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ESE FRAMEWORK FOR RAPID POST-EARTHQUAKE ASSESSMENT OF REPAIR COST AND DURATION FOR RESIDENTIAL BUILDINGS

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Abstract

This research advances the development of the RELA framework by introducing the ESE (Elements-Severity-Extent) sub-framework for rapid post-earthquake repair cost and duration estimation. Unlike fragility-based models relying on seismic intensity, ESE directly observes damage, enabling deterministic repair assessments. Using a structured decision tree methodology, ESE links observed damage to predefined repair methods, work items, and construction norms to quantify materials and labour. Field inspectors document damage through a spreadsheet-based tool, ensuring quick and reliable data collection. The system generates a Repair Bill of Quantities for resource-constrained repair planning. Compared to FEMA P-58 PACT, ESE provides higher accuracy and real-world applicability. While PACT delivers rapid probabilistic estimates, it lacks structured scheduling and resource-driven cost calculations. On the contrary, ESE offers precise, implementable outputs to aid post-earthquake recovery. A case study for masonry walls demonstrates ESE's efficiency, highlighting the favourable speed/accuracy/effort trade-off, as RELA-ESE requires low effort from non-expert inspectors while providing accuracy comparable to a building-specific repair design. By combining rapid assessment with structured planning, ESE delivers a fast, scalable, and precise tool for disaster recovery. Real-time field validation will enhance its applicability.

Keywords: earthquake, rapid loss assessment, observed damage, repair methods, cost, duration.

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1 INTRODUCTION

Earthquakes, one of the most destructive natural disasters, can cause tremendous losses and damage to the built environment. The effective functional recovery process and earthquake disaster mitigation planning are conditioned by well-informed decisions [1] that are based on damage and loss assessment processes. The rapidity and accuracy of these processes are crucial for the successful management of the recovery process of the affected community [2].

Research on natural disaster recovery modelling has significantly increased compared to previous years [3]. Current earthquake loss assessment methodologies and tools are predominantly based on probabilistic assumptions of seismic scenarios [4-7]. The Performance-Based Earthquake Engineering (PBEE) framework [4] provides a probabilistic assessment for the quantification of relevant performance metrics, such as repair cost and recovery time [6]. The PBEE framework was adopted by the Federal Emergency Management Agency (FEMA) initiative [7] for widespread application by compiling a comprehensive library of peer-reviewed fragility curves and corresponding consequence functions. This effort encompasses more than 700 structural and nonstructural building components, developed using standard methodologies [8] and published data [6]. Terzic et al. [6] proposed a new framework for assessing post-earthquake functional recovery (F-Rec), aligning with the PBEE methodology and FEMA Performance Assessment Calculation Tool (PACT) [9]. The F-Rec framework incorporates three integrated models to evaluate post-earthquake functionality, mobilization time, and repair time [6]. Burton et al. have adapted and incorporated PBEE methodology in the probabilistic assessment of building-level functional recovery [10]. The proposed framework includes evaluating a range of building performance limit states that directly contribute to assessing community seismic resilience. Probabilistic methodologies for the assessment of the post-earthquake recovery process at building-level contribute to understanding how individual buildings influence community resilience [6, 10-13].

The observed post-earthquake damage states can be obtained through remote sensing or field surveys [14]. There are various techniques available for damage observation through remote sensing [15], from conventional (e.g. satellite imagery and aerial photography) [16-17] to more contemporary (e.g. LiDAR and machine learning) [18-19]. Ci et al. [20] used aerial imagery, convolutional neural networks, and ordinal regression to assess the damage severity. Remote sensing methods for damage assessment are limited by the inability to inspect the interior of buildings, which affects the accuracy of damage extent estimation [14]. In contrast to remote sensing, field surveys enable inspecting the entire building. The main shortcoming of this approach is that it cannot be considered rapid. On-the-ground field surveys have been applied to some recent earthquakes. After the 2020 Zagreb earthquake, data on damage were collected through field surveys, including visual inspection and geometrical surveys [21-22].

This paper proposes the ESE (Elements-Severity-Extent) Framework integrated within the RELAR system. Compared to cited papers, the ESE framework represents a unique accuracy/speed tradeoff, aiming to achieve the accuracy of slow-paced field surveys while being fast enough to be considered rapid. ESE framework also aims to improve the current research in the field of construction management planning by increasing the granularity of the output, descending to the resource (materials, labour, equipment) consumption level. The framework is designed to provide deterministic repair cost and repair time calculations based on direct damage observations, a decision tree (providing insight into the repair method), and repair norms used to quantify resource consumption.

Firstly, the concept of the ESE framework is explained. To differentiate the ESE Framework from comparable frameworks and tools, the comparison with the PACT estimating tool is described. Afterwards, the proposed framework is presented in detail, along with the results of its application to a case study.

2 THE RELAR-ESE CONCEPT

This research advances the development of the RELA framework for rapid earthquake loss assessment. Unlike the fragility-based, ground motion-triggered damage state (DS) predictions of the traditional approach to rapid loss assessment, RELA utilizes a machine-learning damage classification model and a representative sampling algorithm. The RELA framework, explained in [2], was designed to observe damage states on buildings from the representative sample (RS) while the Random Forest ML model makes DS predictions on the portfolio with acceptable accuracy. Research in ML-based DS predictions is recognized in the science community [23-24], while our RS concept remains unique. RELA estimates the predicted repair cost (PRC) for buildings using the repair matrix, which contains monetary estimates (€/footprint area) to repair each damage state. Using the Repair Matrix to calculate PRC constitutes advancement in precision compared to other approaches where repair costs are estimated as a ratio of replacement value. However, there is room for improvement. Although RELA estimates the portfolio PRC with good precision, we detected a notable number of over and under-estimates for individual buildings. Also, actual data showed that lower DS repair costs sometimes exceeded higher DS repair costs due to the extent of damage, which was not considered in the Repair Matrix. Most importantly, PRC is valuable for estimating a portfolio repair budget but contains no information about resources, which is essential for planning the recovery and repair process.

As the ultimate goal of our research is to enable resource-constrained portfolio-level planning of repairs, we decided to expand the RELA concept. This research advancement is enabled by a 3-year science project named RELAR (Rapid Earthquake Loss Assessment and Recovery Framework), funded by the Ministry of Science of the Republic of Serbia, focusing on repairs and planning the recovery process. Observing the RS to make ML predictions remains the core concept of the framework, but we now alter the content of the field survey by moving away from observing the DS. The new approach is to observe actual damage in each room and exterior of the building on a macro and micro level. The macro level refers to the general condition of the observed element, while the micro level relates mainly to cracks, defined by severity (width, depth and direction) and extent (length or area). To rapidly capture and process on-site data, the proposed procedure uses a spreadsheet-based interface (e.g., Google Sheets). The key feature of the framework is the expert knowledge-based decision tree linking the observed damage to pre-determined repair methods. Repair methods consist of several work items (activities). Standard planning procedures and resource usage rates (norms) enable further decomposition of work items into needed resources - materials, labour, and equipment per unit of measure characterizing the particular repair method. The proposed calculation sequence enables the transformation of the observed damage length or area into resource quantities. Summing resource quantities multiplied by resource unit prices determines the cost to repair the observed damage. Repeating the procedure for all observed damages determines the overall repair cost of the building. The procedure also determines labour working hours for executing the repair method work items. The repair duration is calculated using the required input – the number of available workers. We will explain the procedure in more detail in the next chapter.

As developing the ESE sub-framework is ongoing research, in this paper, we will show how it works for one element – masonry walls. We will use a case study to demonstrate the

ESE operation and output. The same procedure applies to other elements, such as slabs, roofs, or stairs.

To differentiate the ESE sub-framework from similar frameworks and tools, we compare it with the industry standard and state-of-the-art method for estimating repair cost and time, the FEMA P-58 PACT estimating tool. The comparison is shown in Table 1.

Title 1	PACT	ESE
Concept, Methodology	1. Fragility and Performance Groups 2. Probabilistic Analysis	1. Direct Damage Observation 2. Decision Tree for Repair Methods 3. Repair Norms (resource consumption)
Preparation (Pre-earthquake phase)	1. Adjusting design for PACT input 2. Expert knowledge needed for input	1. Adjusting design for ESE input 2. Expert knowledge needed for input 3. Basic training of non-expert inspectors 4. Creating the RS (sampling algorithm)
Execution (Co-earthquake phase)	Time: Instantaneous Resources: Computer station	Time: ~30min for a standard house, a few days for the Representative Sample. Resources: Non-expert inspectors, Computer station
Input	Ground motion (sensors & formulas)	Damage observation (on-the-ground)
Calculation – Repair cost	Probabilistic single-figure repair cost for components. Repair method determined: NO Calculation sequence (automatic): Probabilistic, Monte Carlo (all methods & all probabilities) RC = ∑(single figures)	Deterministic resource-derived repair cost for observed damages. Repair method determined: YES Calculation sequence (automatic): Decision tree - Repair method - Methodology - Work items - Norms » Resource quantities (materials, labour) RC= ∑(quantity x unit price)
Calculation – Repair time	Probabilistic single-figure repair time for components. Calculation sequence (automatic): Probabilistic, Monte Carlo (all methods & all probabilities) Input: Components repair sequence - all at once, or one by one Single-figure repair time for the whole building.	Deterministic resource-derived repair time for observed damages. Calculation sequence (automatic): Decision tree - Repair method - Methodology - Work items – Norms » Resource quantities (materials, labour) Input: Available resources (crews, materials) Scheduled (resource-driven) repair time for the whole building.
Accuracy	Low	High
Uncertainties	High	Low

Table 1: PACT – ESE comparison

As can be seen from Table 1, both approaches need design adjustment and expert knowledge to prepare input. PACT works instantaneously and requires no resources for execution, assuming the existence of a ground-motion sensor network. On the other hand, ESE requires non-expert inspectors to conduct field surveys. The training for inspectors is basic and short, involving just recognizing the general condition of the element (choosing from a pre-defined menu) and the depth and width of the cracks (choosing between pre-defined intervals). A field survey takes approximately 30 minutes for a standard two-story house. However, ESE output surpasses the PACT output in better accuracy and richer content, leading to increased usefulness. Instead of single-figure estimates, ESE results are more detailed, richer in content and directly usable for planning the repair and recovery process. The accuracy/speed tradeoff undoubtedly favours the ESE framework. We will revisit the PACT-ESE comparison in the Conclusion chapter after explaining the procedure in Chapters 3 and 4.

3 ESE PROCEDURE FOR REPAIR COST AND DURATION ASSESSMENT

ESE is based on observing the severity and extent of damage to elements of a building. The elements are determined for each building type, representing parts of the building crucial for assessing the performance of buildings during seismic events. The elements are categorized as:

1. Structural Elements: Primary elements ensuring building stability (e.g., walls, beams, slabs, columns).
2. Non-Structural Elements: Elements crucial for functionality and safety (e.g., partitions, ceilings, finishes, installations).

Each element is characterized by a specific type of work, technology, and building materials, which define corresponding repair methods.

The severity of damage is determined for elements on a macro and micro level. The macro-level severity determines if an element is damaged beyond repair and requires replacement, is not damaged, or needs repair at the micro level. The micro-level severity captures the geometry, width and depth of cracks, influencing the appropriate repair method.

The extent of damage is measured in terms of crack length or affected surface area, enabling quantitative repair cost and time estimations.

Severity and extent are recorded using a spreadsheet-based interface (e.g., Google Sheets) designed to rapidly capture and process on-site data from room to room and the exterior of the buildings. This methodical approach is more detailed than standard field surveys and convenient for future inspection guidelines.

The first step of the ESE framework is using the repair method decision tree to determine the specific repair method for an element depending on the element category, severity and extent of damage. The second step calculates the needed resources - labour, equipment, and materials for executing the repair method, enabling the calculation of repair cost and duration.

3.1 Repair cost and duration assessment

Repair cost and duration assessment is a two-step procedure. Based on the observed damage characteristics, the first step determines the repair method using the decision tree. The second step estimates the repair cost and duration based on the quantity of observed damage using the resource analysis table.

The procedure will be explained for one element common for most building types – masonry walls. ESE framework distinguishes between different types of walls, each having its own decision tree - concrete, brick, plasterboard, and wood walls. Figure 1 shows the decision tree for masonry walls, describing the decision-making process.

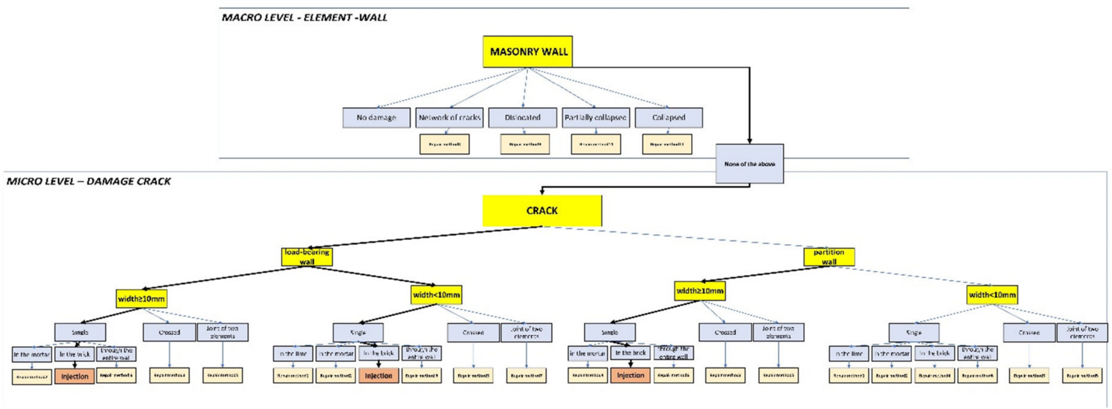


Figure 1. Repair method decision tree for masonry walls

The first step of the ESE framework is to determine the appropriate repair method for the observed damage.

Two damage severity levels are identified for masonry walls: macro and micro. At the macro level, the general condition of the observed wall is determined, while the micro level determines the condition of the crack. At the wall macro level, the following types of damage may occur:

- Not damaged
- A web of cracks
- Dislocated
- Partially collapsed
- Collapsed

If the proposed labels cannot describe the damaged wall, the damage is evaluated on the micro level (crack level). ESE framework proposed three categories that can describe cracks in masonry walls:

- Wall type (bearing or partition wall)
- Crack width (width≥10mm or width<10mm)
- Crack depth (in lime, in mortar, in brick, through the entire wall)

The categorical criteria for describing cracks are created to suit rapid inspection and automated decision-making. For example, a non-expert inspector can more easily and quickly label the depth of a crack in different materials than using exact numerical values.

At the end of each branch, the decision tree proposes an appropriate repair method. In this way, expert knowledge of all damage/repair scenarios of masonry walls is sublimated.

The second step of the ESE framework provides an in-depth analysis of each repair method, with a detailed analysis of the activities, materials, labour, and equipment for executing each repair method. A calculation example performed in the “Resources analysis” spreadsheet is shown in Table 2 for one of the commonly used repair methods – injection.

Resource analysis table
RM13 – Injection of masonry walls
*The calculation refers to **m'** of crack*

Activity	Labour norms		Material norms			Unit prices	Working Hours
	Working hours (h/m')	Number of workers	Inlet nozzles (pcs/m')	Sealan (kg/m')	Cement suspension (l/m')	Per unit mesure (EUR/m')	h/m'
Preparatory works							
Chiseling	0,500	1				3,500	0,500
Cleaning	0,133	1				0,930	0,133
Flushing	0,083	1				0,580	0,083
Primary works							
Installation of inlet nozzles	0,200	2	5			1,420	0,400
Surface sealing of cracks				0,5		4,900	
Flushing	0,067	1				0,470	0,067
Injection	0,917	2			4,5	44,920	1,834
Finishing works							
Removal of injectors	0,050	1				0,350	0,050
Final cleaning	0,167	1				1,170	0,167

Table 2: The "Resource analysis" spreadsheet for the Injection repair method

The same "Resource analysis" spreadsheet is pre-prepared for all decison tree repair methods to calculate repair costs and working hours for one unit of measure. All activities are classified into three categories: preparatory, primary, and finishing. The allocation of time and resources is determined based on expert experience. ESE framework includes a database containing market resource unit prices. A database dynamic interface is foreseen, enabling flexibility and adaptability to specific local conditions regarding unit prices and resource consumption rates (norms).

The comprehensive analysis of the allocated resources eventually determines material and labour costs and needed working hours for one unit of measure. Table 3 shows the cost structure and working hours required for the injection repair method.

Resource analysis table - Summary
The calculation refers to m' of crack

Material cost	30,25 EUR
Labour cost	36,38 EUR
Dry cost (Material + Labour)	66,63 EUR
Working hours	3,23 h

Table 3: Cost and time repair assessment structure

Pre-prepared "Resource analysis" spreadsheets contain labour and material norms and unit prices. To produce a cost and duration estimate, the table needs a single input – the quantity of the observed damage. For injection, it is the observed length of the crack. In this example, if the observed crack is 10m long, repairing it using the injection method would cost 582.4 euros. After processing all observed damage the same way, the Repair Bill of Quantities determines the total repair cost for a building.

The proposed procedure determines the total needed working hours. Determining the repair duration needs an input - the available number of workers. In this example, to repair the 10m crack, two workers would need to work together for 10.6 hours (21.17h / 2 = 10.59).

Allowing this kind of input is extremely useful for portfolio-level repair planning, the next goal of our research.

3.2 Spreadsheet-Based Tool for Rapid Damage Observation

In the proposed ESE procedure, a spreadsheet-based interface (e.g., Google Sheets) is used to rapidly capture and process on-site data since nearly all mobile or tablet devices support spreadsheets. Each row corresponds to a specific damaged element (e.g., a wall) and includes columns for the **building level**, **room**, **wall type**, **damage level**, **crack width**, **crack depth**, and a **crack length** dropdown (in 0.5 m increments). Inspectors can also embed a reference photo directly in each row (Figure 2) to visually document the damage.

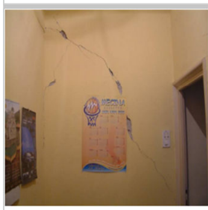
Photo	Level	Room	Wall type	Damage level	Crack length	Crack area	Crack width	Crack depth	Suggested Repair Method
	ground floor	hallway	bearing	crack	1.5m		≥10mm	brick	**Injection**

Figure 2: Sample Google Sheets interface showing columns for building level, room, wall type, damage parameters, and a "Suggested Repair Method" cell determined by the ESE decision tree. A photo is also embedded for quick reference.

To integrate the ESE framework's knowledge-based decision tree, a **"Suggested Repair Method"** column automatically populates once an inspector selects the relevant inputs. For instance, if an inspector chooses "bearing" for wall type, "≥10 mm" for crack width and "brick" in the crack depth column, the system infers the appropriate repair method (e.g., "Injection") based on the ESE decision tree. In addition, respective scripting logic (here, Google Apps Script) aggregates this information across all rows to produce cost and time estimates across repair methods. Each identified repair method is assigned its output sheet, listing the total length or area of damage required by the repair method, acompanied with the associated resource consumption.

This spreadsheet-based workflow is user-friendly as users can quickly select from simple dropdown menus for each damage attribute. By capturing all input data in a standardized format, the ESE logic generates real-time repair forecasts, further streamlining the rapid assessment process.

4 CASE STUDY

The application of the ESE framework will be demonstrated in a case study of a residential building affected by the 2010 earthquake in Kraljevo. The ESE framework will be tested using original images of the residential building from Kraljevo documentation. This step deviates from the proposed ESE framework outlined in the previous chapter. Namely, considering there is no current earthquake in Serbia for direct inspection according to ESE protocol, existing images from the Kraljevo earthquake are utilized.

The database included 83 images representing damages in one of the residential buildings in Kraljevo, Ribnica district. Each image was associated with a caption indicating the wall position. The inspector annotated each image according to the attributes shown in Figure 2 (building level, room, wall type, damage level, crack width, crack depth, and crack length), but in this case, the process was conducted from an office. After annotating all images, the results were automatically summarized, and an output worksheet was created. The outcome of the ESE framework is a report – worksheet structured into three main sections: the first section provides general information about the building; the second section outlines the selected repair method along with the corresponding quantities; and the third section presents resource quantities, different cost categories, and working hours.

The specific predefined characteristics of each repair method are identified through the decision tree. This case study describes the procedure and results for one repair method - Injection. For this repair method, the key observed parameter is the total length of cracks. The ESE framework identified 15 images containing cracks being repaired by Injection, with a total crack length of 32.5 meters. An example of a worksheet for a case study resident building is shown in Figure 3.

WORKSHEET No. XXX

RELAR

I General

Work sheet	xxx
Residental Building No.	xxx
Address	xxx
Gross Area	125m2
Footprint	68m2
Number of floors	2
Number of rooms	12
Date of Inspection	17/02/2025
Drawings (Floor plan, Section)	
Inspector	Marko Markovic

II Repair Method

RM13	**Injection**
Image No.	4;12;18;37;44;45;48;54;55;64;58;72;73;75;78
Total number of walls	15
Total crack lenght	**32,5m**

III Resource Analysis

Resources

Labour	
Qualified labour(nh)	29.80
Semi-qualified labour (nh)	75.29
Material	
Sealan (kg)	16.25
Inlet nozzles (pcs)	162.5
Cement suspension (l)	146.25

Cost and Shedule

Total Labour Cost (EUR)	1,182.35
Total Material Cost (EUR)	983.13
Total Dry Cost (Material + Labour) (EUR)	**2,165.48**
Total Working hours (h)	**105.10**

Note

xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx xxxxxxxxx.

Figure 3: Case study worksheet for RM13

The presented worksheet applies to a chosen repair method - injection. The ESE framework summary worksheet provides an agregation of resources required for all repair methods. In addition, it presents the different cost categories and the estimated repair duration, both at the method level and for the entire building.

In a general sense, the ESE framework implies that each residential building has its worksheet with general data, a list of all selected repair methods with associated quantities, and resource/cost/duration analysis. The final result presents an automatically created Repair Bill of Quantities (RBoQ) for each building.

5 CONCLUSION

The ESE framework presents a novel and practical approach to post-earthquake repair assessment, integrating rapid damage observation, expert knowledge-based decision trees, and standardized planning and scheduling techniques. Unlike existing models, ESE enhances accuracy by relying on field data instead of probabilistic assumptions. ESE bridges the gap between traditional estimation methodologies and real-world implementation by incorporating structured repair workflows.

Compared to the widely used FEMA P-58 PACT tool, ESE significantly improves the precision and usability of repair cost and time estimation. While PACT provides rapid, probabilistic estimates useful for financial risk assessments and regulatory compliance, it lacks specific repair methods, real-world scheduling considerations, and portfolio-wide extrapolation capabilities. In contrast, ESE's deterministic approach provides directly actionable repair schedules, allowing for accurate resource planning, material logistics, and structured execution workflows. The ability to conduct portfolio-wide extrapolation using machine learning represents a key advantage, enabling comprehensive regional recovery planning that PACT does not support.

A case study demonstrated the ESE framework's operation by assessing masonry walls using an image-based damage annotation process and decision-tree-driven selection of repair methods. While the study provided compelling results, future validation through live field applications is necessary to confirm its effectiveness. Additionally, expanding the methodology to cover a broader range of structural elements and repair methods would reinforce its applicability to diverse building types.

The findings suggest that the ESE framework significantly advances earthquake recovery planning by balancing speed, accuracy, and practicality. By transitioning from damage state classification to direct damage quantification, ESE enables resource-constrained, portfolio-level repair scheduling—a capability essential for post-earthquake recovery. Future research will focus on refining its predictive capabilities through machine learning integration, improving automation, and expanding the framework's applicability to more structural and non-structural elements.

With its structured and scalable approach, ESE represents a significant step forward in post-earthquake recovery planning, offering stakeholders an effective tool for real-world damage assessment, repair estimation, and resource management.

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