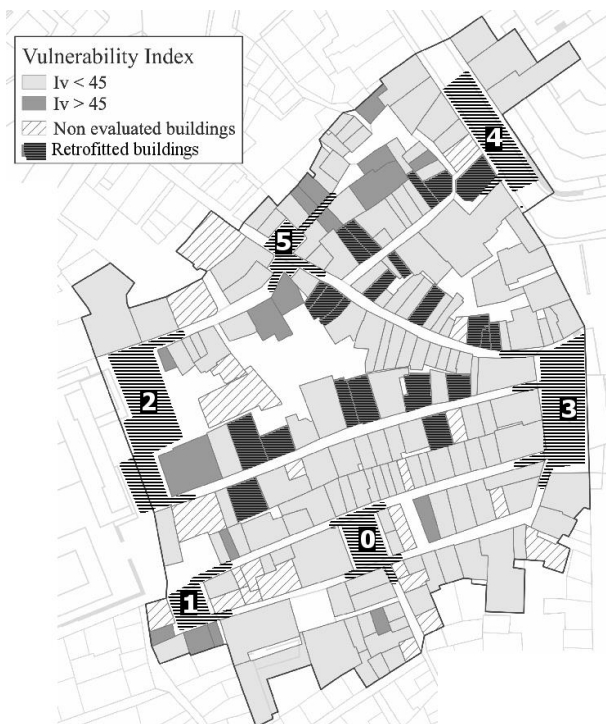

Figure 5. Urban layout involved in SCENARIO C, by outlining the position of assembly areas (and related access) defined according to SCENARIO B (dashed areas) and the retrofitted buildings.

3.2 Comparisons between the three scenarios

Figure 6 compares the evacuation curves for the three scenarios. In general terms, the number of arrived evacuees is similar in the three scenarios. SCENARIO B has a lower number of arrived evacuees (-8% in respect to SCENARIO A) mainly because of the minor number of safe areas. SCENARIO C limits the reduction of the number of arrived evacuees (-3% in respect to SCENARIO A) thanking the limitation of building debris along the paths. Similar data are related to both the overall simulation time and 95% of arrived individuals. Such results demonstrate how the reduction of the assembly areas does not generally affect the overall result, thus not increasing the risk for the exposed population.

Table 2 compares the simulation data by focusing on the risk indexes defined in Section 3.1
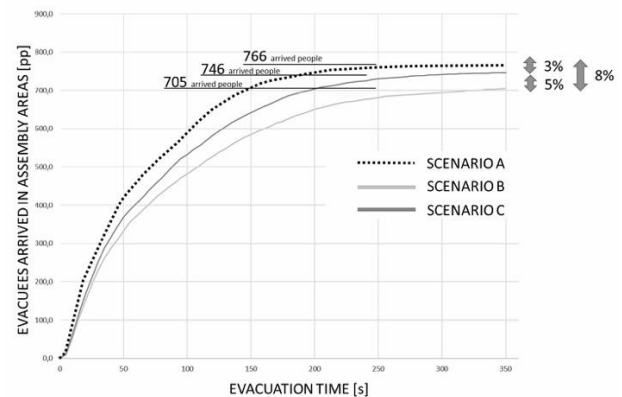

Figure 6. Evacuation curve comparison in the three scenarios.

Concerning the usage of the assembly areas, in SCENARIO B and SCENARIO C, all of them are used by more than the 10% of the evacuees, thus limiting the underuse of such areas and increasing the rescuers' access concentration on a limited number of targets (J values in Table 2).

In each case, the assembly areas do not suffer from overcrowding conditions, since O_r is always lower than 1. The values increase when J grows, while the free-of-debris surface in the assembly areas is the same (also in SCENARIO C).

T values are similar in the three scenarios but can increase for the main assembly areas in which the building retrofit interventions allows evacuees to move towards the final evacuation target. This is the case of the assembly area 3. On the contrary, the T values for the assembly areas 2 and 4 increases because of the re-organization of the assembly areas positions within the urban fabric implies a growth in J. A similar effect is shown by the P values, that generally decrease in SCENARIO B and SCENARIO C.

RI	S	Assembly areas								
		0	1	2	3	4	5	6	7	8
J	A	0.18	0.11	0.06	0.15	0.10	0.09	0.06	0.07	0.13
	B	0.27	0.10	0.20	0.14	0.23	0.09	-	-	-
	C	0.26	0.12	0.20	0.11	0.20	0.11	-	-	-
O_r	A	0.16	0.10	0.02	0.07	0.09	0.09	0.06	0.06	0.08
	B	0.19	0.09	0.05	0.06	0.19	0.14	-	-	-
	C	0.19	0.11	0.05	0.05	0.17	0.18	-	-	-
T	A	1.25	1.16	1.06	1.28	1.03	1.23	1.01	1.23	1.40
	B	1.24	1.17	1.31	1.02	1.72	1.27	-	-	-
	C	1.33	1.18	1.27	1.02	1.58	1.25	-	-	-
P	A	0.10	0.01	0.02	0.03	0.05	0.42	0.35	0.06	0.08
	B	0.05	0.01	0.02	0.03	0.01	0.49	-	-	-
	C	0.05	0.01	0.02	0.02	0.01	0.41	-	-	-
R	A	0.32	0.19	0.09	0.32	0.12	0.49	0.36	0.25	0.43
	B	0.36	0.20	0.37	0.14	0.76	0.57	-	-	-
	C	0.42	0.22	0.34	0.10	0.61	0.49	-	-	-

Table 2. Comparison of risk indexes RI for the considered assembly areas, in each of the considered scenarios S. For the assembly areas codes, refer to Figure 2 for SCENARIO A and to Figure 5 for SCENARIO B and SCENARIO C.

According to such simulation outcomes, it can be noticed that the overall risk R for the safe areas generally diminishes or remains equal in the three scenarios, thus leading to no increasing threats for the evacuees and possible optimization of the first responders' actions. Only for the assembly areas 4 and 5, the risk increases because of the number of evacuees reaching such evacuation facilities increases (J and T increases).

Finally, it is worthy to notice that number and scattering of spontaneous gathering areas are reduced while applying the proposed risk-mitigation strategies. Figure 7 and Figure 8 schematize the position of such areas in SCENARIO B and SCENARIO C, respectively. They additionally compare the results with those of SCENARIO A (Figure 3).

In the SCENARIO B, most of the criticalities connected to the building damages along the paths still exist (Figure 4 about path blockage and debris presence along the paths): some people can still gather near crossroads as in the SCENARIO A (compare areas marked by * in Figure 7). Nevertheless, most of such areas are directly connected to an assembly area, by ensuring the possibility for rescuers to firstly enter the assembly area and the moving towards the spontaneous gathering area (also compare the areas marked by ! in Figure 7).

The building retrofit actions improve the safety conditions because the main evacuees-debris interferences are solved (limitation of areas marked by * in Figure 7). Finally, both the SCENARIOS B and C are characterized by a spontaneous gathering area located near the original assembly area 6, in SCENARIO A (compare Figure 3). This is because the crossroads in which this area is placed is wider than the surrounding paths, leading people to remain here instead of moving towards the assembly area 2. Nevertheless, such an area can be easily reached by rescuers moving towards the assembly area 5.
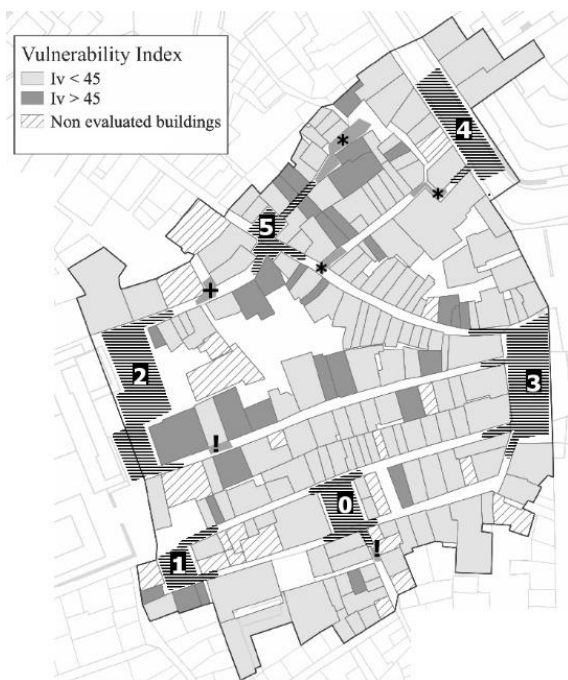

Figure 7. Open spaces usage at the end of the simulation in the SCENARIO B, by evidencing: assembly areas used by more than the 10% of arrived evacuees, and related access (dashed areas); main areas of spontaneously gathering with different marks to compare with the SCENARIO A results in Figure 3 (grey areas along the streets marked by *: similar position; +: placed near to a deleted assembly area; !: close to a new assembly area).
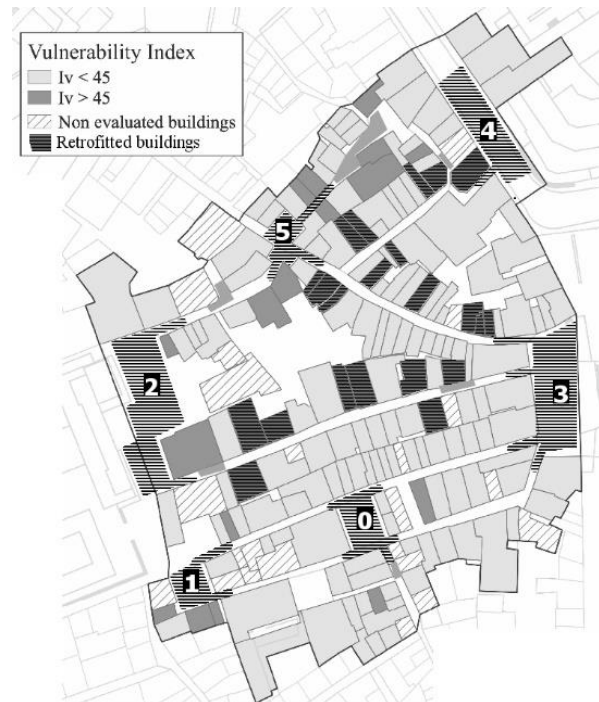

Figure 8. Open spaces usage at the end of the simulation in the SCENARIO C, by evidencing: assembly areas used by more than the 10% of arrived evacuees, and related access (dashed areas); main areas of spontaneously gathering with different marks to compare with the SCENARIO A results in Figure 3 (grey areas along the streets marked by *: similar position; +: placed near to a deleted assembly area; !: close to a new assembly area).

4. CONCLUSIONS

An original simulation-based methodology focused on urban evacuation paths and assembly areas for different earthquake scenarios is presented and discussed in this paper. Recognising the role of the Built Environment on the evacuation process, a validated urban earthquake pedestrians' evacuation simulation software is used to retrieve and compare probable behaviours and movement decisions in relation to different environmental conditions, including damage conditions and different emergency management decisions. The urban resilience assessment can take advantages of such an approach, especially in the case of complex contexts like those of historic city centres.

The current work offers a first attempt in defining and applying Risk Indexes which can combine damage assessment and evacuation process results to quantify evacuation risk and to outline critical conditions in the urban layout. The attention is focused on assembly areas and on the related path to reach them, because of their paramount role in the first emergency phases.

The application to a case study allows demonstrating, in a significant context, how these Risk Indexes can be used to optimize risk-mitigation strategies involving emergency planning and interventions on buildings. In particular, results show how the proposed solutions are based on an iterative simulation process, whose selected strategies generally increase (or even, equal) the safety for the evacuees hosted by the historical urban fabric while concentrating the rescuers' actions on few main evacuation targets. Meanwhile, all the proposed strategies are based on a local analysis of the risk conditions by concentrating the action planning actions on the main elements of interferences for the evacuation process.

The proposed approach and the proposed Risk Indexes can support Civil Protection Bodies to elaborate risk-mitigation plans with Local Administrations. Since this work is mainly aimed at verifying the effects of risk-mitigation strategies on the evacuation process, additional methods should verify the other issues which affect emergency planning choices, such as economic ones (i.e. cost assessment issues, the possibility to implement and support the interventions through public-private strategies), population-awareness/preparedness ones (e.g. dissemination of the emergency plan, the introduction of wayfinding solutions in the urban fabric) and social-vulnerability ones (e.g. presence of people with reduced motion abilities and integration of related rescuers' actions in the general plan). This will allow reaching a complete and comprehensive community resilience assessment in the given scenario.

Finally, it is worth noting that this approach can be easily adapted and applied to assess another type of hazards at the urban scale (e.g. flood, fires, heatwaves, etc.), as well as in non-historic contexts.

ACKNOWLEDGEMENTS

REFERENCES

Aguado, J.L.P., Ferreira, T.M., Lourenço, P.B., 2018: The Use of a Large-Scale Seismic Vulnerability Assessment Approach for Masonry Façade Walls as an Effective Tool for Evaluating, Managing and Mitigating Seismic Risk in Historical Centers. *International Journal of Architectural Heritage*, 12, 1259–1275, doi:10.1080/15583058.2018.1503366.

Benedetti D., Petrini V., 1984: Sulla Vulnerabilità Di Edifici in Muratura: Proposta Di Un Metodo Di Valutazione (in Italian). *L'industria delle Costruzioni* 149:66–74.

Bernardini, G., Lovreglio, R., Quagliarini, E., 2019: Proposing behavior-oriented strategies for earthquake emergency evacuation: A behavioral data analysis from New Zealand, Italy and Japan. *Safety Science* 116: 295–309. doi:10.1016/j.ssci.2019.03.023.

Bernardini, G., Lucesoli, M., Quagliarini, E., 2020: Sustainable planning of seismic emergency in historic centres through semeiotic tools: Comparison of different existing methods through real case studies. *Sustainable Cities and Society* 52, 101834. doi:10.1016/j.scs.2019.101834.

Coaffee, J., 2008: Risk, resilience, and environmentally sustainable cities. *Energy Policy*, 36, 4633–4638. https://doi.org/10.1016/j.enpol.2008.09.048.

D'Orazio, M., Quagliarini, E., Bernardini, G., Spalazzi, L., 2014: EPES - Earthquake pedestrians' evacuation simulator: A tool for predicting earthquake pedestrians' evacuation in urban outdoor scenarios. *International Journal of Disaster Risk Reduction* 10: 153–177. doi:10.1016/j.ijdrr.2014.08.002.

Ferreira, T.M., Vicente, R., Varum, H., 2014: Seismic vulnerability assessment of masonry facade walls: development, application and validation of a new scoring method. *Structural Engineering and Mechanics*, 50: 541–561. doi: 10.12989/sem.2014.50.4.541.

Ferreira, T.M., Maio, R., Costa, A.A., Vicente, R, 2017: Seismic vulnerability assessment of stone masonry façade walls: Calibration using fragility-based results and observed damage. *Soil Dynamics and Earthquake Engineering*, 103:21–37. doi: 10.1016/j.soildyn.2017.09.006.

Ferreira, T.M., Mendes, N., Silva, R: Multiscale Seismic Vulnerability Assessment and Retrofit of Existing Masonry Buildings: *Buildings*, 2019, 9, 91, doi:10.3390/buildings9040091.

French, E.L., Birchall, S.J., Landman, K., Brown, R.D., 2019: Designing public open space to support seismic resilience: A systematic review. *International Journal of Disaster Risk Reduction* 34: 1–10. doi:10.1016/j.ijdrr.2018.11.001.

Gavarini, C., 2001: Seismic risk in historical centers. *Soil Dynamics and Earthquake Engineering*. https://doi.org/10.1016/s0267-7261(01)00027-6.

Indirli, M., 2009: Organization of a geographic information system (GIS) database on natural hazards and structural vulnerability for the historic center of San Giuliano di Puglia (Italy) and the city of Valparaiso (Chile*). International Journal ofArchitectural Heritage.*

Klüpfel, T., Meyer-König, H., 2014: PedGo Guardian: an assistant for evacuation decision making, in: Weidmann, U., Kirsch, U., Schreckenberg, M. (Eds.), *Pedestrian and Evacuation Dynamics 2012.* Springer International Publishing,: 445–454.

Italian technical commission for seismic micro-zoning, 2014: *Handbook of analysis of emergency conditions in urban scenarios* (Manuale per l'analisi della condizione limite dell'emergenza dell'insediamento urbano (CLE); in Italian), 1st ed. Rome, Italy.

Lin, J., Zhu, R., Li, N., Becerik-Gerber, B., 2020: How occupants respond to building emergencies: A systematic review of behavioral characteristics and behavioral theories. *Safety Science* 122, 104540. doi:10.1016/j.ssci.2019.104540

Santarelli, S., Bernardini, G., Quagliarini, E., 2018: Earthquake building debris estimation in historic city centres: From real world data to experimental-based criteria. *International Journal of Disaster Risk Reduction* 31: 281–291. doi:10.1016/j.ijdrr.2018.05.017.

Sato, T., Izumi, T., Nakatani, Y., 2014: Tourist Evacuation Guidance Support System for Use in Disasters. In: Kurosu, M. (ed.) *Human-Computer Interaction, Part III, HCII 2014.* Springer International Publishing: 494–501.

Shiwakoti, N., Sarvi, M., Rose, G., 2008: Modelling pedestrian behaviour under emergency conditions – State-of-the-art and future directions. *31st Australasian Transport Research Forum*: 457–473.

Vicente, R., Ferreira T.M., Mendes da Silva J.A.R., 2015: Supporting urban regeneration and building refurbishment. Strategies for building appraisal and inspection of old building stock in city centres. *Journal of Cultural Heritage* 16(1): 1-14. doi: 10.1016/j.culher.2014.03.004.