SECED 2023 Conference
Earthquake Engineering & Dynamics for a Sustainable Future
14-15 September 2023, Cambridge, UK

EXPLORATION OF STATE-DEPENDENT RAPID LOSS ASSESSMENT AND EVENT-BASED OPERATIONAL EARTHQUAKE LOSS FORECASTING INCORPORATING STRUCTURAL HEALTH MONITORING: AN OPEN-SOURCE TOOL

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Abstract: Soon after an earthquake occurs, several stakeholders become interested in estimating the damage and losses generated by the event, as this can inform decision-making processes regarding first response, aid and recovery. The scenario might change rapidly if subsequent aftershocks cause further damage, which might occur even with low shaking intensities, given the cumulative weakening of the structures due to successive shocks. Recently-developed strategies for large-scale derivation of state-dependent fragility models allow for this to be taken into account when carrying out Rapid Loss Assessments (RLAs) during an ongoing sequence, as well as when estimating short-term future losses based on seismicity forecasts in the context of Operational Earthquake Loss Forecasting (OELF). Moreover, recent advances in the estimation of damage by means of Structural Health Monitoring (SHM) offer the possibility of incorporating information recorded at the buildings themselves to both RLA and OELF. Partner institutions of the European Horizon 2020 RISE project have been working on several of these fronts and, as part of the project, an open-source Python module has been developed that runs RLA and OELF calculations by calling OpenQuake and continuously updating the building stock to reflect the probabilities of buildings suffering from different damage states at different stages of an ongoing earthquake sequence. The module also calculates expected direct economic losses as well as number of injuries and deaths, and uses the latter to update the number of occupants at any point in time. While our workflow builds upon existing work, we believe it to be the first that is publicly available as open-source software and it is thus particularly suited for incorporating further aspects of the earthquake consequence chain (e.g., other sources of damage estimation, longerterm recovery) and evaluating the feasibility of computational demands, while being amenable to further development towards rendering these new technologies fully operational.

Introduction

The occurrence of an earthquake of relevance in the vicinity of exposed populations prompts a need from different stakeholders to gain an understanding of the potential impact and consequences the event may have and perhaps even a prognosis of what could be expected

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from subsequent seismic activity in the area. A simple qualitative assessment—in terms, for example, of a no impact, minor impact, major impact classification, a so-called *Rapid Impact Assessment*—is often sufficient in the first few minutes following the earthquake. As time progresses, a quantitative estimate of losses (e.g., number of collapsed buildings, number of fatalities or homeless people, direct economic loss), or so-called *Rapid Loss Assessment (RLA)*, becomes more relevant in order for stakeholders such as early responders, governments, and the insurance industry to be able to plan and better manage the recovery phase after the earthquake (e.g., search for trapped survivors, need for emergency shelter, request and channelling of national and international funds, addressing of potential insurance claims). Similarly to the well-established PAGER (Prompt Assessment of Global Earthquakes for Response) service (Earle et al., 2009) of the United States Geological Survey (USGS), a European ShakeMap is now online (http://shakemapeu.ingv.it/) and a prototype scientific service that allows the damage and losses to be assessed for any ShakeMap in the European ShakeMap system (the ESRM20 Rapid earthquake Loss Assessment code) has now also been released (Crowley et al., 2023) with the support of the European Horizon 2020 RISE project.

RLAs can be carried out fully using pre-defined models that describe the expected ground motions associated with a certain earthquake rupture and expected vulnerability of the exposed buildings and populations (and their associated variability), but can also gain in accuracy by being able to incorporate observed measurements, such as the USGS ShakeMap system does with ground motions measured by seismic stations and felt reports from citizens (the *Did You Feel It* system). The increasing availability of low-cost sensors that can be used to continuously monitor the dynamic response of buildings—the so-called practice of *Structural Health Monitoring (SHM)*—offers the possibility to go one step further and use sensor data to generate near-realtime estimates of damage (e.g., Reuland et al., 2023b) that could be incorporated into the RLAs. To the authors' knowledge, this possibility has so far only been explored by the research community or for individually-monitored buildings, but there is yet no operational system able to do this at a city or regional scale.

The natural complement to the focus of RLAs on the estimation of losses due to earthquakes that have already occurred is the capacity to forecast the evolution of seismicity and losses in the days, weeks and months that follow a seismic event of relevance, the so-called *Operational Earthquake Forecasting (OEF)* and *Operational Earthquake Loss Forecasting (OELF)*. OEF systems have already been implemented in countries such as Italy, New Zealand and the United States (e.g., Marzocchi et al., 2014), with the objective of providing short-term time-dependent earthquake probabilistic forecasts. OELF, the extension of OEF into the loss domain, which is, by nature, one step closer to the decision-making process, has only been implemented in Italy by means of the MANTIS-K system (Iervolino et al., 2015).

Up to recent years, the development of fragility models to be used in seismic damage and loss assessments had mostly focused on the response of initially undamaged structures, leading to so-called *state-independent* models. The recognition that earthquakes usually occur in clusters or sequences and that the occurrence of damage may have a non-negligible impact on the capacity of a building to withstand subsequent earthquake demands has, however, led to the development of *state-dependent* fragility models and strategies to account for the accumulation of damage by an increasing number of researchers (Iervolino et al., 2016; Orlacchio, 2022). The use of such state-dependent models is key not only to producing realistic estimates of damage and losses during an earthquake sequence (in a succession of RLAs) but also for OELF, as the forecast naturally focuses on a succession of seismic events to come. In Italy, MANTIS-K has recently been expanded into MANTIS v2.0 as part of the RISE project to account for the evolution of the structural damage over time (Chioccarelli et al., 2022).

As an active part of the earthquake hazard and risk community, partners of the European Horizon 2020 RISE project have been working on several of the aforementioned fronts. An open-source Python module called Real-Time Loss Tools (RTLTs, https://git.gfz-potsdam.de/real-time-losstools/real-time-loss-tools) was developed with the double purpose of demonstrating how different developments of the RISE project can be assembled to work together while at the same time creating a publicly-available tool that the research community could use to explore all the aspects of this integration and develop strategies for future scalability and operationalisation. The main aspects of the Real-Time Loss Tools are described in the present paper, which includes as well a case-study application based on the 2016-2017 Central Italy seismic sequence. Full details can be found in Nievas et al. (2023).

The Real-Time Loss Tools (RTLTs)

Overview

The Real-Time Loss Tools (RTLTs) have been designed to carry out RLAs and event-based OELFs incorporating probabilities of damage states based on SHM methods, estimating cumulative damage by means of state-dependent fragility models, calculating expected economic losses and human casualties (injuries and deaths) and updating the number of occupants in the buildings, by accounting for the time of the day of the earthquake as well as whether occupancy can be resumed and to what extent (depending on inspection and repair times as well as casualties). The RTLTs recursively call the OpenQuake engine (Pagani et al., 2014; Silva et al., 2014), updating its input files for each earthquake and keeping track at every point in time of the damage states of buildings and the number of people unable to return to the buildings they usually occupy. The triggering of RLA or OELF calculations is carried out by means of an input CSV file, and the software runs until all triggers have been processed, as shown in Figure 1.

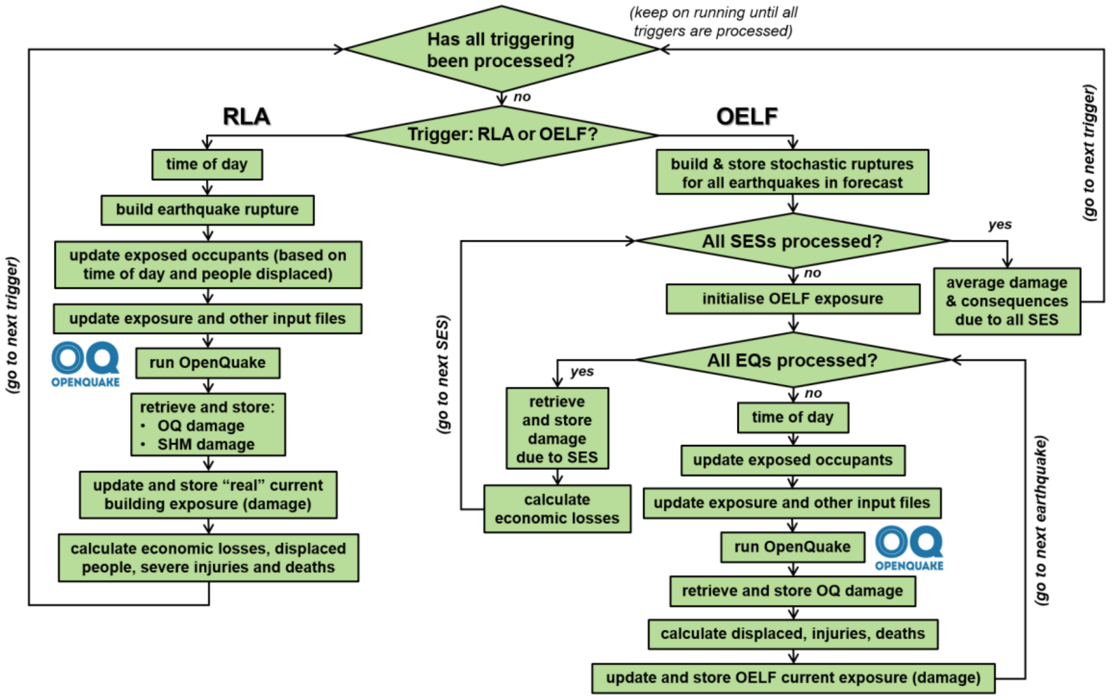

Figure 1. General overview of the processing algorithm of the Real-Time Loss Tools (RTLTs).

Rapid Loss Assessment (RLA) incorporating Structural Health Monitoring (SHM)

The RLA calculation starts with the transformation of the UTC time of occurrence of the earthquake into local time, which is translated into one of three time intervals of the day (day, night, transit) for which adjustment coefficients are input in the configuration file. This information is combined with previous results on existing damage and injured/dead people from RLAs run by the software so far to update the number of occupants in the buildings of the exposure model. The current version of the RTLTs creates rupture input XML files for OpenQuake based on rupture data input by the user, assuming normal faulting, but the code will soon be adapted to enable the user to directly input rupture XML files if they wish to. Other input files for OpenQuake are updated as well, and a scenario damage calculation is run with OpenQuake using state-dependent fragility models that take into account the current damage state of the building (an alternative algorithm that works with state-independent fragility models has been coded as well for research purposes, but will not be discussed any further in the present paper).

Damage results in terms of probabilities and/or number of buildings in different damage states are retrieved from this OpenQuake calculation for all buildings in the exposure model. If SHMbased damage probabilities (or damage probabilities stemming from any other external calculation) are available for some buildings (as per an input CSV file), these override the damage probabilities calculated with OpenQuake for those buildings. The resulting damage probabilities are subsequently used to update the exposure model and redistribute the replacement costs and theoretical census occupants (i.e., number of occupants irrespective of previous earthquakes or time of day). The expected economic losses are finally calculated based on the current probabilities of each damage state by means of an economic consequence model defined by the user. These losses are cumulative, as they are based on cumulative damage states. The injuries and deaths are also calculated based on the current probabilities of each damage state for each asset in the exposure model by means of a human consequence model, and the timelines for people to be allowed and able to return back to their buildings are calculated and stored. The algorithm then moves on to processing the next trigger.

Event-based Operational Earthquake Loss Forecasting (OELF)

The OELF calculation starts by reading a seismicity forecast (input by the user as a CSV file) and using a stochastic rupture generator to build ruptures associated with each of the earthquakes in the forecast. The stochastic rupture generator makes use of models of uniform area sources provided in the OpenQuake seismogenic source model XML format to sample rupture properties starting with the hypocentral depth, which is usually not available from short-term seismicity forecasts. Once the depth is defined, the rupture nodal properties are sampled and the rupture area is calculated from a magnitude-to-area scaling relation selected by the user. An initial rupture generated from these parameters is compared against the input upper and lower seismogenic depths, it is adjusted if the vertical extent of the rupture width is less than the seismogenic thickness of the source zone, and it is finally assigned to the earthquake and the associated OpenQuake rupture XML file is created. This procedure is only carried out for earthquakes above a magnitude threshold and within a maximum epicentral distance from the input exposure model, all these defined as input by the user. All other earthquakes in the seismicity forecast are assumed to not cause any change in the damage state of the buildings. This event-based OELF approach departs from the closed-form rate-based analytical formulation of MANTIS-K (Iervolino et al., 2015) to address the recent trend in the seismicity forecasting community to transition from generating forecasts in terms of earthquake rates to outputting large numbers of stochastic realisations of seismicity (i.e., full catalogues of possible earthquakes), and is similar to what was done by Papadopoulos et al. (2020) in the context of probabilistic seismic risk assessment.

Each realisation of seismicity is referred to as a stochastic event set (SES) in the RTLTs, following the nomenclature used by OpenQuake. As shown in Figure 1, the OELF calculation loops through each SES and, within each SES, through each earthquake. At the beginning of each SES, the exposure model is initialised taking the current “real” exposure as a starting point. “Real” is used in this context to refer not to a representation of directly-observed damage states but to the exposure model that is updated by the RLA calculations when earthquakes actually happen. This is a fundamental difference between the RLA and OELF routines of the RTLTs, as the OELF routine does not update the “real” exposure because it is a forecast that may or may not occur. Within each SES, damage builds up and the OELF exposure model associated with the SES is updated, analogously to what happens in a RLA calculation. The calculation of the local time, the updating of the number of occupants and the running of the scenario damage calculator of OpenQuake is the same as for RLA (except for no SHM damage results being considered).

The OELF economic losses are calculated at the end of each SES based on the final damage status of the assets (for that SES), but the human casualties and their associated timelines for people to be allowed or able to return need to be calculated for each earthquake. Damage states, economic losses and human casualties are averaged out for all SESs and the resulting expected values are output as the results of the OELF calculation (uncertainties could be tracked as well in future versions of the software).

Keeping track of damage states

The use of state-dependent fragility models for the calculation of cumulative damage requires that the RTLTs keep track of the damage state of buildings. The tools do so by updating the exposure model (which is written in the CSV format used by OpenQuake) after each new earthquake is run. While OpenQuake only uses the concept of exposure *asset* to refer to a building or group of buildings with the same assigned location and building class (i.e. each row of the exposure CSV file), the RTLTs make use of two additional definitions: the term *building_id* is used to refer either to an individual building or a geographic aggregation of buildings, which can include different building classes (in the case of an individual building, these could be classes with a probability of being the appropriate ones for the building), and *original_asset_id* is used to refer to a specific building class of a specific *building_id*, in the initial damage state input by the user. The term *asset_id* then becomes the equivalent of OpenQuake’s *asset*, and refers to a specific combination of *building_id*, *original_asset_id* and damage state. This is schematically shown in Figure 2, together with the way the exposure model is updated in terms of expected numbers of buildings that result in each damage state. When the *building_id* refers to an individual building, the values assigned are the probabilities of the damage states (combined with the probabilities of each building class, i.e., each *original_asset_id*).

Each time the exposure model is updated, the replacement cost and number of occupants (at the time of the day of the earthquake and accounting for previous injuries and deaths) are distributed proportionally to the splitting in terms of numbers of buildings. Once the replacement costs have been distributed, economic losses are calculated. The calculation of injuries and deaths requires some additional considerations, which are described next.

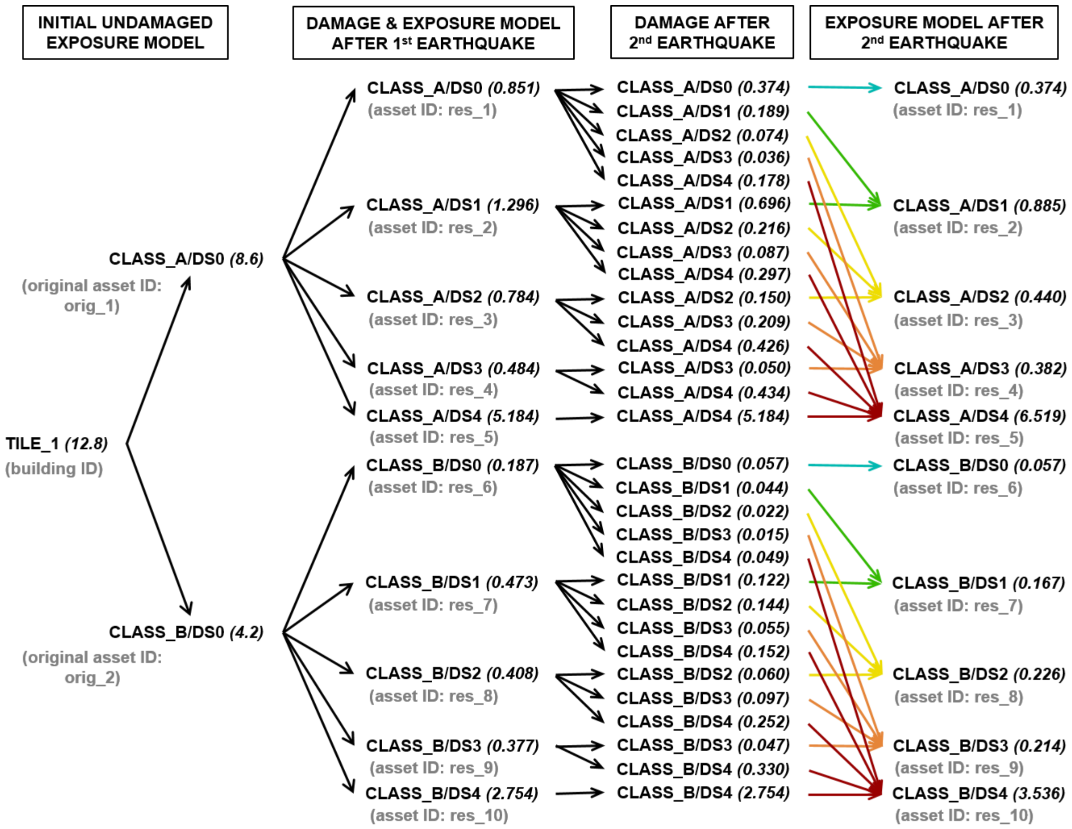

Figure 2. Example of the update of damage states in the exposure model for one tile with buildings of two different classes. Numbers in italics in parentheses are numbers of buildings.

Updating the number of occupants

There are several reasons why the number of occupants of buildings may change after an earthquake, including deaths and/or hospitalisations resulting from the earthquake, the safety of buildings to be occupied, and potential interruptions to lifelines (electricity, gas, water) and roads. The RTLTs do not intend to model the complex dynamics of post-earthquake recovery in all their extent—though a potential link with the OpenQuake Recovery and Rebuilding Effort (OQ-RRE) software developed as part of the RISE project by Reuland et al. (2022) could be made in the future—but focus on just the two first aspects to estimate an expected number of occupants at the time each earthquake occurs. To the authors' knowledge, this is the first attempt to carry out such an update for an earthquake sequence.

In order to run, the RTLTs require that the users input expected numbers of days needed for inspection and repair (as a function of the damage state of the building), and numbers of days that people are expected to spend in hospital (as a function of the severity of their injuries), all counted with respect to the point in time at which an earthquake occurs. When a RLA (or damage assessment due to one earthquake within an OELF) is carried out, the RTLTs calculate two timelines: one with the points in time (UTC) in which people are allowed back into buildings (conceptualised as a 0-1 Boolean of not allowed-allowed specified per damage state) and another with the number of people "still away" from the buildings they usually occupy, at each point in time (also UTC) (see Figure 3).

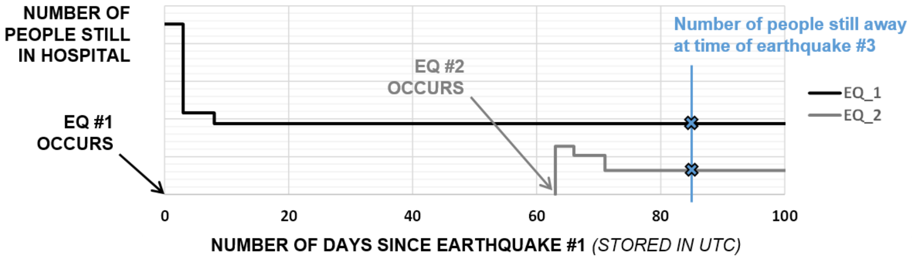

Figure 3. Schematic timeline of number of people still away due to injuries/death.

When a new earthquake calculation starts, previous timelines due to all previous earthquakes are sought and the number of occupants for each *original_asset_id* is calculated as: $\textit{occupants at time of day}_{\textit{current}} = F_{\textit{time of day}} \cdot F_{\textit{occupancy}} \cdot [\textit{census}_{\textit{original}} - \textit{still away}]$ (1)

where $F_{\textit{time of day}}$ is the factor associated with the day, night or transit times of the day, $F_{\textit{occupancy}}$ is the 0-1 binary factor that depends on the current damage state of the building, $\textit{census}_{\textit{original}}$ is the number of census occupants, and *still away* is the number of people whose health status does not allow them to return to the building.

This updating of the number of occupants is a simplified version of what could, perhaps, become a more rigorous calculation that would involve keeping track of all the paths of damage that each *original_asset_id* can follow, instead of re-grouping *asset_ids* by current damage state, as shown in the last step of Figure 2. Each path for an *original_asset_id* to end in any damage state would lead to their own future timeline of possible damage and further injuries, but expanding the branching at every earthquake quickly leads to a significant increase in computational demand. Alternative strategies for approaching this matter could be explored in the future.

Output

The final output of each RLA and OELF calculation is generated by *building_id*. For each RLA calculation, the outputs are: (1) number of buildings or probability of a *building_id* resulting in each damage grade; (2) expected economic losses for each *building_id*, in terms of both absolute values and loss ratios (with respect to their total replacement cost); (3) expected human casualties for each *building_id*, classified by (user-defined) levels of severity, in terms of both absolute values and loss ratios (with respect to the total number of census occupants). The outputs for each OELF calculation are the same as for a RLA, averaging out the results for individual SESs. Future implementations could expand these outputs to include measures of the uncertainty in the results, which might be particularly relevant in the case of OELF calculations.

Case-study application

Overview

A series of proof-of-concept applications based on the 2009 L'Aquila and 2016-2017 Central Italy earthquake sequences were developed as part of the demonstration and integration activities of the RISE project, with the purpose of showcasing how different RISE developments in the fields of RLA, SHM and OELF could fit together by means of the RTLTs. Although three and four different locations of exposure were considered for each of the two sequences, respectively, only that of the AMT seismic station in the town of Amatrice is presented in what follows (see Figure 4). Details on all case studies can be found in Nievas et al. (2023).

The exposure model (Figure 4) used for the case-study is fictitious, as it gathers three individual buildings studied within RISE, two of which are monitored in reality (the Grenoble City Hall, France, and a building in Budva, Montenegro) and a third representing a typical residential Swiss structure, as well as a series of Italian masonry and reinforced concrete building classes for which state-dependent fragility models were developed (Orlacchio, 2022, taking as a starting point the state-independent models of ESRM20, see Crowley et al., 2021), classified as per the GEM Building Taxonomy v3 (Silva et al., 2022). The definition of the exposure in terms of nine quadtiles of zoom level 18 (around 100-m side in central-southern Europe) and individual building footprints from OpenStreetMap follows the approach of the Global Dynamic Exposure Model (Schorlemmer et al., 2020, 2023). Building replacement costs and number of census occupants were defined mostly based on the European Seismic Risk Model 2020 (ESRM20; Crowley et al., 2020, 2021). SHM-based fragility models were developed for the three monitored buildings following the method developed by Reuland et al. (2023a), based on damage-sensitive features (Reuland et al., 2023b) extracted from sensor data. As the three monitored buildings did not experience the 2016-2017 Central Italy sequence, their response to these earthquakes was simulated by means of non-linear time-history analyses run using real accelerograms recorded by the AMT station, available from the Italian Accelerometric Archive (ITACA; Russo et al., 2022). All fragility models used (ground motion- and SHM-based) are defined in terms of the same five damage states used for ESRM20: no damage (DS0), slight damage (DS1), moderate damage (DS2), extensive damage (DS3) and complete damage (DS4; not a synonym of collapse but of damage that is not repairable and requires replacement—a proportion of buildings with DS4 will have collapsed).

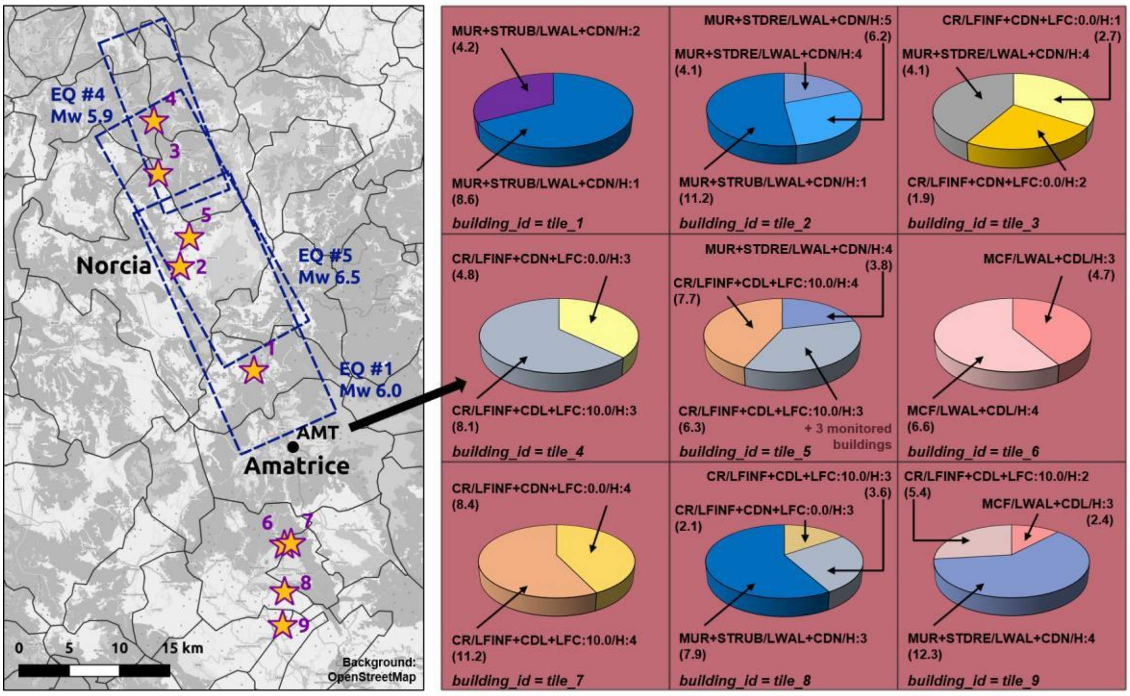

Figure 4. Earthquakes with M_w equal to or greater than 5.0 of the 2016-2017 Central Italy earthquake sequence (numbered stars), selected site around the AMT seismic station in Amatrice (black dot), rupture planes of the largest shocks from ITACA, and exposure model used (building types as per GEM Building Taxonomy v3, number of buildings in parentheses).

For the RLAs the focus was placed on the nine earthquakes of the sequence with moment magnitude Mw of 5.0 and above (as per ITACA), whose epicentres are depicted in Figure 4 (together with the ruptures associated with the largest events). For the OELFs, 24-hour seismicity forecasts of 10,000 SES each were generated by means of the *ETAS.inlabru* method (Naylor et al., 2023; Serafini et al., 2023), using the HORUS earthquake catalogue (Lolli et al., 2020), at 00:00 hour of the day of the first shock, right after each of the nine RLA events, and at 00:00 hour of the day of the third and sixth RLA shocks, given the large time interval in between real earthquakes within the sequence. For each earthquake run (RLA or OELF), 1,000 realisations of ground motion (and, consequently, 1,000 realisations of damage probabilities) were calculated. The ruptures for the RLAs were retrieved from ITACA; those for the OELFs were defined by the RTLT's stochastic rupture generator using the Italian MA4 area source model (Visini et al., 2022).

The economic consequence model in terms of damage ratios for each damage state in the fragility model used in the ESRM20 (Crowley et al., 2021) was adopted. For the human consequence model, the injury classification scale reported in HAZUS (FEMA, 2003), which ranges from severity level 1 (no need for hospitalisation) through to severity level 4 (instantaneously killed or mortally injured) has been employed. The indoor casualty rates for unreinforced masonry buildings and reinforced concrete frames provided in HAZUS, with the modifications employed for the Portuguese case study in the LESSLOSS project (Spence, 2007), were adopted and combined with the model for fatalities in ESRM20, the result being a series of casualty rates (percentage of occupants) associated with each injury severity level, each damage state and each building class. Mean numbers of days a person with each level of injury is expected to stay in hospital were defined for each of the four severity levels using statistics from the Organisation for Economic Cooperation and Development (OECD, 2023). Mean number of days required to inspect and repair buildings (as a function of their damage state) were defined based on several considerations, as discussed in Nievas et al. (2023). The values adopted result in people being able to return to buildings before the third and sixth RLA earthquakes, and before the fourth and eight OELF calculations (apart from the first OELF and RLA of the sequence).

Results

Figure 5 and Figure 6 show the three main points in time in the sequence in which the damage and economic losses increase significantly. The initial 16.7% of undamaged buildings after the first RLA drops to half by the fifth event, while the 43.1% of buildings expected to result in DS4 rises up to 64.4% and 72.0% after the fifth and seventh earthquakes (final value: 73.1%). As can be observed in the insets in Figure 5, damage is not uniformly distributed across the whole building portfolio. In terms of economic loss, the initial 40.1% loss ratio after the first RLA results in a final expected 62.7%. Such plots with the temporal evolution and spatial distribution of damage and losses can be produced for any point in time, and for any level of spatial aggregation. In Figure 6, the temporal evolution of expected economic loss ratios due to the earthquakes that did occur (for which RLAs are run) is combined with the average expected economic loss ratios obtained considering all 10,000 realisations of seismicity by means of the OELFs.

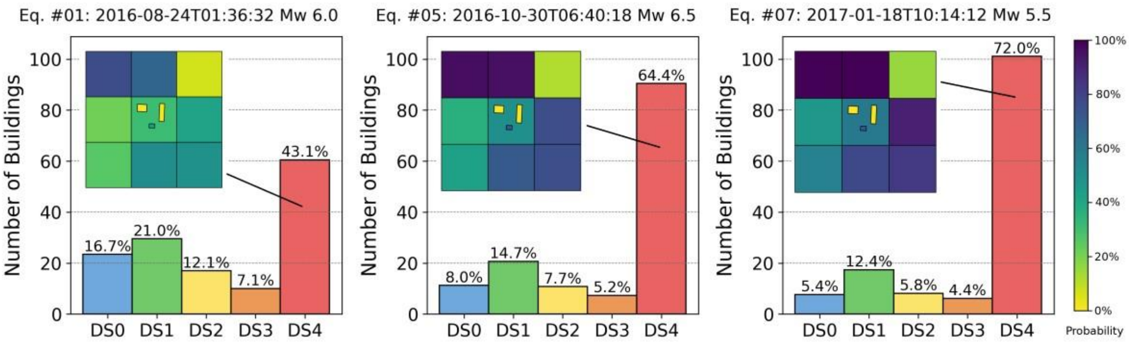

Figure 5. Expected cumulative aggregate number of buildings after the 1st, 5th and 7th RLA events. Insets show probabilities of DS4 per tile and building.

After the first earthquake, during which 1,334.75 people were modelled inside the exposed buildings, the expected human casualties amount to 6.82 people (0.37% of the census occupants) instantly killed or mortally injured (severity 4), and 54.34, 10.66 and 0.44 people (2.91%, 0.57% and 0.02%) suffering from injuries of severity 1 through 3 (basic medical aid in the field, non-lifethreatening but requiring medical technology, immediately life-threatening), respectively. As mentioned earlier, only the third and sixth earthquakes produce a few additional human casualties, with 291 and 171 people modelled inside the buildings in each case. The final number of expected casualties after the whole sequence are 54.92 (2.94%), 10.72 (0.57%), 0.44 (0.02%), and 6.82 (0.37%) for each severity from 1 through 4 by the end of the sequence. Numbers of injured people are not integers because they represent an expected value in a statistical sense.

Final remarks

We believe the Real-Time Loss Tools provide a useful demonstration of how the scenario calculators of the OpenQuake engine can be used in a time-dependent manner that allows for the consideration of damage accumulation and the updating of occupants of the building stock during seismic sequences, while facilitating a transparent and accessible exploration of the connections between the different components of the computational chain. The event-based OELF calculations would benefit from attempts to optimise the use of computational resources by the algorithm, as their running times can become too long if the seismicity forecasts contain large numbers of events. The motivation for such an investment may arise from the possibility of accounting for correlations and conditional dependencies (e.g., spatio-temporal and inter-period correlation of ground motions, integration of uncertainties in finite rupture properties), as these can be readily integrated into a stochastic event set calculation but are more complex in a classical risk framework. A potential holistic full-scale implementation of an integration of RLA, OELF and SHM of the kind presented herein would benefit from further exploring models that fully characterise the post-earthquake recovery phase (e.g., Reuland et al., 2022) to improve the assumptions made to model the return of occupants to their buildings as well as the incorporation of the possibility of repairing and replacing buildings in the medium- to long-term. It is noted that the use of the Real-Time Loss Tools is not limited to any of the specific inputs used for the casestudies developed within the RISE project. Details on input formats and requirements, as well as a more extensive discussion on each of the components of the calculation can be found in Nievas et al. (2023) and the GitLab repository of the RTLT software.

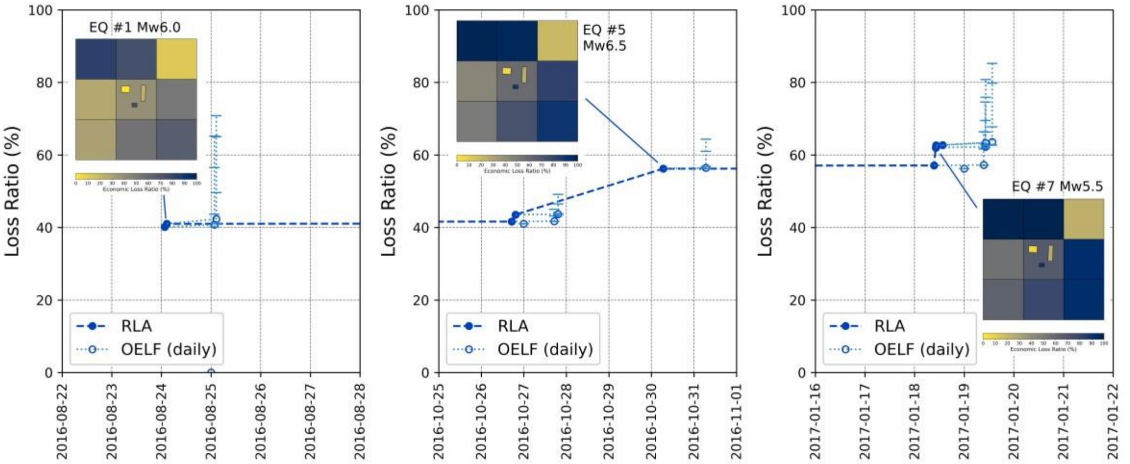

Figure 6. Cumulative economic loss ratios. Vertical error bars show minimum, mean, 95th, 99th and 99.5th percentiles associated with each OELF (at end of 24-hour forecast period). Insets show loss ratios per tile and building after the 1st, 5th and 7th RLA events.

Acknowledgements

This work has been carried out as part of the RISE project (European Union's Horizon 2020 research and innovation programme, grant agreement No 821115).

References

Chioccarelli E, Pacifico A and Iervolino I (2022), *Operational earthquake loss forecasting for Europe*, RISE Project Deliverable 4.3.

Crowley H, Despotaki V, Rodrigues D, Silva V, Toma-Danila D, Riga E, Karatzetzou A, Fotopoulou S, et al. (2020), Exposure model for European seismic risk assessment, *Earthquake Spectra*, 36(1_suppl): 252-273. DOI: 10.1177/8755293020919429.

Crowley H, Dabbeek J, Despotaki V, Rodrigues D, Martins L, Silva V, Romão, X, Pereira N, Weatherill G and Danciu L (2021), *European Seismic Risk Model (ESRM20), EFEHR Technical Report 002, V1.0.1*, 84 pp, DOI: 10.7414/EUC-EFEHR-TR002-ESRM20

Crowley H, Dabbeek J, Ozcebe S, Bossu R, Finazzi F, Cauzzi C, Danciu L, Papadopoulos A, Han M, Mizrahi L, Michelini A, Faenza L and Lauciani V (2023), *Report on the Development of RLA, EEW and OEF at European Scale*, RISE Project Deliverable 6.5.

Earle PS, Wald DJ, Jaiswal KS, Allen TI, Hearne MG, Marano KD, Hotovec AJ and Fee J (2009), *Prompt Assessment of Global Earthquakes for Response (PAGER): A System for Rapidly Determining the Impact of Earthquakes Worldwide*, U.S. Geological Survey OpenFile Report, no. 2009–1131, DOI: 10.3133/ofr20091131.

Federal Emergency Management Agency (FEMA) (2003), *HAZUS-MH Technical Manual*, Washington, D.C.

Iervolino I, Chioccarelli E, Giorgio M, Marzocchi W, Zuccaro G, Dolce M and Manfredi G (2015), Operational (short-term) earthquake loss forecasting in Italy, *Bulletin of the Seismological Society of America*, 105: 2286–2298, DOI: 10.1785/0120140344.

Iervolino I, Giorgio M and Chioccarelli E (2016), Markovian modeling of seismic damage accumulation, *Earthquake Engineering & Structural Dynamics*, 45(3): 441-461.

Lolli B, Randazzo D, Vannucci G and Gasperini P (2020), The HOmogenized instRUmental Seismic catalog (HORUS) of Italy from 1960 to present, *Seismological Research Letters*, 91(6): 3208-3222, DOI: 10.1785/0220200148.

Marzocchi W, Lombardi AM and Casarotti E (2014), The establishment of an operational earthquake forecasting system in Italy, *Seismological Research Letters*, 85: 961–969. Naylor M, Serafini F, Lindgren F and Main I (2023), Bayesian modelling of the temporal evolution of seismicity using the ETAS.inlabru R-package, *Frontiers in Applied Mathematics and Statistics*, SI Physical and Statistical Approaches, DOI: 10.3389/fams.2023.1126759.

Nievas CI, Crowley H, Reuland Y, Weatherill G, Baltzopoulos G, Bayliss K, Chatzi E, Chioccarelli E, Guéguen P, Iervolino I, Marzochhi W, Naylor M, Orlacchio M, Pejovic J, Popovic N, Serafini F and Serdar N (2023), *Integration of RISE Innovations in the Fields of OELF, RLA and SHM*, RISE Project Deliverable 6.1. Available from: http://static.seismo.ethz.ch/rise/deliverables/Deliverable_6.1.pdf.

Organisation for Economic Cooperation and Development (OECD) (2023), Length of hospital stay (indicator). DOI: 10.1787/8dda6b7a-en (Accessed 06/01/2023).

Orlacchio M (2022), *The effects of seismic sequences on seismic hazard and structural vulnerability*, PhD Thesis, University of Naples Federico II, Naples, Italy.

Pagani M, Monelli D, Weatherill G, Danciu L, Crowley H, Silva V, Henshaw P, Butler L, et al. (2014), OpenQuake engine: An open hazard (and risk) software for the global earthquake model, *Seismological Research Letters*, 85(3): 692-702, DOI: 10.1785/0220130087.

Papadopoulos A N, Bazzurro P and Marzocchi W (2020), Exploring probabilistic seismic risk assessment accounting for seismicity clustering and damage accumulation: Part I. Hazard analysis, *Earthquake Spectra*, 37(2): 803-826, DOI: 10.1177/8755293020957338.

Reuland Y, Bodenmann L, Blagojevic N and Stojadinovic (2022), *Development of RRE forecasting services in OpenQuake*, RISE Project Deliverable 4.4.

Reuland Y, Khodaverdian A, Crowley H, Nievas C, Martakis P, Chatzi E (2023a) Monitoringdriven post-earthquake building damage tagging, *10th International Conference on Experimental Vibration Analysis for Civil Engineering Structures*, Milan, Italy.

Reuland Y, Martakis P and Chatzi E (2023b), A Comparative Study of Damage-Sensitive Features for Rapid Data-Driven Seismic Structural Health Monitoring, *Applied Sciences*, 13(4): 2708, DOI: 10.3390/app13042708

Russo E, Felicetta C, D Amico M, Sgobba S, Lanzano G, Mascandola C, Pacor F and Luzi L (2022), *Italian Accelerometric Archive v3.2*, Istituto Nazionale di Geofisica e Vulcanologia, Dipartimento della Protezione Civile Nazionale. DOI: 10.13127/itaca.3.2

Schorlemmer D, Beutin T, Cotton F, Garcia Ospina N, Hirata N, Ma KF, Nievas C, Prehn K and Wyss M (2020), Global Dynamic Exposure and the OpenBuildingMap – A big-data and crowd-sourcing approach to exposure modelling, *EGU General Assembly 2020 Conference Abstracts*, p. 18920, DOI: 10.5194/egusphere-egu2020-18920

Schorlemmer D, Cotton F, Delattre F, Evaz Zadeh T, Kriegerowski M, Lingner L, Oostwegel L, Prehn K and Shinde S (2023), *An open, dynamic, high-resolution dynamic exposure model for Europe*, RISE Project Deliverable 2.13.

Serafini F, Lindgren F and Naylor M (2023), Approximation of Bayesian Hawkes process with inlabru. *Environmetrics*, e2798. https://doi.org/10.1002/env.2798.

Silva V, Crowley H, Pagani M, Monelli D and Pinho R (2014), Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment, *Natural Hazards*, 72: 1409-1427, DOI: 10.1007/s11069-013-0618-x.

Silva V, Brzev S, Scawthorn C, Yepes C, et al. (2022), A building classification system for multihazard risk assessment, *International Journal of Disaster Risk Science*, 13(2): 161-177.

Spence R (ed) (2007), *Earthquake Disaster Scenario Predictions and Loss Modelling for Urban Areas*, LESSLOSS Report No. 2007/07.

Visini F, Meletti C, Rovida A, et al. (2022), An updated area-source seismogenic model (MA4) for seismic hazard of Italy, *Natural Hazards and Earth System Sciences*, 22: 2807-2827.