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Post-earthquake damage assessment of buildings – procedure for conducting building inspections

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Subject review

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Post-earthquake damage assessment of buildings – procedure for conducting building inspections

Assessments of building damage and usability were of primary importance after the Zagreb earthquake of 22 March 2020. Due to deficiencies of preparatory phase, where education of experts was not carried out before the earthquake, but later on, the assessments contained certain subjectivity and interpretations, based on knowledge and experience, but also on intuition of individuals. Detailed methodology, which should improve rapid assessments and detailed engineering inspections to be performed before reconstruction, is highlighted in the paper. This methodology may be utilized if another devastating earthquake occurs, which could happen already tomorrow.

Key words:

post-earthquake building inspections, damage, usability, masonry and reinforced concrete buildings

Pregledni rad

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Procjena oštećenja građevina nakon potresa - postupak provođenja pregleda zgrada

Procjene oštećenja i uporabljivosti građevina u Hrvatskoj, iskočile su u prvi plan nakon potresa u Zagrebu 22. ožujka 2020. S obzirom na manjkavosti pripreme faze, pri čemu nije provedena edukacija stručnjaka prije potresa, nego u hodu, procjene su sadržavale dozu subjektivnosti i interpretacije na temelju znanja, iskustva, ali i intuicije pojedinaca. U radu je detaljno prikazana metodologija koja može pomoći u brzim procjenama te kod detaljnih inženjerskih pregleda koji se moraju napraviti prije obnove. Prikazana metodologija se može iskoristiti u slučaju novoga razornog potresa koji se može dogoditi već sutra.

Ključne riječi:

pregledi zgrada nakon potresa, oštećenja, uporabljivost, zidane i AB zgrade

Übersichtsarbeit

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Bewertung von Bauschäden nach Erdbeben – Verfahren zur Durchführung von Gebäudeinspektionen

Die Bewertung von Gebäudeschäden und Nutzbarkeit war nach dem Erdbeben in Zagreb vom 22. März 2020 von größter Bedeutung. Aufgrund von Mängeln in der Vorbereitungsphase, in der die Ausbildung von Experten nicht vor dem Erdbeben, sondern nachher durchgeführt wurde, enthielten diese Bewertungen bestimmte Subjektivitäten und Interpretationen, die auf Wissen und Erfahrung, aber auch auf der Intuition des einzelnen beruhten. In dem Artikel wird eine detaillierte Methodologie hervorgehoben, die schnelle Bewertungen und detaillierte technische Inspektionen verbessern soll, die vor dem Wiederaufbau durchgeführt werden sollen. Diese Methodologie kann angewendet werden, wenn ein weiteres verheerendes Erdbeben auftritt, das bereits morgen passieren kann.

Schlüsselwörter:

Bauinspektionen nach dem Erdbeben, Schäden, Nutzbarkeit, Mauerwerk und Stahlbetongebäude

1. Introduction – general guidelines for experts conducting on-site building inspections

Organisation of damage inspections and usability assessments of buildings in earthquake-struck areas is of great importance for ensuring the safety of the local population and, obviously, such inspections must be carried out as soon as possible after a destructive earthquake. In the first hours after the earthquake, and in parallel with the cooperation with the emergency services, it is of utmost importance to carry out inspections and to quickly repair and ensure the safety of the critical buildings. These include hospitals for receiving casualties, buildings for storing toxic substances, hydroelectric power plants, major industrial facilities, key infrastructure structures, telecommunications buildings and facilities, other hospitals, schools, and similar buildings and facilities. For example, in the first hours after the Zagreb earthquake, experts trained for such inspections, i.e. engineers with experience in damage assessment, or experts who have undergone relevant training and exercise programmes, immediately inspected all hospitals in the old part of the city. At the same time, appropriate specialist companies were called upon to inspect the bridges over Sava river most of which were built more than fifty years ago and are highly important for the city functionality. In addition, overpasses and other critical infrastructure elements were also inspected, which are crucial for the functioning of the city after an earthquake. It is of utmost importance to ensure serviceability and proper functioning of roads for firefighters and emergency medical service vehicles, and then to provide for the cleaning of debris and removal of potentially dangerous parts of buildings and similar objects.

Nevertheless, the safety of citizens should not be neglected, and considering that aftershocks could cause further damage to already severely affected buildings, it is necessary to establish priorities in the days immediately following the earthquake, and begin rapid inspection of all other buildings where the extent of damage and potential threat to the local population must be assessed. In doing so, it is crucial to define in advance a system that facilitates decision-making and reduces the number of subsequent casualties to an absolute minimum. Care should be taken to establish uniform assessment criteria, to ensure that a sufficient amount of basic equipment is available, that management, administration and professionals are well trained, and that there is good communication between the state and local services based on expert advice. Residents are directly affected by decisions about the usability / serviceability of the buildings, as these decisions determine to a large extent the number of people for whom temporary accommodation needs to be provided. On the other hand, the presence (advice) of experts (who usually offer comforting words to people) also reassures the affected citizens, i.e. it allows for a faster resumption of normal activities in local communities (especially when it comes to the services of the country's capital). Furthermore, it should not be forgotten that such traumatic events can lead to long-term emigration (a trend that had been observed in Croatia even before the earthquake). Usually, experts who could provide psychological assistance to the victims are sent to the affected houses, which unfortunately was not the case after the earthquake in Zagreb. It

would be important to anticipate the provision of such a service in the future, especially since the residents expressed their grief and sorrow very emotionally to the civil engineering experts, who had to comfort them and do as much as possible to reassure them, although sometimes it was very difficult to understand the real reason for the traumatic behaviour. For this reason, there is a need for experts who are specially trained to provide psychological support. In addition, this activity would also allow a better service to citizens, and undoubtedly speed up inspections. Thus, it can be stated that organisation of the building usability assessment system is a highly sensitive task that, although it contributes greatly to mitigating the consequences of earthquakes, also entails a great responsibility [1]. Inspections of earthquake-damaged buildings are carried out under the supervision of a competent command unit which is responsible for registering and recording professional teams and for deploying them to specific affected areas according to the needs identified at a given time. Guidelines for conducting building inspections are provided below:

- The first step is to visually inspect the exterior of the building. The building must be inspected from all easily accessible sides, and obvious hazards, if any, should be identified (possible collapse of the building or of part of the building, failure of a structural element affecting the stability of the entire building or part of the building, settlement of the building foundations and soil, etc.). It is also necessary to check whether there are hanging parts of adjacent buildings or other external risks for the building to be inspected. Inspectors should also look for signs of damage to chimneys, roof, exterior walls or facade wall.
- If the damage found during the exterior inspection leads to the conclusion that the building is unusable (unfit for occupancy), the inspection will be terminated, and the building will immediately be placed in the "high risk" category. This information is entered in the inspection form, along with the mandatory description of the inspection's level of accuracy and appropriate comments.
- The inspection of the interior of the building begins on the ground floor. First, it is necessary to determine the type of the building's structural system. There may be an evacuation plan for the building showing a plan view of each storey of the building, which may prove helpful and facilitate the building inspection. All visible structural elements of the ground floor (walls, columns, beams, stairs, stairwells, etc.) and all infill and partition walls must be visually inspected. The verticality of the load-bearing system must be checked, with particular attention to unsupported gable walls. If severe damage is found, the inspection must be terminated and the building evacuated.
- If the damage observed at the ground floor is not extensive and does not indicate a hazard, the rest of the building can be inspected. The inspection should include as many load-bearing elements of the building as possible (walls, columns, beams, etc.) as well as the largest possible area of the building, from the basement to the roof, except for the parts of the building that are obviously dangerous.
- The attic and roof areas should be inspected if the possibility of collapse of any part of the roof structure is excluded. The condition of the floor structure in the attic should be assessed as

well as the possibility of roof tiles or portions of the roof falling to lower storeys of the building.

- Sometimes it is appropriate to perform simple tests to determine the condition and quality of mortar in masonry structures, or to remove a portion of the plaster to more easily determine the direction of crack propagation along structural elements.
- All sections of the earthquake-damaged building inspection form must be completed. In this context, it is important to record additional observations, and make recommendations and suggestions for further actions, such as removal of local hazardous elements and emergency measures (propping, shoring, etc.), especially for temporarily unusable buildings. A building may be declared temporarily unusable if a detailed inspection by specially trained experts is required, or if a satisfactory level of safety can be achieved by short term countermeasures (i.e. simple emergency measures), after which the building can be declared usable. A recommendation should also be made for the marking and fencing off hazardous areas.
- The paper form should also be accompanied by photographs of the building, or digital photographs if a digital form based on appropriate software is used.
- At the end of the inspection, after completing the form and deciding on the usability level, the building should be clearly marked near its entrance with a tag indicating the usability category (e.g. green, yellow or red), and users should be informed about the meaning of the tag, about the recommendations given on the tag and about the need to evacuate from the building or from some parts of the building. Danger zones should also be marked to warn passers-by of potential hazards.

Safety rules to follow during building inspections:

- Always remember that an aftershock can occur.
- Always conduct inspections in teams consisting of at least two people (binomial rule).
- Always wear protective and recognisable equipment: hard hat and vest.
- Watch out for harmful substances, gas, damaged utilities, etc.
- Do not remove any collapsed elements.
- Do not use elevators.
- Do not expose yourself to danger.

2. Proposal of a Form that can be used for building inspections in emergency post-earthquake situations

An inspection form for earthquake-damaged buildings (Figure 1), i.e. an adaptation of the form used in Italy, is proposed in [1]. It should be emphasized that the form was defined in 2014 as a basis for a detailed elaboration of a form that would be officially

Figure 1. Proposed form for inspection of buildings [1]

approved. It was used during building inspections immediately after the Zagreb earthquake as it was the only form that could be used for emergency situations. Based on feedback from inspection teams on typical damage, the form was adapted and a mobile application for building inspections was created.

The form can be used for rapid and detailed inspection of ordinary buildings of various sizes and occupancies. It is primarily intended for the assessment of masonry and reinforced concrete buildings, but it can also be used for other building types, such as steel structures or buildings with mixed load-bearing systems. For statistical processing of the collected data, the form can also be used for more complex buildings. However, for the assessment of usability of buildings of special use, highly significant buildings, cultural and historical monuments, and buildings related to infrastructure, the proposed procedure that includes the simplified assessment of usability is often not appropriate and in such cases more detailed inspections and analyses should be planned, which require more reliable data and more time. Bridges are partially considered in [1], mainly based on experience from the USA, but this procedure is not described in this paper.

In defining the individual segments of the form, care was taken to cover specific features of the building types and construction methods widely used in Croatia, with a particular focus on the City of Zagreb. It is assumed that the form will be completed

by the engineers carrying out the building inspections, which implies the ability to apply sound engineering judgement. This is consistent with the recommendation for additional preventive professional training, which is aimed at a thorough understanding of the procedure and the acquisition of specific skills necessary to perform inspections quickly and efficiently and to evaluate buildings in emergency situations. In general, the following basic guidelines were used in selecting each segment of the form:

- ease of use in emergency situations, under difficult conditions, and in limited time,
- focus on the types of buildings and construction methods typically used in Croatia, and especially in the City of Zagreb,
- eliminating unnecessary details that are difficult to collect during inspections, and that do not contribute significantly to the objectivity of the process,
- emphasis on the data that is critical to understand the structural system of the building and for assessing the expected behaviour,
- providing information on indirect hazards to account for external risk associated with adjacent buildings or geotechnical problems such as landslides,
- collecting additional data for the assessment of threat to the building occupants and general costs related to damage of individual buildings.

A form must be filled out for each building. The building must be differentiated from the adjacent buildings in the same block. The form consists of eleven sections and information is sometimes entered freely and sometimes one of the suggested answers must be given in relation to the building. In some sections more than one answer can be selected, but only if this is specifically stated in the instructions.

A part of the form (Part A) containing information about the inspection and the team is presented in Table 1. The information about the City District in which the building is located, including the Local Board name, must be entered. The person responsible for managing the inspection activities assigns the form number and enters the code under which the working group (team) is registered. The leader of the team, usually the most experienced team member, is identified by first and last name.

Table 1. Form for inspection of buildings in post-earthquake emergency situations – Part A

A Data on inspection and working group	
City district:	Local board:
Form No:	Team code:
Head of the team:	

Table 2. Form for inspection of buildings in post-earthquake emergency situations – Part B

B Identification of the building				
Building tag:		GPS coordinates:		
Address: Street/Avenue/Boulevard/Access Street/Square/Stairs No:				
Name of the building and/or first and last name of the owner:		Ownership	<input type="checkbox"/> Public	<input type="checkbox"/> Private
Position:	<input type="checkbox"/> Detached	<input type="checkbox"/> Row building	<input type="checkbox"/> Building at the end of the row	<input type="checkbox"/> Corner building
Terrain morphology:	<input checked="" type="checkbox"/> Reef	<input type="checkbox"/> Steep slope	<input type="checkbox"/> Flat slope	<input type="checkbox"/> Flat terrain
Inspection accuracy:	<input type="checkbox"/> External inspection	<input type="checkbox"/> Partial inspection	<input type="checkbox"/> Complete inspection	<input type="checkbox"/> Inspection not conducted for the following reason:
Sketch of building floor plan with position within the block:				

Table 3. Form for inspection of buildings in post-earthquake emergency situations – Part C

C Description of the building				
Total number of storeys:	Number of basement storeys:	Average storey area:		
Mean storeys height: <input type="checkbox"/> ≤ 2.5 <input type="checkbox"/> 2.5 – 3.5 <input type="checkbox"/> 3.5 – 5.0 <input type="checkbox"/> > 5.0	Number of occupants:			
Construction/reconstruction:	<input type="checkbox"/> ≤ 1920 <input type="checkbox"/> 1921 - 1945 <input type="checkbox"/> 1946 - 1964 <input type="checkbox"/> 1965 - 1981 <input type="checkbox"/> 1982 - 1998 <input type="checkbox"/> 1999 - 2013 <input type="checkbox"/> > 2013			
Use:	<input type="checkbox"/> Residential <input type="checkbox"/> Commercial <input type="checkbox"/> Industrial <input type="checkbox"/> Public <input type="checkbox"/> Other:			
Number of units per use:				
Utilisation:	<input type="checkbox"/> > 65% <input type="checkbox"/> 30 – 65% <input type="checkbox"/> < 30% <input type="checkbox"/> Out of use <input type="checkbox"/> Under construction <input type="checkbox"/> Not completed <input type="checkbox"/> Abandoned			
Building condition prior to earthquake:	<input type="checkbox"/> Properly maintained <input type="checkbox"/> Insufficiently maintained <input type="checkbox"/> In very poor condition <input type="checkbox"/> Reconstructed			

Table 4. Form for inspection of buildings in post-earthquake emergency situations – Part D

D		External risk			
1	Collapse or fall of parts of other structures	<input type="checkbox"/> For the building	<input type="checkbox"/> For the access road	<input type="checkbox"/> None	
2	Settlement of foundations	<input type="checkbox"/> Existing	<input type="checkbox"/> Further enhanced by earthquake	<input type="checkbox"/> Caused by earthquake	<input type="checkbox"/> None
3	Landslide	<input type="checkbox"/> Existing	<input type="checkbox"/> Further enhanced by earthquake	<input type="checkbox"/> Caused by earthquake	<input type="checkbox"/> None

Table 5. Form for inspection of buildings in post-earthquake emergency situations – Part E

E		Roof structures			
<input type="checkbox"/> Thrusting heavy	<input type="checkbox"/> Non thrusting heavy	<input type="checkbox"/> Thrusting light	<input type="checkbox"/> Non thrusting light		

The identification of the building (Part B) is shown in Table 2. Using the available information obtained from the Local Board, the team identifies the building to be inspected with an appropriate tag. The exact address of the building must be entered and, if possible, also the GPS coordinates of the site on which the building is located. Depending on the availability of the building plan, and layout plan of the building within the Local Board zone, the team can use an appropriate field in the form to draw the floor plan of the building with its position within the block, or alternatively it may attach the documentation it has received.

For buildings that are not detached, it is also necessary to determine their position in relation to other buildings in the row/block. The name or description of the building is entered in the form for public buildings, while the first and last name of the owner is entered for privately owned buildings. Morphology is determined by inspecting the area surrounding the building. The extent of the possible inspection must be determined depending on the accessibility of the building and taking into account the safety of the team. A yellow colour in the forms means that the building is located on a reef or on a steep slope and is therefore more prone to earthquake damage.

Part C of the form describes the basic properties of the building, based on specified parameters (Table 3). The following information must be entered: total number of storeys, number of basement storeys embedded by more than half of their height, approximate average height of a storey, and estimated average storey area. The number of occupants refers to the maximum possible number

of people present in the building. It is also necessary to indicate the construction period, which is closely related to the relevant regulations, and can roughly indicate the level of the seismic force that was assumed in the original calculations. If necessary, another time period in which the last reconstruction was made can also be entered. For of a mixed-use building, any number of responses may be selected, but in all cases the number of units per use must be indicated. The use refers to the moment of maximum occupancy of the building. In developing the form, an additional final section was added to indicate the condition of the building prior to the earthquake event.

The assessment of external risk is presented in Table 4 (Part D). If such risk exists, a possible external hazard due to the fall or detachment of parts of other structures should be indicated and it should be further specified whether this hazard is limited to the building itself or may also affect access roads/pathways. The red colour indicates that the pronounced external hazard may affect the building being inspected to such extent that it is completely unusable because of the condition of the adjacent buildings. In addition, potential impacts should be assessed in terms of existing or impending ground instability, depending on whether or not there is a risk of settlement or landslides. Yellow and orange colours emphasize the fact that earthquake-induced or pre-existing ground instability may either slightly or moderately increase the seismic risk of the building.

Since the seismic response of structures can be affected either positively or negatively by the roof structure, especially for

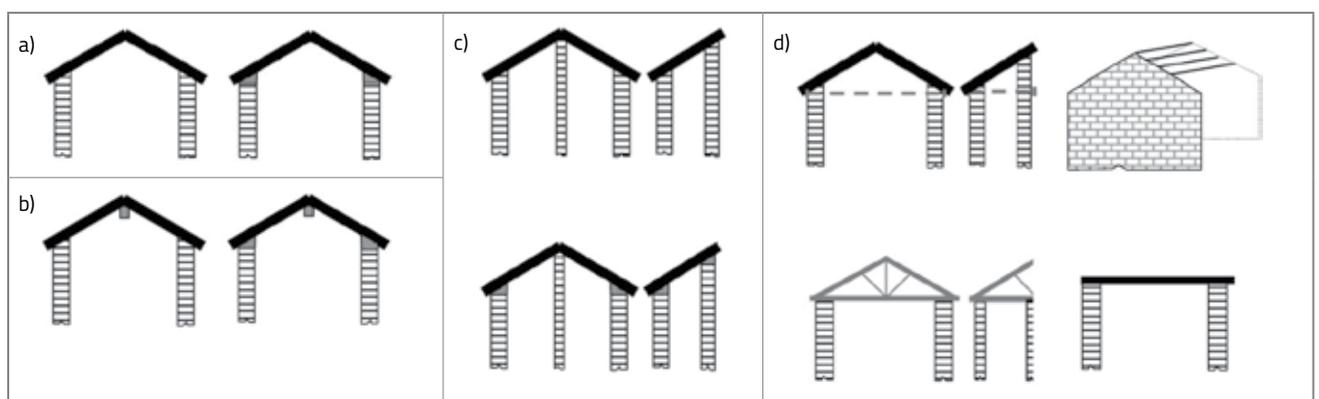


Figure 2. Examples of roof structural systems according to [2]: a) thrusting roofs; b) roofs with thrust depending on the constraints; c) generally non thrusting roofs; d) non thrusting roofs

Table 6. Form for inspection of buildings in post-earthquake emergency situations – Part F

F		Type of structure				
		RC and steel structures		Masonry structures		
		<input type="checkbox"/> RC frame	<input type="checkbox"/> RC walls	<input type="checkbox"/> Steel frames		
		Structure		Infill		
1	Regularity in plan (horizontally)	<input type="checkbox"/> Regular	<input type="checkbox"/> Irregular	<input type="checkbox"/> Regular	<input type="checkbox"/> Irregular	
2	Regularity in elevation	<input type="checkbox"/> Regular	<input type="checkbox"/> Irregular	<input type="checkbox"/> Regular	<input type="checkbox"/> Irregular	
Masonry structures		Vertical structural elements				
Horizontal structural elements		Unknown	Irregular layout and low-quality walls		Regular layout and good-quality walls	
			Without tie beams or tie rods	With tie beams or tie rods	Without tie beams or tie rods	With tie beams or tie rods
1	Unknown	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
2	Vaults without tie rods	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
3	Vaults with tie rods	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
4	Beams with flexible floor system	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
5	Beams with semi rigid floor system	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
6	Beams with rigid floor system	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Mixed structural system		<input type="checkbox"/> In elevation	<input type="checkbox"/> In plan (horizontally)	Free standing columns	<input type="checkbox"/> Yes <input type="checkbox"/> No	

masonry buildings, Part E of the form (Table 5) focuses on the roof structure, which is evaluated from the aspect of weight and presence of thrust (horizontal reactions that are transferred to the supporting walls). Light roof structures are primarily roof structures where the roof covering is made of steel or timber elements, while heavy roof structures imply the use of reinforced concrete. Examples of different structural systems of roof structures, and their comparison depending on the horizontal load, are presented in Figure 2. Heavy thrusting roof structures must be evaluated as the most unfavourable ones, as they contribute greatly to the mass of the structure (and thus to the seismic forces), while simultaneously transferring unfavourable horizontal reactions to the walls. Therefore, they are marked with orange colour. The influence of heavy non thrusting roof structures and light thrusting roof structures is slightly less unfavourable (yellow colour), while light non thrusting roof structures are the most favourable ones. A basic classification of structural system properties is provided

in Part F of the form (Table 6). For reinforced concrete (RC) and steel structures, the types of vertical structural elements must be defined, with several options to choose from. Regularity in plan and in elevation is estimated (Figure 3) for structural and nonstructural elements, i.e. for masonry infill walls. Masonry structures can be described by a series of combinations of vertical and horizontal structural elements. It is also necessary to estimate the quality of the walls considering the materials used, the regularity and construction method. The presence of tie beams or tie rods can also be mentioned, provided that they are sufficiently represented. For mixed structural systems, it is possible to choose whether different materials are combined from storey to storey along the building elevation or within the floor plan of the same storey. The selection of individual columns refers to structural elements made of any material. Yellow and orange colours indicate a low or moderate increase in exposure to seismic risk for unfavourable combinations of structural elements.

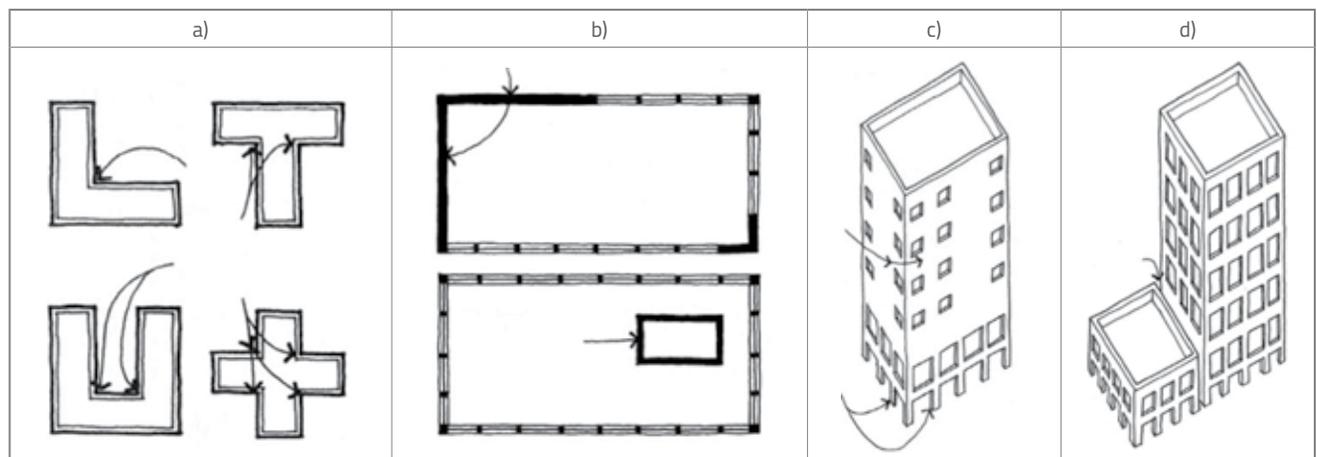


Figure 3. Examples of irregularity of buildings: a) in plan (asymmetry and/or re-entrant corners); b) in plan (torsion); c) in elevation (soft storey); d) in elevation (change in height)

Table 7. Form for inspection of buildings in post-earthquake emergency situations – Part G

G		Damage to structural elements									
		HEAVY – VERY HEAVY			SLIGHT – MODERATE			NEGLIGIBLE			NONE
		> 65%	35 – 65%	< 35%	> 65%	35 – 65%	< 35%	> 65%	35 – 65%	< 35%	
Part of structure											
1	Vertical elements	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2	Floor structure	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	Staircases	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4	Roof structures	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5	Infills/partitions	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6	Foundations	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	Damage that occurred prior to the earthquake	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Table 8. Form for inspection of buildings in post-earthquake emergency situations – Part H

H		Damage to non-structural elements			
		VERY HEAVY	MODERATE – HEAVY	SLIGHT	NEGLIGIBLE
Type of damage					
1	Detachment of plaster, parts of lining, and false ceilings	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2	Detachment of parts of roof tiles and chimneys	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	Detachment of eaves and parapets	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4	Detachment of other internal or external objects	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5	Damage to water supply, drainage or heating systems	<input type="checkbox"/>			<input type="checkbox"/>
6	Damage to electrical or gas supply network	<input type="checkbox"/>			<input type="checkbox"/>

Structural damage (Part G – shown in Table 7) is estimated by visual inspection of individual structural elements, and information on the severity of damage, and the overall extent of damage, is entered in the form. The severity of damage was harmonised with the European Macroseismic Scale EMS-98 [3] and, in that respect, NEGLIGIBLE damage corresponds to grade (level) I, SLIGHT to MODERATE damage corresponds to grades II and III, and HEAVY to VERY HEAVY damage corresponds to grades IV and V. The yellow, orange, and red colours indicate a slight, moderate or significant increase in exposure to seismic risk, depending on the extent of each damage grade.

- The total damage is described line by line for each type of structural elements taking into account the building's condition before the earthquake.
- Each box indicates the level and extent of damage by the type of element in the critical storey and direction.
- For each type of structural element, the percentage of the extent must be defined for each level of damage and for each storey, while the level and the extent of damage must be specified for the most critical storey and direction. If any of the three levels of damage is not applicable to a particular type of structural element, the field for that level and extent of damage will be left blank.
- All rows in the table must be filled in. If there is no damage to a particular structural element type, the box in the NONE

column of that particular row must be checked, while other boxes in the same row should not be checked. If there is damage to a structural element type, a corresponding box should be checked. As a rule, no row should be left blank.

- Using the multiple choice feature, all damage levels and all damage extent options should be entered, as seen on the structure.
- For each structural element type, the total sum of damage extent percentages must not exceed 100 %. For example, the extent of > 65 % is not allowed for the negligible damage level (1-2) and for the slight to moderate damage level (2-3). If for a particular structural element type the sum of damage extent percentages is less than 100 %, it means that a part of that structural element type has not sustain damage. For instance, if the damage extent for vertical elements for both negligible damage level and slight-moderate damage level is < 35 %, and the damage extent for the heavy-very heavy damage level (4) is not checked, then it is considered that 30 % of vertical elements are considered to have suffered no damage.
- Any damage that is suspected to have occurred prior to the earthquake must also be estimated.

Guidelines to facilitate engineering judgement and decision making in assessing the usability of the building are provided in Section 3.

Table 9. Form for inspection of buildings in post-earthquake emergency situations – Part I

I		Summary and usability evaluation		
Risk assessment	Cause	High risk	Moderate risk or low risk with countermeasures	Low risk
	Structural	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	Non-structural	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	External	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	Geotechnical	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	Usability	<input type="checkbox"/> UNUSABLE DUE TO EXTERNAL RISK	<input type="checkbox"/> TEMPORARILY UNUSABLE for DETAILED INSPECTION	<input type="checkbox"/> USABLE WITHOUT LIMITATIONS
		<input type="checkbox"/> UNUSABLE DUE TO DAMAGE	<input type="checkbox"/> TEMPORARILY UNUSABLE but can be USABLE after short term countermeasures	<input type="checkbox"/> USABLE, with RECOMMENDATION
		Number of people to be evacuated and provided with temporary accommodation		

The level of damage is also estimated for nonstructural elements (Part H – Table 8) in accordance with EMS-98 and, at that, SLIGHT damage corresponds to grade I, MODERATE to HEAVY damage corresponds to grades II and III, and VERY HEAVY damage and total collapse correspond to grades IV and V. Guidelines and criteria enabling a more uniform and objective estimation of damage to structural and nonstructural elements are given in the following part of this section.

The extent of damage does need not to be stated for non-structural elements.

At the end of the inspection, on the basis of the data previously collected and the assessment of the damage leading the team members to the conclusion on the expected behaviour of the building, the summary of the risk assessment in relation to the load-bearing capacity of the building is completed and the decision on the usability is made (Part I).

In deciding on the usability of a building, it is necessary to consider not only the structural damage, but also the risk (Table 9) of a recurrence of an earthquake (an aftershock) of a certain reference magnitude, the population density of the building (does the building have many occupants; e.g. buildings with multiple dwellings), the importance of the building and the building category (can the building be considered a building of vital importance, e.g. buildings occupied by people with disabilities, hospitals, educational institutions, fire stations, emergency service buildings, etc.), the location of the building, and its hazard to the immediate surroundings. The observations made in the previous parts of the form (A-H) must be summarized and on that basis, the following types of risk should be estimated:

- structural risk: it refers to the condition (type of structural elements and level of damage) of the load-bearing elements (vertical and horizontal load-bearing elements, infill walls that contribute to the seismic capacity of the building),
- non-structural risk: refers to the condition of non-structural elements (partition walls, roof tiles, chimneys, utilities, etc.), which may be dangerous not only for the building occupants, but also for people staying near the building,

- external risk: caused by the possible partial or total collapse of an adjacent building onto the inspected building or onto access roads to the inspected building,
- geotechnical risk: it refers to the condition of the soil around the inspected building and its foundations.

Part I of the form refers to the risk assessment and must always be completed, even if there is no damage or if certain favourable vulnerability indicators are present (in this case, "Low risk" part is filled in). Depending on the risk assessment, one of the offered categories of building usability can be chosen (USABLE without limitations; USABLE with recommendation; TEMPORARILY UNUSABLE for DETAILED INSPECTION; TEMPORARILY UNUSABLE but can become USABLE after short term countermeasures; UNUSABLE DUE TO EXTERNAL RISK; UNUSABLE DUE TO DAMAGE). Building can be classified as temporary unusable when a detailed inspection by specialized engineers is required, or when a satisfactory level of safety can be achieved by short-term countermeasures (urgent interventions) after which the building can be declared usable.

Once assessed, the number of people to be evacuated and temporarily housed from unusable buildings will need to be determined. In addition, necessary and/or recommended urgent measures are indicated (provision of supports for the structure, removal of chimneys, roof tiles, parapets, decorations, brick debris, etc.), especially in the case of buildings which are classified as USABLE WITH RECOMMENDATION or TEMPORARY UNUSABLE.

In the last part of the form (Part K), it is necessary to enter any additional observations and describe the cases not included in the categories provided for in the forms.

Six usability categories were used in Zagreb (the corresponding tags are shown in the figure 4.). Descriptions of usability tags/categories are given on the web page www.hcpi.hr, and the same descriptions are also used in the *Law on the reconstruction of earthquake-damaged buildings in the City of Zagreb, Krapina-Zagorje County and Zagreb County* (Official Gazette 102/2020):

Table 10. Form for inspection of buildings in post-earthquake emergency situations – Parts J and K

J Proposal of temporary short term countermeasures (urgent interventions) that are either limited (a) or extensive (b)					
(a)	(b)	Proposed measures	(a)	(b)	Proposed measures
<input type="checkbox"/>	<input type="checkbox"/>	Tightening elements using steel wires or steel sections and PVC or carbon strands.	<input type="checkbox"/>	<input type="checkbox"/>	Removal of other external or internal elements
<input type="checkbox"/>	<input type="checkbox"/>	Repair of slight damage to infill and partition walls	<input type="checkbox"/>	<input type="checkbox"/>	Repair of utility systems (services)
<input type="checkbox"/>	<input type="checkbox"/>	Repair of roof structures	<input type="checkbox"/>	<input type="checkbox"/>	Barriers and passage protection
<input type="checkbox"/>	<input type="checkbox"/>	External supports	<input type="checkbox"/>	<input type="checkbox"/>	Banning access to the building by fencing it off
<input type="checkbox"/>	<input type="checkbox"/>	Internal supports	<input type="checkbox"/>	<input type="checkbox"/>	Building monitoring
<input type="checkbox"/>	<input type="checkbox"/>	Supports for staircases	<input type="checkbox"/>	<input type="checkbox"/>	Additional specialist inspection
<input type="checkbox"/>	<input type="checkbox"/>	Removal of plaster, coverings and false ceilings	<input type="checkbox"/>	<input type="checkbox"/>	Other*
<input type="checkbox"/>	<input type="checkbox"/>	Removal of roof elements: roof tiles, chimneys, parapets			
<input type="checkbox"/>	<input type="checkbox"/>	Removal of facade elements: eaves, parapets, overhangs			
K Other observations and notes					
Date:			Signature of the team leader:		

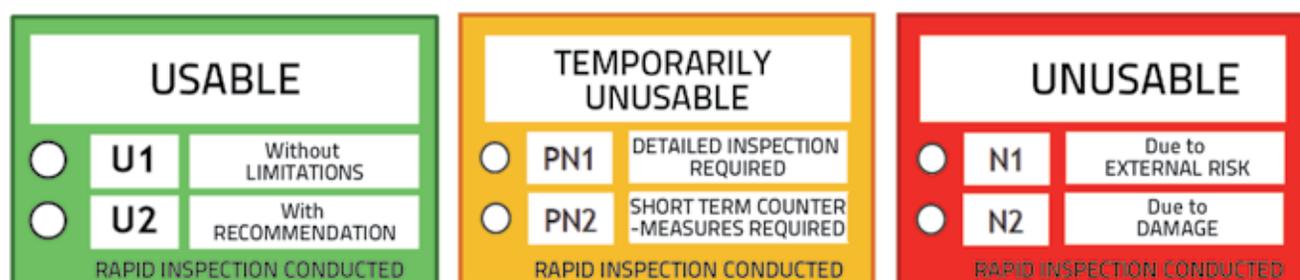


Figure 4. Categories of building usability

N1: Unusable – due to external risk

The building is considered dangerous due to the risk of collapse of massive parts of adjacent building (mainly gable walls and massive chimneys). It is recommended not to stay in such buildings (especially because of large number of aftershocks).

N2: Unusable – due to damage

The building has suffered significant damage to its load-bearing system, with failures of structural and non-structural elements. It is recommended not to enter or stay in the building. This does not necessarily mean that the building must be demolished – such decisions will be made at later stages.

PN1: Temporarily unusable – detailed inspection required

The building has suffered moderate damage and it is not in risk of collapse. The load-bearing capacity of the building is partially impaired. It is not recommended to stay in the building, i.e. people can stay in the building at their own risk only. Shorter stays in the building are possible, provided that the recommendations of the building expert regarding the measures to be taken and the restrictions on staying (depending on the degree of danger) are followed. The building surveyor will make recommendations to eliminate the hazard.

PN2: Temporarily unusable – short term countermeasures (urgent interventions) required

The building has suffered moderate damage and it is not in risk of collapse. However, the building cannot be used as some elements of the building are at risk of failure. The building expert determines urgent intervention measures and gives instructions to the occupants. Temporary unusability may also be limited to some parts of the building (attic, certain storey, apartment, etc.).

U1: Usable without limitations

The building is usable. The building has suffered no damage or has suffered only slight damage that cannot affect the load-bearing capacity and usability of the building.

U2: Usable with recommendation for measures to be taken

The building can be used in accordance with its intended use, with the exception of some parts of the building that pose an immediate risk. The building surveyor will make recommendations for the removal of the hazard (e.g. chimney) and recommendations to the occupants regarding temporary restriction of occupancy of certain parts of the building. Once the hazard has been removed, the building can be used without restriction.

It is important to always keep in mind that the goal of assessing the usability of damaged buildings is to determine whether these buildings can be used safely, the main concern being to protect human life, but also to save properties. After the Zagreb earthquake, tags ("labels") for buildings were used by municipal and national institutions for different purposes, i.e. for purposes for which they were not originally intended. Since many engineers use the usability tags of buildings as an initial basis for preparing design documents for reconstruction, a special focus on such tags is given in this section, while a detailed description of the usability assessment is given below.

3. Categorisation of damage and usability assessment of buildings

In order to estimate damage to structural elements, it is necessary to determine not only the severity of the damage (DS), but also the extent of that damage, separately for each direction of the structural system.

Guidelines for estimating the damage at the level of individual elements and for estimating the total usability are given in this section, while guidelines and criteria for estimating the damage to structural and non-structural elements, depending on the material used, are given in Sections 4 and 5, where examples of damage are also presented and illustrated with photographs. In each case, the basic instruction is to select one of the proposed damage severity levels through engineering assessment, while guidelines, criteria and photographs with examples are provided for guidance only, i.e. to make decisions about the usability of the building as objectively as possible.

It is important to point out that the original post-earthquake building inspection form (Section 2) was prepared in accordance with the Italian experience, and adapted for the detailed inspection of buildings. Since in the first phase after the Zagreb earthquake the inspections between rapid and detailed were carried out, it was found during the practical inspections that many engineers could not easily decide whether buildings of the damage grade II and III (Table 11) are usable or not, which is also

in line with the Italian experience [4]. Therefore, in accordance with the Greek experience [5], the criteria for the assessment of the severity of the damage to the elements and for the assessment of the overall usability were added, as they proved to be more specific in the building inspection phase and in the decision on the usability of masonry and reinforced concrete buildings. In fact, the Greek criteria contain detailed instructions on what crack widths, crack types, and element types can affect the usability of part of the building or the whole building.

In the case of older buildings, and such buildings represent the majority of damaged buildings in the centre of the city of Zagreb, in many cases structural changes were made during the service life of these buildings, and the existing damage may in fact be the result of a number of influences that have gradually accumulated over time. For this reason, the current overall condition of the building must be considered when assessing its usability. In other words, if the capacity of the building has been reduced compared to the condition prior to the earthquake, engineers should estimate whether the building can withstand yet another earthquake of similar intensity (rather than the earthquake according to current design standards, in which case the entire Lower Town of the city could be declared RED).

The traditional classification that is most often cited and very often used as the basis for similar categorisations of damage and usability of buildings is based on the EMS-98 scale mentioned earlier, which is also widely used to determine the earthquake intensity. Examples of the classification of buildings into five categories in terms of severity of damage and usability of buildings after a seismic event are shown in the following table (Table 11). A schematic overview of the levels of damage and the most common conditions of structural and non-structural elements of the masonry and reinforced concrete buildings according to EMS-98 classification is presented in Table 12 [3]. Element damage categorisation according to the Greek criteria [5] by severity (1-4) and extent of damage (1-4) corresponds roughly to the colours representing the damage categories as presented in the Croatian form, cf. Figure 6.

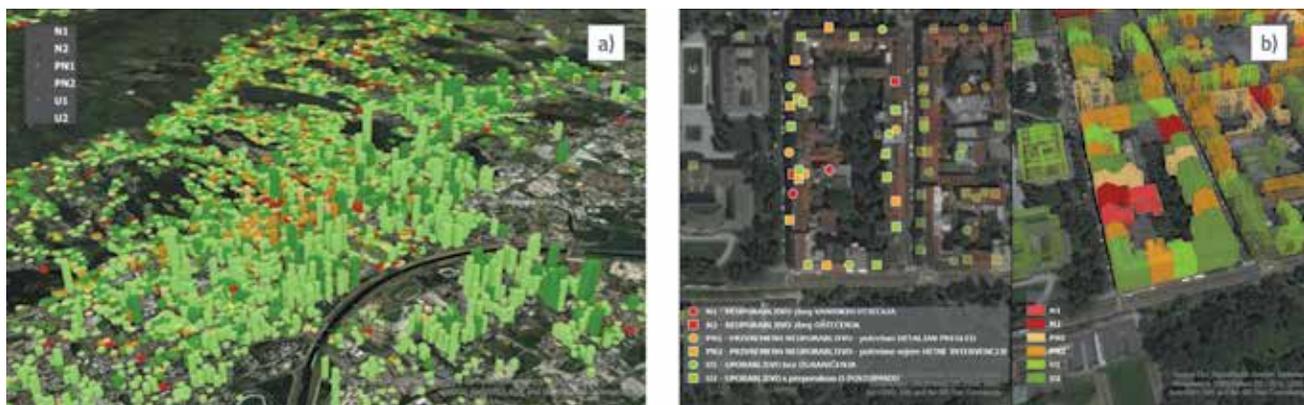


Figure 5. Results of damage and usability assessment after the March 2020 Zagreb earthquake: a) damage to residential and commercial-residential buildings by usability tags (colours) and gross floor area of buildings (height of columns) on a perspective view of Zagreb and b) usability of buildings in a block in Down Town area [6]

Table 11. Damage categories according to EMS-98

Grade	Use of building	Description	Examples	
I	No limitations	<p>SLIGHT NON-STRUCTURAL DAMAGE No visible damage, small cracks on secondary elements Safety of occupants is not compromised by the fall of non-structural elements</p>		
II	Limited use	<p>SLIGHT STRUCTURAL DAMAGE Cracks on walls, damage to non-structural parts of the building, fine cracks on load-bearing RC elements, structural capacity is not affected. Possible detachment of some parts of non-structural elements</p>		
III	Temporarily unusable	<p>MODERATE STRUCTURAL DAMAGE Large and extensive cracks on walls, cracks and damage to columns, load-bearing capacity partially reduced, temporary evacuation, structural repair</p>		
IV	Unusable	<p>HEAVY STRUCTURAL DAMAGE Open holes and failure of walls, failure of approximately 40% of structural components, building is in dangerous condition, evacuation is mandatory, detailed repair or demolition</p>		
V	Unusable	<p>COLLAPSE OF THE ENTIRE BUILDING Collapse of most parts of the building or the entire building, demolition and reconstruction</p>		

Table 12. Levels of damage for masonry and RC buildings according to EMS-98 classification

Grade	Masonry buildings		RC buildings	
	Sketch	Detailed description	Sketch	Detailed description
I		<p>Negligible to slight damage - negligible structural damage, - slight non-structural damage</p> <p>Hair-line cracks in some walls. Detachment of small pieces of plaster. Very rare cases of detachment of individual loose parts of walls.</p>		<p>Negligible to slight damage - negligible structural damage, - slight non-structural damage</p> <p>Fine cracks in plaster over frame elements or in ground floor walls. Fine cracks in partition and infill walls.</p>
II		<p>Moderate damage - slight structural damage, - moderate non-structural damage.</p> <p>Cracks in many walls. Detachment of larger pieces of plaster. Partial failure of chimneys.</p>		<p>Moderate damage - slight structural damage, - moderate non-structural damage.</p> <p>Cracks in columns, beams or load-bearing walls. Cracks in partition and infill walls. Detachment of brittle cladding and plaster. Detachment of mortar from joints of non-structural walls.</p>
III		<p>Substantial to heavy damage - moderate structural damage, - heavy non-structural damage.</p> <p>Large and extensive cracks in most walls. Detachment of roof tiles. Failure of chimneys at roof level. Failure of individual non-structural elements (partition walls, gable walls).</p>		<p>Substantial to heavy damage - moderate structural damage, - heavy non-structural damage.</p> <p>Cracks at frame connections at the base and at joints of coupled walls. Spalling of concrete cover. Buckling of reinforcing bars. Large cracks in partition walls and infill, and failure of individual infill panels.</p>
IV		<p>Very heavy damage - heavy structural damage, - very heavy non-structural damage.</p> <p>Extensive failure of walls. Partial failure of roof structures and floor structures.</p>		<p>Very heavy damage - heavy structural damage, - very heavy non-structural damage.</p> <p>Large cracks in structural elements with compression failure of concrete. Fracture and bond failure of reinforcing bars. Tilting of columns, failure of some columns and of a single upper storey.</p>
V		<p>Collapse - very heavy structural damage.</p> <p>Total or near total collapse.</p>		<p>Collapse - very severe structural damage.</p> <p>Collapse of ground storey or of parts of the building.</p>

When estimating damage at the element level using the Greek criteria, the analysis begins by determining the structural element type, and then the overall usability is assessed based on the severity of the damage and the extent of the damage. Guidelines for the determining the severity of the damage for individual structural elements, based on the type of structure (masonry or RC), are provided in Sections 4 and 5.

For structural elements of category A (columns, beams, beam and column connections, concrete and masonry walls), the problem when deciding on usability are the structural elements with damage severities of 2 or 3 (Table 13). In such cases, it is very important to determine the extent of damage. For the damage severity 2, if the extent of damage is in category 1 or 2 (one, two or three damaged elements in critical direction of one storey), the building can be classified as usable, and if the extent of damage is in the category 3 or 4 (several, more than several or most elements damaged in critical direction of one storey), the building can be classified as unusable or temporarily unusable, either partially or completely. For damage severity 3, the extent of damage in category 2 is sufficient to classify the building as partially or completely unusable.

When assessing the usability for category B.1 structural elements (staircases), the same criteria (Table 14) is applied as for Type A elements.

For elements of category B.2 (infill masonry walls), it can be seen that infill masonry walls are more favourable compared to brick

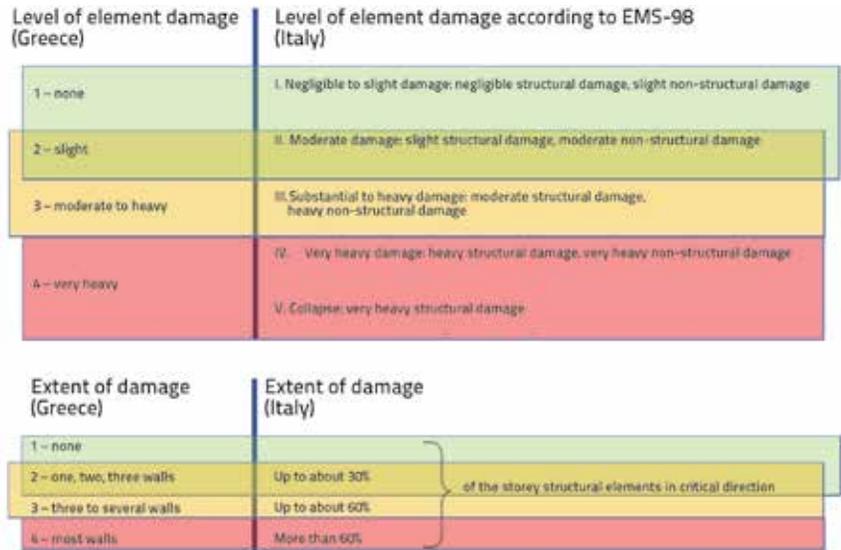


Figure 6. Element damage assessment – colours representing categories of damage shown in the Croatian form as compared to the Italian and Greek criteria

walls, which was to be expected. The building can be classified as green even at damage severity level 3 and damage extent category 2, while at damage extent category 3 or 4, the building is considered partially or completely unusable (Table 15).

The estimation method for B.3 elements (parapets, roofs and chimneys) is the same as for category A and B.1 structural elements, except for chimneys, which may have damage severity 4 (collapse or significant chimney failure), but the building can still be considered usable (Table 16).

The verticality of buildings (Table 17) and ground related problems (Table 18) are very important criteria. The severity of the damage must be checked with respect to the verticality of the buildings, because high damage indicates that the buildings are unusable.

Table 13. Usability assessment criteria for category A structural elements

A. Columns, beams, beam and column connections, concrete and masonry walls	Damage severity	Extent of damage
	1, 2	1, 2
	2	3, 4
	3	2
	3	3, 4
	4	2, 3, 4

Table 15. Usability assessment criteria for category B.2 structural elements

B.2 Infill masonry	Damage severity	Extent of damage
	1, 2	1, 2, 3, 4
	3	2
	3	3, 4
	4	2
	4	3, 4

Table 14. Usability assessment criteria for category B.1 structural elements

B.1 Staircase	Damage severity	Extent of damage
	1, 2	1, 2
	2	3, 4
	3	2
	3	3, 4
	4	2, 3, 4

Table 16. Usability assessment criteria for category B.3 structural elements

B.3 Parapets, roof, chimneys	Damage severity	Extent of damage
	1, 2	1, 2
	2	3, 4
	3	2
	4	2, 3, 4

Table 17. Usability assessment criteria as related to verticality of buildings

C. Verticality of building	Damage severity
	1, 2
	3
	4

Table 18. Usability assessment criteria as related to problems with ground

D. Problems with ground	Damage severity
	1
	2, 3, 4

Table 19. Criteria for determining the overall usability of buildings in the case of damage to different categories of structural elements, according to the Greek criteria [5]

	Element category				Assessment of damage by elements	Overall usability of the building
	A	B.1	B.2	B.3		
1	A	B.1	B.2			
2	A	B.1	B.2			
				B.3		
3		A	B			
		C	D			
4		A	B			
		C	D			
5	A	B.1	B.2			RECOMMENDATION
				B.3		
			C	D		
6	A	B.1	B.2	B.3		

The assessment of damage to the elements is taken into account in the overall assessment of the usability of the building. Table 19 shows criteria according to Greek experience [5] for the overall assessment, taking into account the severity of damage to different categories of structural elements. If a structural element of category – A, B.1 or B.2 – is classified with red colour, the overall assessment of the usability of the building is also red, i.e. the building is classified as UNUSABLE due to damage. If these elements are classified with the yellow damage tag, then the overall usability of the building is classified as partially usable or temporarily unusable, regardless of the fact that the elements of category B.3 (roof, parapet or chimney) have a green damage tag.

If any structural element A and/or B has a green damage tag, and if the verticality of the building or problems associated with the ground point to a high severity of damage, the entire building is classified as either temporarily unusable or completely unusable. Similarly, if the structural element A and/or B has a yellow damage tag, and if the verticality of the building or problems associated with the ground point to a high severity of damage, the entire building is classified as unusable. As already mentioned, if structural elements of categories A, B.1 or B.2 and C and D are marked with green colour, and if a structural element of category B.3 (roof, parapet or chimney) has a yellow or red damage tag, the building can be classified as usable with recommendation.

The classification of usability of buildings according to Greek criteria [5], depending on assessment of building damage, is presented in the table 20. Although the procedure for assessing the damage and usability of buildings has been described above, it is nevertheless necessary to point out some important steps. In assessing the

damage in the process of making overall usability decisions, the following must be given special attention:

- In the case of local non-structural damage (chimneys, roofs, infill, etc.) that poses a low risk to the building and shows that the building is usable, it is imperative to indicate RECOMMENDATION for further action and to give adequate warning to the building's occupants.
- The extent of element damage must be determined by inspecting the entire storey (each direction separately).
- The critical crack width for walls is approximately 3 (5) mm (see Section 4 for further details); it is important to note that this refers to structural elements and not plaster.
- For confined walls, it is important to check the condition of the infill first, as it is usually the first to fail in such systems; the condition of the confining elements must be checked afterwards. Often the walls are damaged but not the confining elements.
- Attention should be paid to the detachment of gable walls and facade walls, as they often lean and fail out-of-plane.
- It is also important to estimate the consequences of failure of critical elements, and to estimate the risk and robustness of the structure.
- The type of floor structure should be indicated (rigid, flexible, vaults, etc.).
- The regularity of the structure should also be included, e.g. freestanding columns in plan.
- Buildings with multiple storeys and the buildings with multiple apartments are often of higher risk.
- Finally, the most important component is the engineering judgement.

Table 20. Assessment of the usability of buildings according to the Greek criteria, depending on the severity of damage

Classification	Severity of damage (important: extent of damage)	Usability
U - Usable building	1-2 = none– negligible	Usable – with possible limitation or recommendation
<p>The inspection has shown that the original seismic capacity of the building has not been significantly reduced and that no major hazard is present. Negligible or slight structural damage. Minor non-structural damage. In this case, the use is permitted, except in zones identified as UNSAFE AREA where a local hazard has been identified.</p> <p>Usable for damage severity 1-2 with a small extent of damage. For the extent of more than 30% the building is considered unusable.</p>		
PN - Temporarily unusable building	2-3 = slight-moderate	Unusable or only partially usable
<p>The original seismic capacity of the building has been reduced and it is possible that an aftershock will affect the safety of the building. Limited entry to the building is permitted at the owner’s risk, but prolonged occupancy of the building is not permitted. Entry by public is prohibited. Damaged and dangerous parts of the building must be repaired and/or strengthened, and the need for urgent support of the structure and some parts of the building should be considered.</p> <p>Not usable for damage severity 3 even if the extent of damage is small. Limited entry is permitted for performing urgent interventions.</p>		
N – Unusable building	3-4 = heavy – very heavy	Unusable
<p>The building is unsafe because it may collapse suddenly. Serious structural damage or failure of some parts of the building’s structure has been registered. The building must be entered only by competent and authorized persons; access roads and the surrounding area must be fenced-off and protected. The decision whether to repair or demolish the building will be taken after the detailed engineering assessment.</p> <p>Use and occupancy of the building is forbidden; it is dangerous to enter! Severity of the damage: 4</p>		

4. Classification of damage for masonry buildings

Masonry buildings are generally characterized by a wide variety of structural types due to the use of different materials, construction methods, and horizontal and vertical structural elements. Particular attention should be paid to the condition of the walls, the type of floor structure, arches and vaults, roof structure properties, and non-structural elements that may become a hazard.

Figure 7 shows the masonry wall failure mechanisms (mostly out-of-plane) so that the existing cracks can be related to the possible causes of their occurrence. According to [7], eight elementary mechanisms of out-of-plane and in-plane wall failure are presented. The occurrence of local collapse of vertical additions or gable ends is also considered. The collapse of floors and roof structures is treated as related to out-of-plane collapse. The occurrence of the first six mechanisms (A-E) depends on the condition and type of connection between facade walls and

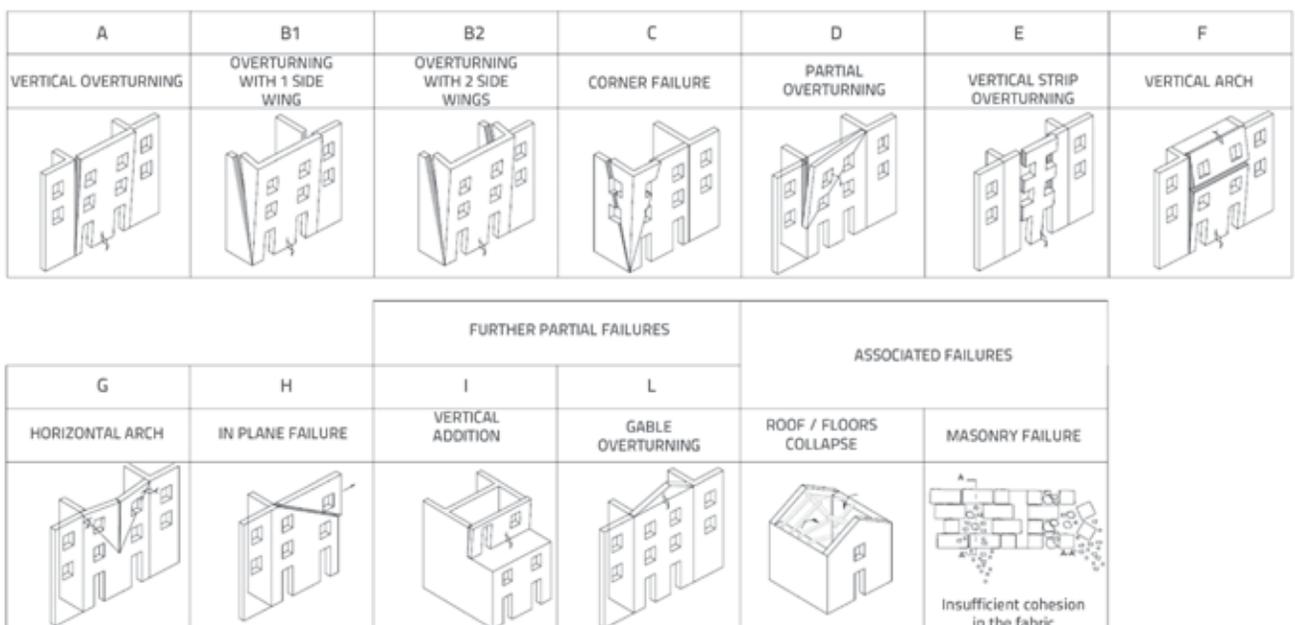


Figure 7. Overview of masonry wall failure mechanisms according to [7]

side walls. In the case of mechanism A, the facade wall overturns without participation of the side walls, and it usually occurs when there are no connections at wall edges in two directions and at floor structures, or when these connections are very weak. Mechanisms B1 and B2 occur instead of mechanism A when this connection is sufficient to include either one or both side walls in the overturning. The mechanism occurs by opening of a diagonal crack in the side walls and horizontal hinge at the facade. Type C occurs in the corners when the walls are well connected in two directions, but the material quality in wall planes is weak. The rotation around the corner occurs, or two diagonal cracks propagate towards the edge of the walls, which may affect considerable parts of both walls. Mechanism D may occur instead of mechanism B1 when the connection at edges is uneven and when the quality of the walls is poor. Mechanism E can be caused by a regular distribution of openings along the verticals and poor connection of spandrels, resulting in a continuous vertical crack. Mechanism F occurs when there is poor connection between the wall (which has a lower load-bearing capacity around the axis parallel to the horizontal joints) and a floor structure, at solid connection of the wall with roof structure and other floor structures. Type F failure can also occur due to linear weakening of the wall (for instance, when making the support to a new reinforced-concrete slab during reconstruction). Type G failure occurs when there is a poor connection between a wall and a floor structure, at simultaneous low flexural strength around the axis perpendicular to horizontal joints. Type H mechanism is an in-plane wall failure resulting from exceedance of shear and tensile strength due to horizontal action in the plane of the façade. Type I mechanism, which involves failure of a vertical addition, is due to weak wall support at the level of roof structure. Gable end overturning (type L mechanism) is due to the absence of the gable end support at the top of the wall (at sloping planes of the roof), i.e. due to insufficient load-bearing capacity of such wall cantilever with respect to bending action around the axis parallel to horizontal joints. The roof may collapse due to deterioration and insufficient mechanical resistance to seismic forces, but it may also collapse due to failure (spreading) of the supports, which may be caused by any of the previously described mechanisms of wall failure. Local failure of a wall material is almost always due to the exceedance of tensile or shear strength of the walls.

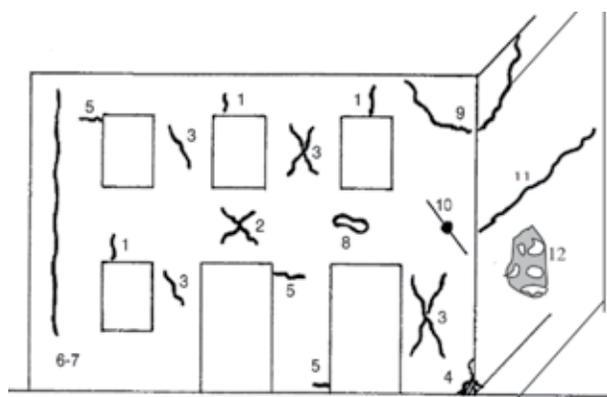


Figure 8. Reference scheme of cracks on masonry structures according to [4] EMS-98

According to the EMS-98 classification [3], the crack descriptions shown in Figure 8 [4] refer to cracks in walls, and not to cracks in plaster (note: severity (levels) of damage denoted by the Roman numerals I to V in the preceding text are defined here as D1 to D5 for clarification)

1. Nearly vertical crack on the openings lintels. Level D1 for smaller cracks at the top and bottom parts of walls, while levels D2 and D3 correspond to open cracks pointing to significant detachment of the walls from the lintels. Smaller cracks are usually caused by arch action and are induced by exceedance of tensile strength; however, it is another failure mechanism they propagate along the entire length. Levels D4 and D5 refer to significant damage (wider cracks that are no longer of local character, detachment out of plane, connection with other forms of damage, etc.).
2. Diagonal cracks in spandrels. Level D1 for smaller cracks points to the exceedance of shear strength (D2, D3), but the force is transferred through friction due to small crack width. Levels D2 and D3 refer to open cracks with visible dislocations. In the case of very small dislocations and limited extent of damage, the structural risk is low but, in the opposite case, it should be considered high (D4, D5).
3. Diagonal cracks in vertical elements (vertical walls between openings). Level D1 for smaller cracks indicates that the shear strength is exceeded (D2, D3), but the force is transferred through friction due to small crack width. Levels D2 and D3 refer to open cracks with visible dislocations. In the case of very small dislocations and limited extent of damage, the structural risk is small but, in an opposite case, it should be considered high (D4, D5).
4. Local crushing of walls with or without expulsion of material. Level D1 refers to visible cracks less than 1 mm in width, indicating local crushing of the wall with mortar or brick, without detachment of material. Whenever possible, it is recommended to remove plaster so that this type of damage can be examined in more detail. Medium-sized cracks may indicate failure due to crushing, with brittle fracture, and may affect the load-bearing capacity with respect to vertical actions, so that in the case of significant and concentrated vertical loads – especially in multi-storey buildings – the structural risk is very high (D4, D5).
5. Nearly horizontal cracks at the top and at the bottom of wall piers between openings. Level D1 for smaller cracks, and levels D2 and D3 for open cracks. Most cracks of this type occur due to local concentration of stress next to the corners of openings. Levels D4 and D5 refer to significant damage (wider cracks that are no longer of local character, out-of-plane detachment, etc.).
6. Cracks that occur due to detachment at the connection of vertical walls, cracks of medium depth (partial detachment). At level D1, failure is at the initial stage, and the crack width is small. Greater and longer cracks can point to the loss of connection between walls. The attention should be paid here to the existence of connections with other walls and slabs: if they are lacking, stronger detachment can lead to the overturning of walls, which is considered a very high structural risk (D4, D5). Appropriate actions are normally undertaken so as to prevent possible collapse.

7. Same as in 6 but with through cracks (full detachment). At level D1, the failure is in the early stages, and the crack width is small. Larger and longer cracks may indicate the loss of connection between walls. The attention should be paid here to the presence of connections with other walls and slabs: if these are absent, more severe detachment can lead to the overturning of walls, which is considered a very high structural risk (D4, D5). Appropriate actions are normally undertaken so as to prevent possible collapse.
8. Cracks that usually occur due to pounding of wooden beams, supports, etc. In the case of less noticeable damage, it can be assumed that boundary conditions and wall capacity have not been greatly affected (D1). These cracks can be considered a moderate to significant damage if element supports are displaced so that they can cause additional local pressure, or if the load-bearing capacity of walls is reduced because of detachment of some parts (D2, D3). More considerable damage to supports, with cracks that are no longer of local character, should be assigned to a higher damage class (D4, D5).
9. This form of damage originating in the top part of the structure usually occurs due to lack of appropriate connections (beams, ties, tie rings, etc.). A sliding wedge mechanism is activated at the vertical wall connection, and the failure can spread to lower floors of the building. If the failure is local with small cracks, it can be considered as not dangerous (D1), however, it is important to note such occurrences because of possible propagation that may result from aftershocks. At higher levels of damage (D2, D3), a wedge that may detach and that

needs to be supported, is clearly visible. If there are evident dislocations pointing to initial sliding of the wedge, structural risk must be considered high (D4, D5).

10. Failure of ties rods or bond slippage. It is considered a minor damage if significant deformations can be seen without yielding, and if anchoring points are without cracks.
11. Horizontal cracks at the floor level or at the attic level. Horizontal cracks at connections, presenting very small displacements, point to sliding in zones between the wall and slab (or roof), and to low damage level, D1. Cracks with dislocations of several mm point to serious sliding between floors and walls (D2, D3). This damage case is often localised at the attic level. If the displacement is greater than several mm and is caused by additional pressure from the roof, it can be classified as a high structural risk (D4, D5).
12. Separation of one of the leaves of a double-leaf wall.

Table 21 shows the damage levels according to [5], with four damage levels for masonry buildings, with a limit added for the usability of the building in terms of the extent of damage. It should be noted that this limit is not precisely defined here. Therefore, it must be emphasized again that engineering judgment is very important for damage levels 2 and 3.

The following are examples of damage taken from various reports following earthquakes in Italy (tables 22-24) and in Zagreb (Table 25). It should be noted that the damage levels refer to the entire building (they also include the extent of the damage, which in most cases cannot be seen in the attached photographs).

Table 21. Damage severity for masonry structures according to [5]

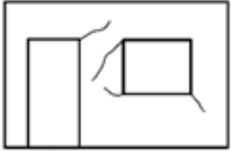
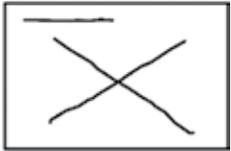
Damage level	Description	Sketch of damage
1 none	Hairline cracks in partition walls visible on one side of the wall only.	
Usability limit – the extent of damage at storey level and in each load-bearing capacity direction is such that approximately 60% of the walls are affected by damage		
2 blago	<ul style="list-style-type: none"> - Minor cracks in load-bearing walls propagating from the corners of several openings ($d \leq \sim 3$ mm). - Small cracks in load-bearing walls, visible from both sides of the wall ($d \leq \sim 3$ mm). - Parts of plaster falling from ceilings and walls. Fall of some roof tiles 	
Usability limit – the extent of damage at storey level and each load-bearing capacity direction is such that approximately 30% of the walls are affected by damage		
3 moderate to severe	<ul style="list-style-type: none"> - Diagonal cracks in load-bearing walls ($d < \sim 5$ mm), but the extent of damage is not sufficient to cause complete loss of load-bearing capacity of walls. - Significant cracking of partition walls ($d > \sim 3$ mm). - Displacement and/or full failure of chimneys, parapets or roof. - Displacement, detachment or local failure of roof supports or floor structure supports. - Local, severe damage in some part of the building. 	
4 very severe	<ul style="list-style-type: none"> - Load-bearing walls with open cracks ($d > \sim 5$ mm) visible from both sides of the wall. - Partial or complete failure and disintegration of load-bearing walls at the floor structure and/or roof level. - Any kind of damage pointing to serious hazard or collapse 	

Table 22. Examples of damage to masonry structures – level I (according to EMS-98)

I	Diagonal cracks between openings and vertical cracks in walls	Vertical cracks in re-entrant corner	Vertical and diagonal cracks between openings
			
	Cavezzo, Modena 2012 [8]	Tortora, Cosenza 1998 [2]	Mirandola, Modena 2012 [8]
I	Vertical and diagonal cracks in spandrels	Diagonal cracks between openings	Cracks at the edges of openings
			
	Coreggio, Reggio Emilia 1996 [2]	Novi di Modena, Modena 2012 [8]	Casumaro, Ferrara 2012 [8]

Table 23. Examples of damage to masonry structures – levels II and III (according to EMS-98)

II - III	Vertical cracks in walls	Crack across the vault	Crack and detachment of the corner under the roof
			
	Finale Emilia, Modena 2012 [9]	Cento, Emilia 2012 [9]	Cerqueto, Perugia 1998 [2]
II - III	Internal crack and detachment of walls	Diagonal cracks in walls	Cornice failure at the corner
			
	Tortora, Cosenza 1998 [2]	Moglia, Mantova 2012 [8]	Concordia, Modena 2012 [8]

Table 24. Examples of damage to masonry structures – levels IV to V (according to EMS-98)

IV-V	Partial failure of roof structure and top storey	Failure in the corner under the roof structure	Soft storey failure
			
	San'Antonio Mercadello, Modena 2012 [8]	Cento, Emilia 2012 [2]	Finale Emilia, Modena 2012 [10]
IV-V	Arch failure	Partial failure of upper storey	Column failure
			
	Mirabello, Ferrara 2012 [8]	Sant'Agostino, Ferrara 2012 [11]	Sant'Agostino, Ferrara 2012 [11]

Table 25. Examples of damage with description of crack types in masonry structures in Zagreb [12]

		
I: vertical (type 1) and diagonal cracks in lintel	I: diagonal cracks in structural walls (type 3)	I: cracks in ceiling
		
I: diagonal cracks in the walls (type 3)	I: vertical cracks in the parapets (type 1)	I: slight damage to staircase

Table 25. Examples of damage with description of crack types in masonry structures in Zagreb [12] - continued

		
<p>I-II: vertical cracks along connection of two orthogonal walls (type 6)</p>	<p>I-II: diagonal cracks in spandrels (type 2)</p>	<p>I-II: vertical and diagonal cracks in walls</p>
		
<p>I-II: diagonal cracks in spandrels (type 2)</p>	<p>I-II: vertical cracks along connection of two orthogonal walls (type 6) and horizontal cracks at the contact between floor structure and wall</p>	<p>I-II: diagonal cracks in parapets (type 2)</p>
		
<p>II: arch damage at the crown</p>	<p>II-III: wide crack with detachment</p>	<p>II-III: longitudinal vertical (type 1) and diagonal (type 3) cracks; almost horizontal cracks (type 11) at the attic level</p>
		
<p>II-III: detachment of the walls (6)</p>	<p>II-III: damage to the floor structure, cracks in the center</p>	<p>II-III: damage to the floor structure, cracks in the middle</p>
		
<p>III: diagonal (type 3) and horizontal cracks at the floor level (type 11)</p>	<p>III: cracks in the center of the ceiling, layering of structure</p>	<p>III: large inter-connected cracks and out-of-plane displacement of a part of the wall</p>

Table 25. Examples of damage with description of crack types in masonry structures in Zagreb [12] - continued

		
<p>III: diagonal crack in the wall (type 3)</p>	<p>III: significant damage to cantilevered staircase</p>	<p>III: severe vertical cracks (type 7), initial detachment of facade</p>
		
<p>III-IV: long diagonal crack (type 3) without dislocation</p>	<p>III-IV: very severe and widespread diagonal cracks (type 3), initial detachment of walls</p>	<p>III-IV: diagonal crack on the wall (type 3)</p>
		
<p>III-IV: severe lintel damage, possible collapse</p>	<p>IV: partial collapse of multi-leaf wall due to significant detachment of the inner leaf (type 12)</p>	<p>IV: very heavy staircase damage (cantilever staircase)</p>
		
<p>IV: wide cracks at the contact between the walls, also passing through the ceiling, detachment of the walls</p>	<p>IV: out-of-plane detachment</p>	<p>IV: diagonal cracks (type 3) and out-of-plane detachment</p>
		
<p>IV: diagonal cracks (type 9) and out-of-plane detachment</p>	<p>IV: diagonal cracks (type 3) and out-of-plane detachment</p>	<p>IV: out-of-plane detachment</p>

Tablica 25. Examples of damage with description of crack types in masonry structures in Zagreb [12] - continued

		
<p>IV: diagonal cracks along the entire wall with wall dislocation (type 3)</p>	<p>IV: wide horizontal crack at the floor level (type 11) and out-of-plane displacement of the wall</p>	<p>IV-V: partial wall and roof failure</p>
		
<p>IV-V: partial wall failure at the point of irregularity in plan and in height</p>	<p>IV-V: partial wall failure</p>	<p>IV-V: diagonal crack in the wall</p>
		
<p>IV-V: detachment and leaning of the gable wall</p>	<p>IV-V: collapse of a part of the gable wall and leaning of the remaining parts of the wall</p>	<p>IV-V: failure of lintel and a part of roof structure</p>
		
<p>IV-V: collapse of a part of the gable wall and leaning of the remaining part of the wall</p>		

5. Classification of damage to RC structures

In the city of Zagreb, many buildings with reinforced concrete structure did not suffered major damage after the Zagreb earthquake. Nevertheless, some of them were affected and damage was also observed on some parts of masonry buildings with elements made of reinforced concrete such as building

additions. Moreover, for buildings designed as reinforced concrete frames with masonry infill, not only the damage to the RC structural elements, but also the damage to the infill walls must be estimated. Tables 26 and 27 present the damage levels with a description of typical damage to reinforced concrete structures. Examples of typical damage in terms of damage severity and extent follow (Tables 28-31).

Table 26. Severity of damage to RC structural elements according to [5]

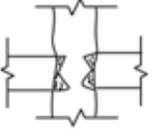
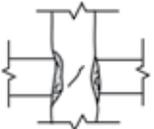
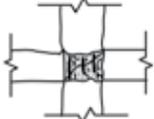
Level of damage	RC COLUMNS	RC WALLS	RC BEAMS	RC JOINTS
1 = no damage	<ul style="list-style-type: none"> Fine cracks in mortar Slight spalling of concrete. 	No visible cracks.	Fine cracks in mortar.	
Usability limit – the extent of damage at the storey level and at each load-bearing capacity direction is such that approximately 60% of the walls are affected				
2 = slight	<ul style="list-style-type: none"> $d_{horiz} \leq 2 \text{ mm}$ $d_{diag} \leq 0,5 \text{ mm}$ concrete spalling 	<ul style="list-style-type: none"> $d_{horiz} \leq 1 \text{ mm}$ $d_{diag} \leq 0,5 \text{ mm}$ 	<ul style="list-style-type: none"> $d_{vert} \leq 2 \text{ mm}$ $d_{diag} \leq 0,5 \text{ mm}$ concrete spalling 	<ul style="list-style-type: none"> concrete spalling at the corners 
Usability limit – the extent of damage at storey level and at individual load-bearing capacity directions is such that approximately 30% of the walls are affected				
3 = moderate to heavy	<ul style="list-style-type: none"> $d_{horiz} \leq 5 \text{ mm}$ $d_{diag} \leq 2 \text{ mm}$ partial disintegration of concrete 	<ul style="list-style-type: none"> $d_{horiz} \leq 3 \text{ mm}$ $d_{diag} \leq 1 \text{ mm}$ concrete spalling 	<ul style="list-style-type: none"> $d_{vert} \leq \sim 4 \text{ mm}$ $d_{diag} \leq \sim 2 \text{ mm}$ extensive spalling and crushing of concrete 	<ul style="list-style-type: none"> spalling of concrete inclined cracks $d \leq \sim 2 \text{ mm}$ 
4 = very heavy	<ul style="list-style-type: none"> $d_{horiz} > 5 \text{ mm}$ $d_{diag} > 2 \text{ mm}$ extensive disintegration of concrete buckling of longitudinal reinforcement 	<ul style="list-style-type: none"> $d_{horiz} > 5 \text{ mm}$ $d_{diag} > 2 \text{ mm}$ disintegration of concrete 	<ul style="list-style-type: none"> $d_{vert} > 4 \text{ mm}$ $d_{diag} > 2 \text{ mm}$ buckling of reinforcing bars 	<ul style="list-style-type: none"> inclined cracks $d_{diag} > 2 \text{ mm}$ disintegration of concrete 
Notation: d_{diag} → diagonal cracks (inclined to the element axis) d_{horiz}, d_{vert} → horizontal and vertical cracks (to the element axis)				

Table 27. Description of damage to non-structural elements of RC structure, by extent of damage according to [5]

Level of damage	STAIRCASE	INFILL WALLS	CHIMNEYS AND ROOF PARAPETS	INCLINATION OF BUILDING
1 = no damage	Hairline cracks on plaster	Hairline cracks on plaster	None	None
2 = slight	d < 3 mm Spalling of concrete	Small cracks d < 3 mm of limited length	Cracking or partial failure of chimney or parapet. Sliding or falling of roof tiles from the roof.	Inclination barely visible.
3 = moderate to heavy	3 mm < d ≤ 10 mm Reinforcing bars exposed.	Large diagonal or other cracks spreading along the entire area of the element (d > 3 mm). Separation from boundary elements.	Displacement or partial collapse or chimneys and parapets. Dislocation of roof tiles. Local roof damage.	Small inclination. Residual displacements of load-bearing elements.
4 = very heavy	d > 10 mm Disintegration of concrete. Residual displacements.	Large cracks visible on both sides of the element. Disintegration. Partial or total collapse.	Collapse of chimneys and parapets. Extensive roof sliding. Partial or total roof collapse.	Significant inclination. Residual displacement of load-bearing elements.

Table 28. Examples of damage to RC structure – level I (according to EMS-98)

-	Damage to plaster of the infill walls	Cracks in facade brick	Damage to wall plaster
			
	L'Aquila, Abruzzo 2009 [13]	Mirandola, Modena 2012 [8]	Cavezzo, Modena 2012 [8]
-	Cracks in facade brick	Damage to plaster between the openings	Pronounced gap
			
	Coreggio, Reggio Emilia 1996 [2]	Finale Emilia, Modena 2012 [8]	Mirandola, Modena 2012 [8]

Table 29. Examples of damage to RC structure – levels II and III (according to EMS-98)

II - III	Detachment of the ceiling covering	Crack along the column length	Infill wall damage
	 <p>Moglia, Mantova 2012 [8]</p>	 <p>Finale Emilia, Modena 2012 [9]</p>	 <p>Mirandola, Modena 2012 [11]</p>
II - III	Infill wall damage	Cracks in facade covering and detachment of plaster	Column damage
	 <p>Mirandola, Modena 2012 [8]</p>	 <p>Mirandola, Modena 2012 [11]</p>	 <p>Novi di Modena, Modena 2012 [9]</p>

Table 30. Examples of damage to RC structure – levels IV to V

IV - V	Column and beam joint failure	Wall failure	Soft storey failure
	 <p>Lauria, Basilicata 1998 [2]</p>	 <p>Mirandola, Modena 2012 [8]</p>	 <p>L'Aquila, Abruzzo 2009 [13]</p>
IV - V	Column failure	Complete failure of frame structure	Beam failure
	 <p>Cavezzo, Modena 2012 [9]</p>	 <p>Sant'Agostino, Ferrara 2012 [7]</p>	 <p>Finale Emilia, Modena 2012 [10]</p>

Table 31. Example of damage to RC structures in Zagreb [12]

		
<p>I-II: Damage at beam to column joint and concrete spalling</p>	<p>II-III: damage to staircase, crack along the width revealing reinforcement, (condition of reinforcement should be checked)</p>	<p>III: concrete spalling and layering in column; vertical and inclined cracks</p>
		
<p>III-IV: cracks caused by shear and longitudinal forces in column</p>	<p>IV-V: Very severe damage to staircase</p>	<p>IV-V: very severe damage to column, reinforcement buckling</p>

6. Conclusion

A major need observed in building inspections is the creation of databases, especially those containing data on structural properties of buildings. In the future, it will be crucial to adapt inspection forms to the characteristic types of structures, and especially to databases that would provide such data. In general, it can be stated that databases are the crucial problem in Croatia. In addition, potential official sources are not systematized and connected, and in most cases they have not been maintained, supplemented with new data and updated. There is currently no data on the number of buildings, let alone the data on dimensions, cross sections, building materials used, occupancy of buildings, etc. However, limited data on housing units is available from population census but, despite numerous incentives, the data on buildings has not been included in the new population census which is to take place in 2021. These data are crucial for the creation of a high quality database needed for risk assessment, strategic evaluations, but also for the inspection of damaged buildings [14].

The use of digital technologies and a high quality database are the basis for the development of inspection forms, as this could avoid many of the problems observed so far. After the earthquake in Zagreb, initial/rapid building inspections were immediately initiated - on a voluntary basis - focusing

primarily on the safety and usability of the buildings. Soon after the earthquake, the Ministry of Culture established a parallel system for the inspection of cultural property/assets based on separate detailed forms. The system for the financial damage assessment, required by law and a related regulation (described earlier), was established three months after the earthquake, but needed to be adjusted before implementation. In addition, the assessment methodology applied for rapid/initial inspections required additional steps that should include detailed engineering inspections. However, these were included, by political decision, in the new Law on Reconstruction. The bridge inspection forms, also developed in the scope of the *Study on Seismic Risk Mitigation*, which would be used during specialist inspections, have already been mentioned. It should be added here that the system should also cover other facilities such as dams, embankments, railways, roads, waterfronts, aircraft runways, etc. Furthermore, it is important to pay proper attention to water pipelines, sewerage systems, power lines, and all other lines and utilities necessary for the functioning of the city/country.

Moreover, all these different types of structures/inspections should be categorised internally in advance to facilitate data processing. For example, after the Zagreb earthquake, with the help of students from the Faculty of Civil Engineering, additional attributes such as educational facilities, health facilities, sports halls, etc. were added.

All this clearly points to the need to harmonise and systematically define comprehensive methodologies that would include all necessary inspections and corresponding forms. An additional benefit of this system would lie in easier education and maximum use of available experts, which would be greatly facilitated by a properly established database. Furthermore, in the case of international assistance, it would be of crucial significance to inform the experts about the nature of the inspections, characteristic structural types in a given location, etc., which would be greatly facilitated by a comprehensive system.

Although only some of the activities to be implemented are mentioned here, it has become clear that it is crucial to coordinate and manage damage inspections centrally, from an institution that does not have to adapt to new conditions and divert staff who are normally occupied with other professional activities. It is important to have professionals ready to organise and link all systems for continuous monitoring of global efforts to develop inspection forms and methods, i.e. professionals who are constantly prepared for a disaster that can strike Croatia any day.

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