MODELLING EARTHQUAKE DAMAGE REPAIR COSTS: IMPROVING ACCURACY FOR PREPAREDNESS DECISION MAKING

Nadeeshani Wanigarathna[1], Christian Henjewele, Keith G Jones, Federica Pascale and Mariantonietta Morga

School of Engineering and the Built Environment, Anglia Ruskin University, UK

Natural disasters damage physical assets causing causalities and interruption to businesses. Disaster impacts can be addressed proactively (preparedness) or reactively (recovery). Building adaptation measures; as a form of disaster preparedness; can reduce the level of damage should the disaster occur. Nevertheless, building owners need to be convinced that it is cost-effective to invest in pro-active adaptation measures. An accurate prediction of the repair costs associated with recovery is paramount to determining the economic viability of ex-ante disaster risk reduction investments. Currently, antecedent loss modelling is based on numerous assumptions about risk; vulnerability; and the required damage repair cost. Determining the critical factors influencing overall damage repair costs can reduce such inaccuracies. Damage recovery costs and selected details for 7999 properties recorded from 66 towns in the Italian province of Emilia Romagna damaged by the 2012 Earthquake were assembled. Statistical analysis was undertaken to correlate the repair costs and the damage status; location of the property; floor area of the property and the repair duration. The paper questions the reliability of antecedent loss modelling related to property damage using simplistic and generic economic models. Factors that predict the repair cost are also highlighted.

Keywords: antecedent loss modelling; risk reduction; disaster recovery; repair

INTRODUCTION

Natural disasters damage physical assets causing causalities and disruption to businesses. In addition, they can cause significant disruption to education, impact mental health and increase the crime rate. In this paper, we use the term losses to mean the monetary value of the resultant damage. Among all natural disasters, earthquakes are the greatest threat to life and cause significant economic losses to individuals, communities, and nations (MunicRe, nd). Losses caused by earthquakes are on the rise, and in the last two decades, earthquakes losses have exceeded USD 775 billion (SwissRe, 2021). Accurate prediction of the scale of such losses prior to an earthquake could provide vital information for effective disaster preparedness. According to Daniel and Wenzel (2014), modelling is considered an effective way to appraise the effectiveness of various proactive and reactive mitigation options to

---

[1] nadeeshani.wanigarathna@aru.ac.uk

Wanigarathna, N, Henjewele, C, Jones, K G, Pascale, F and Morga, M (2022) Modelling Earthquake Damage Repair Costs: Improving Accuracy for Preparedness Decision Making *In:* Tutesigensi, A and Neilson, C J (Eds) *Proceedings of the 38th Annual ARCOM Conference,* 5-7 September 2022, Glasgow, UK, Association of Researchers in Construction Management, 155-164.

physical assets (e.g., structural improvements to buildings), operational procedures (e.g., implementation of an early warning system), or financial recovery procedures (e.g., purchasing disaster insurance). Loss modelling can also reduce the time taken for impact assessment and support rapid allocation of resources to business organisations and local authorities without waiting for lengthy field observation.

This paper discusses loss modelling practices related to direct economic loss associated with physical damage to buildings; construed as the total repair costs required to reinstate damaged buildings to pre-disaster status (Ramirez *et al.,* 2012; Leil and Deierlein, 2013). Several researchers have contributed to advances in earthquake loss modelling (Hill and Rossetto, 2008, Vitiello *et al.,* 2017). Loss assessment models first estimate physical damage to properties as a function of potential earthquake characteristics and the buildings' structural vulnerability. These damage levels are then converted to monetary values by applying damage cost functions. The former phase of damage modelling entails advanced seismic and structural modelling, whilst the latter is concerned with economic modelling. Loss assessment research has primarily focused on advancing damage modelling, with limited attention being paid to cost modelling approaches and in particular, converting damage states into economic losses.

LITERATURE REVIEW

Recent research comparing loss modelling estimates with actual losses with from recent earthquakes in Italy, Turkey, and Greece (see works of Del- Vecchio *et al.,* 2018, Spence *et al.,* 2003; Eleftheriadou *et al.,* 2016) highlighted significant inaccuracies of antecedent loss modelling approaches. Whilst authors have highlighted the inaccuracies related to the weaknesses in damage modelling methods, no detailed investigation has been made to identify the weakness of converting damage state into losses or the impact of this conversion on the accuracy of loss estimates. The advancement of modelling approaches to both phases (damage estimation and loss) is crucial to improving antecedent loss modelling accuracy and subsequent mitigation decisions based on the models.

To this end researchers have highlighted the need for further research to accurately predict the relationships between damage state and losses to improve loss assessment accuracy and avoid making inappropriate assumptions (Hill and Rossetto, 2008; Meroni *et al.,* 2017). Using actual damage repair cost data for (the direct economic loss) of residential properties across 60 towns damaged by the 2012 Emilia Romagna Earthquake in Italy, this paper presents the relationship between physical damage levels and monetary losses. It evaluates the accuracy of standard damage cost functions used in the antecedent earthquake loss modelling. Such results will provide valuable insights to loss modellers regarding the adjustments they could make to standard damage cost functions and the provision of any contingencies to the total loss assessment.

Earthquake Disaster Loss Modelling

Disaster loss modelling has received considerable attention from scholars and modellers. Authors such as Ramirez and Miranda (2009), Meroni *et al. (*2017), Erdik *et al. (*2011), Alani and Khosrowshahi (2007), and Kahandawa *et al. (*2020) have reviewed existing loss assessment methodologies in detail. Other studies (see Daniell and Wenzel, 2014, Erdik *et al.,* 2014) have reviewed software platforms to simplify complex modelling calculations. For example, the FEMA P-58 methodology developed by Applied Technology Council in 2012 is considered one of the most widely accepted approaches to loss assessment. Performance Assessment Calculation Tool (PACT) within the FEMA P-58 could simulate a probabilistic estimate of downtime, repair cost, casualties, and unsafe placarding based on quantitative inputs related to ground shaking intensities and structural vulnerability and other economic data.

Scholars have assessed the reliability of the FEMA P-58 methodology by comparing predicted data and observed actual earthquake data (e.g., Cremen *et al.,* 2016; Del Vecchio *et al.,* 2020, Cremen and Baker, 2019, Baker *et al.,* 2016). Researchers have developed a range of algorithms to model the physical damage or damage status (e.g., Cremen *et al.,* 2020; Hashemi and Alesheikh, 2011; Indirli *et al.,* 2013; Munich Re, nd; Giovannetti and Pagliacci, 2017; Canesi and Marella 2017; Kim *et al.,* 2005). These algorithms used variables related to the characteristics of the earthquake (e.g., magnitude, distance, probability; location), the nature of the ground (e.g., subsoil conditions, resonant frequency), and typology of buildings (e.g., foundation type, primary construction material, age); as well as socio-economic characteristics of the location.

Physical damage can either be modelled at the building or element/component levels. Building level damage modelling methodologies are widely used and considered to offer several benefits for rapid loss assessments in peace times and the immediate aftermath of an earthquake (Vona *et al.,* 2018). Similarly, for component level damage, assessment methodologies could be used when more accurate estimates are needed for decision making. Recent investigations (Cremen and Baker, 2019, Baker *et al.,* 2016) showed that loss estimates based on component level analysis are more accurate and consistent. However, component level analyses involve complex procedures and requires substantial expertise based on a multidisciplinary view of structural assessment (Del Vecchio *et al.,* 2020, Vona *et al.,* 2018).

Economic models (damage-cost functions or damage-cost ratios) convert the damage status into economic loss values. Damage cost functions represent the relationship between damage levels (such as slight damage, complete damage etc.) and a property's (building or component) replacement cost. As a typical example, the Hazus MR4 loss assessment methodology assumes 2%, 10%, 44.7%, 100% (of the property value) as the basis for the damage-cost function to calculate the repair cost associated with 'Slight', 'Moderate', 'Extensive', and 'Complete' damage states (respectively) for single-family dwellings. For a multi-family dwelling, 2%, 6.5%, 41.3%, 100%, respectively are used. Meroni *et al. (*2016) produced similar damage-cost functions for use with the EMS 98 damage scales applied to European buildings; 5%, 20%, 45%, 103% damage cost functions to calculate the repair cost associated with 'Slight damage', 'Moderate damage', 'Substantial-heavy damage', and 'damage beyond repair.

Other scholars such as Chaves (1998, cited in Roca *et al.,* 2006), Milutinovic and Trendafiloski (2003), Kappos and Dimitrakopoulos (2007), Polese *et al. (*2010), Vecchio *et al. (*2017) have also developed damage-cost functions. Kappos and Dimitrakopoulos (2007) and Milutinovic and Trendafiloski (2003) have identified value ranges for damage-cost functions, as opposed to single percentage values. Key approaches to determining damage-cost functions are either based on expert judgement (e.g., Stojadinovic et al.,2017; Roca *et al.,* 2006) or empirical investigation using computer simulations (e.g., Scholl *et al.,* 1982, Vecchio *et al. (*2017). The reliability of these functions has not been independently verified. Further details on how earthquake loss assessment has advanced over time can be found in Vitiello *et al. (*2017).

METHOD

The work presented in this paper is based on a single case study into damage repair costs for residential buildings damaged by the 2012 Earthquake in the Italian region of Emilia Romagna. This region had no similar recent disaster events and accompanying repair cost databases to conduct a multiple case study. It is one large case study with multiple units of analysis. After the earthquake and damage to the buildings, separate restoration programmes were set up for residential buildings, historical buildings, cultural heritage and infrastructures, and business premises.

The region developed an IT platform - MUDE (Unique Digital Building Model) to manage applications for funding for the reconstruction of residential buildings damaged by the earthquake. All applications were to be made through the platform by December 2017. The present study accessed a copy of the data on request in 2016 while the applications were still in progress. Additional data was accessed later when it was made publicly available via the Open portal (https://openricostruzione.regione.emilia-romagna.it/ricostruzione-privata). This data set contained records from 66 towns (multiple embedded units of analysis) within the Emilia Romagna region.

Previous authors (Del Vecchio *et al.,* 2018; Eleftheriadou *et al.,* 2016) have used multiple embedded case study approach to evaluate selected buildings for their repair costs. Results from those studies aimed at improving the accuracy of the repair cost prediction at building level. The research presented here attempts to investigate a large data set to improve economic modelling at a regional level and provide additional insights to building level repair cost estimation.

Data Extraction

A total of 7999 cases (individual applications) were accessed from 66 administrative authorities such as towns, municipalities, and cities (collectively known as “Comune” in Italian) in the Emilio-Romagna Region. For brevity and disambiguation, the term "Comune" (with capital C) will be used throughout to mean a town, municipality, or city in the region. The region is divided into nine administrative provinces. Four provinces within the region had reported cases of damage from the earthquake. The number of reported cases from Comunes ranged from the lowest of 1 case (in Bagnolo in Piano municipality to the highest of 847 cases (in Mirandola city in the Province of Modena). The top 15 (24%) most affected Comunes contributed over 5263 cases (80%) - which is closer to the Pareto distribution (20% of Comunes contributing to 80% of the damage).

Each case related to an application made by the owner of damaged buildings for financial resources to repair or restore their buildings. Applications contained details related to a brief description of the intervention(s), intervention type (repair and reconstruction, or repair and reconstruction and seismic improvement), details of the building such as address and location and name of the applicant, construction duration, details of the designer and constructor, number of dwellers residing within the damaged buildings, total floor area and their functional use(s), damage level and operational level (the usability status of the buildings building prior to repairs) of the building(s) assessed by professionals, and the cost (€) assigned for undertaking repair and restoration intervention(s).

Whilst factors such as building age, foundation and structural type, number of stories and other building characteristics has an impact on the building damage and recovery, the large dataset studied here is limited and did not contain this information.

Data Analysis

The data set was analysed to investigate two research questions listed below.

1. What variables impact the earthquake damage repair costs? For this purpose, all 7999 cases were first analysed to identify the correlations between the repair/reconstruction rates and nine other selected variables.
2. What are the possible variations to the damage-cost functions used within antecedent loss assessments? For this purpose, a subset of the data set, 3176 cases related to minor repairs (those buildings assigned 'B/C damage and operational level' status within the database) were analysed: A) to calculate the average repair cost rates for each Comune; b) to calculate repair cost/house value proportion (damage-cost functions) for each Comune.

Since the buildings related to each case are different, the total costs of interventions were normalised for comparison. For each case, the cost assigned for undertaking interventions was divided by the total floor area to calculate repair and reconstruction rates in the form of cost/m2. Recoding the dataset helped recategorise continuous cost and time data into a five-point Likert scale for visibility. The new dataset was, therefore, more suited to nonparametric statistical analysis. The first analysis cross-tabulated the data for greater visibility of the new categories (see Table 1).

Table 1: Crosstab of damage level against intervention

	Intervention Type			
Category and level damage the building sustained	Repair and restore	Repair and restore with seismic improvement	Partial/complete reconstruction with Seismic improvement	Total cases
B/C Low damage habitable before repair	3177	1	0	3176
E0 - Low Damage partial habitable before repairs	0	675	16	691
Repair and restore with seismic improvement	0	599	62	661
E1 -E2 Heavy building damage	0	483	141	624
E3 - Demolish and reconstruct	1	214	1183	1398

There were two primary interventions: (1) Repair and restore, and (2) Repair and restore with seismic improvement. During the recording process, a third category was added to separate seismic improvement for reconstruction from improvements made to a simple repair and restore. Spearman Correlation analysis was then undertaken to establish the critical factors that strongly influence the overall cost to repair and restore damaged buildings following the earthquake. The analysis correlated the unit cost with nine other variables recorded in the MUDE. Results confirmed a strong correlation among the variables. There is a very strong positive correlation between two key variables (Rho = 0.962; $p<0.01$): the damage level and the intervention type. In other words, the two variables were almost synonymous with the similarity of 92% (measured by the coefficient of determination). Simple descriptive statistics functions available within MS Excel were used to compute the mean repair rate and damage cost functions for each Comune to answer the second research question.

FINDINGS

In total, € 3,160,621,021.97 was assigned to 9,916 housing repair and reconstruction interventions throughout the programme (ER openricostruzione, 2022). Figure 1 below shows the extent of the earthquake's impact on the region (Right) and the funding spent on each town (Left). Dark coloured towns in the Left picture represent places that received high amounts of monetary resources.

Factors Affecting Repair and Reconstruction Rates

With regards to the predicators of the recovery cost, the correlation analysis established three statistically significant links (and we identify these as tier 1 factors):

1. Type of intervention (Rho = 0.853; p<0.01)
2. Level of damage (Rho = 0.830; p<0.01).
3. The duration to complete the repair (Rho = 578, p<0.01).

The analysis did not find a direct statistical correlation between the recovery cost and use of the respective properties, such as the number of units or occupants in residential properties, number of commercial units, number of office units and storage units. These factors, however, were statistically correlated to one another. These internal correlations imply an indirect correlation with the recovery cost as they are linked to habitable floor areas used to compute the unit recovery cost rates.

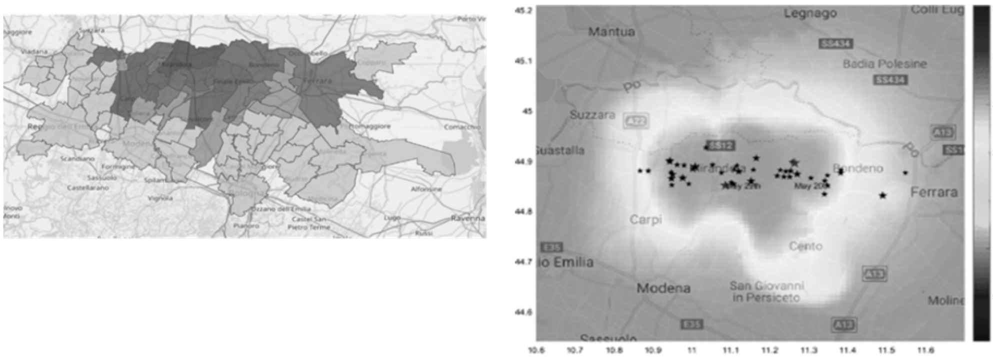


Figure 1: Maps showing reconstruction resource allocation and the impact of the earthquake in Regia Romagna Province (ER openricostruzione, 2022 and Rossi et al., 2019)

Regional Variations for Repair Rates for Minor Repairs

Figure 2 compares the observed damage repair rates for the Comunes. The analysis did not find substantial variations between the minimum and mean repair cost rates for different Comunes. The variability may have influenced these results in the number of cases for each region. Whilst 'Bagnolo In Piano', 'Castelnovo Di Sotto' and 'Quattro Castella' the N=1, other Comunes recorded a higher number of cases - e.g., Mirandola (n=375), Ferrara (n=299), Finale Emilia (n=241). However, this graph shows a striking difference between the maximum repair cost rates from the mean value, affecting some regions more than others. Correlation analysis did not find a statistical difference between the mean and maximum repair costs across Comunes, and they are not correlated either (Correl = 0.1866). These results suggest that location did not influence cost variations for minor damage repairs. A more detailed analysis would be needed to establish specific reasons for the high costs of repairing individual cases. For example, a closer look into the intervention descriptions of extremely high-cost interventions found extremely high costs were reported for contextual reasons such as repairing monumental buildings with decorative elements, small-sized units within a larger building and where the repair was required to comply with new regulations introduced following the earthquake event.

The correlation between the mean repair cost and the average house value for minor damage repairs is weak and statistically insignificant (-0.1876). This finding contradicts previous findings (e.g., Canesi and Marella 2017, Meroni *et al.,* 2017), who claimed (in general for all repair types) a correlation existed between construction (repair) price levels and house values of regions due to economic and social reasons.

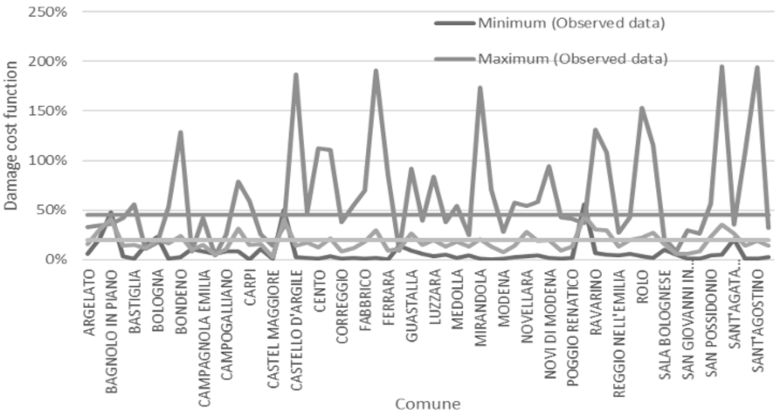
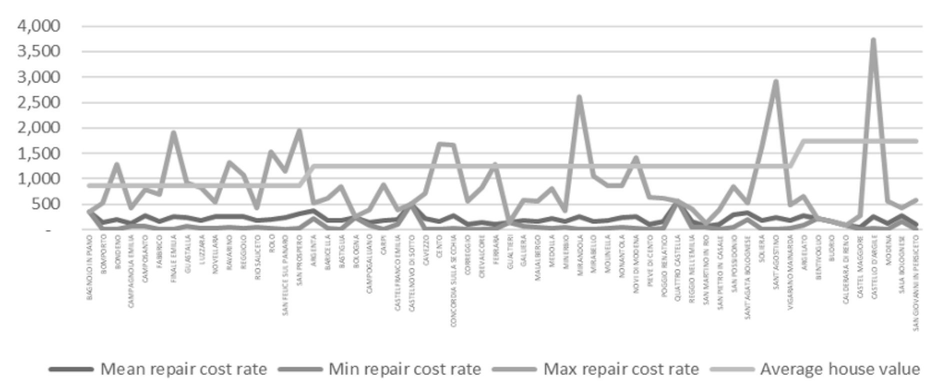


Figure 2: Repair rates for the communes (€ per m2 of floor area)

Reliability of Typical Damage Cost Functions

Further analysis was undertaken to compare damage cost relationships with standard damage cost functions used within antecedent loss assessments for European buildings (EMS-98) (Figure 3). Nine outliers were omitted to improve the consistency and readability of the results.

Figure 3: Damage cost functions for minor/low damaged buildings



Results show that the observed mean damage-cost relationship closely aligned with the standard damage cost ratio of 20%, which is used to predict losses associated with moderate damage (Chaves 1998, cited in Roca *et al.,* 2006). In addition, the data set considered here contained residential units belonging to various building typologies. However, the analysis showed that the maximum damage repair values were almost always above the standard damage-cost ratio of 50% for the “substantially" to "heavily” damaged buildings.

These two findings signify the degree of uncertainty in modelling repair costs between "low-moderate" damage and "Substantial and Heavy" Damage. The findings highlight the importance of making decisions based on probabilistic risks and considering factors that increase damage repair costs associated with individual buildings. The findings suggest that simplified loss assessment methodologies using typical damage cost functions may provide reasonably accurate estimates for repairing minor damage for large building stocks, i.e., regional-level estimates. Hence widely used simplified approaches for loss assessment may offer benefits and provide an accurate basic for decision making for local authorities or organisations owning a stock of buildings for low impact earthquakes.

This paper investigated only the economic modelling of the tangible losses related to damage to buildings, which is a part of overall disaster losses. A broader loss estimation needs to consider environmental, social, and historic losses and their impact to overall economic loss. Social losses tend to persist over a person's lifetime hence cause long-term socio-economic impacts to the society and businesses (The Australian Business Roundtable, 2016). Approaches to the valuation of intangible outcomes (such as revealed preference approaches, stated preference approaches and subjective wellbeing approaches) and macro-economic approaches are useful in broad loss assessment attempts. More research is required to identify the impact of indirect losses on the restoration of buildings and other tangible assets.

CONCLUSIONS

This research investigated repair and reconstruction costs for residential units damaged during the Emilia Romagna Earthquake in Italy in 2012. Standard damage-cost functions used in loss assessment for European buildings closely tally with mean observed damage-cost functions for minor damaged buildings. Therefore, estimates based on standard damage-cost functions would not have significant inaccuracies at the regional level for low impact earthquakes or building stocks undergoing minor damages. However, high repair cost rates did deviate from modelling estimates, irrespective of the location. Therefore, estimates at the individual building level may need careful consideration to identify possible increases from typical cost models. Further investigation into high-cost interventions is needed to identify the causes of the cost increases and provide valuable insights to determine contingency allowances for individual building level estimates.

ACKNOWLEDGEMENTS

The research reported here used the data from the LIQUEFACT project, which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 700748.

REFERENCES

Alani, A M and Khosrowshahi, F (2007) Development of an effective methodology for assessment, repair and maintenance of the earthquake-damaged buildings, *Facilitie*s, **25(**1/2), 32-47.

Baker, J W, Cremen, G, Giovinazzi, S and Seville, E, (Eds) (2016) *Proceedings of the 2016 Annual Conference of the New Zealand Society for Earthquake Engineering*, Christchurch, New Zealand.

Canesi, R and Marella, G (2017) Residential construction costs: An Italian case study, *International Journal of Applied Engineering Research*, **12(**10), 2623-2634.

Cremen, G and Baker, J W (2019) A methodology for evaluating component-level loss predictions of the FEMA P-58 seismic performance assessment procedure, *Earthquake Spectra*, **35(**1), 193-210.

Cremen, G, Werner, M J and Baptie, B (2020) A new procedure for evaluating ground-motion models, with application to hydraulic-fracture-induced seismicity in the United Kingdom, *Bulletin of the Seismological Society of America*, **110(**5), 2380-2397.

Daniell, J and Wenzel, F (2014) *The Production of a Robust Worldwide Rapid Socio-Economic Loss Model for Earthquake Economic Loss and Fatality Estimation: Success from 2009-2014*, Australian Earthquake Engineering Society, Australia, 21-23.

De Groeve, T, Corbane, C and Ehrlich, D (2015) *Guidance for Recording and Sharing Disaster Damage and Loss Data: Towards the Development of Operational Indicators to Translate the Sendai Framework into Action Reduction Translate the Sendai Framework into Action EUR 27192*, Luxembourg: Publications Office of the European Union, JRC95505.

Del Vecchio, C, D I Ludovico, M, Pampanin, S and Prota, A (2018) Repair costs of existing RC buildings damaged by the L'Aquila earthquake and comparison with FEMA P-58, *Earthquake Spectra*, **34(**1), 237-263.

Eleftheriadou, A K, Baltzopoulou, A D and Karabinis, A I (2016) Urban seismic risk assessment: statistical repair cost data and probable structural losses based on damage scenario-correlation analysis, *International Journal of Advanced Structural Engineering*, **8(**2), 133-150.

Erdik, M, Şeşetyan, K, Demircioğlu, M.B, Hancılar, U and Zülfikar, C (2011) Rapid earthquake loss assessment after damaging earthquakes, *Soil Dynamics and Earthquake Engineering*, **31(**2), 247-266.

Erdik, M, Şeşetyan, K, Demircioğlu, M B, Zulfikar, C, Hancılar, C, Tuzun, C, Harmandar, E (2014) Rapid earthquake loss assessment after damaging earthquakes, *In*: A Ansal (Ed) *Perspectives on European Earthquake Engineering and Seismology*, **1**.

Giovannetti, E and Pagliacci, F (2017) Natural disasters as stress-tests for housing systems Vulnerability and local resistance to the 2012 earthquake in Italy, *Regional Science Policy, and Practic*e, **9(**4), 231-249.

Hashemi, M and Alesheikh, A A (2011a) A GIS-based earthquake damage assessment and settlement methodology, *Soil Dynamics and Earthquake Engineering*, **31(**11), 1607-1617.

Hill, M and Rossetto, T (2008) Comparison of building damage scales and damage descriptions for use in earthquake loss modelling in Europe, *Bulletin of Earthquake Engineering*, **6(**2), 335-365.

Kappos, A J and Dimitrakopoulos, E (2008) Feasibility of pre-earthquake strengthening of buildings based on cost-benefit and life-cycle cost analysis, with the aid of fragility curves, *Natural Hazards*, **45(**1), 33-54.

Kim, T, Lee, K, Chung, Y and Shin, H M (2005) Seismic damage assessment of reinforced concrete bridge columns, *Engineering Structures*, **27(**4), 576-592.

Liel, A B and Deierlein G G (2013) Cost-benefit evaluation of seismic risk mitigation alternatives for older concrete frame buildings, *Earthquake Spectra*, **29(**4), 1391-1411.

Meroni, F, Squarcina, T, Pessina, V, Locati, M, Modica, M and Zoboli, R (2017) A damage scenario for the 2012 Northern Italy earthquakes and estimation of the economic losses to residential buildings, *International Journal of Disaster Risk Science*, **8(**3), 326-341.

Milutinovic, Z V and Trendafiloski, G S (2003) Risk-UE An advanced approach to earthquake risk scenarios with applications to different European towns, Contract: EVK4-CT-2000-00014, WP4, *RISK-UE WP4 Handbook: Vulnerability of Current Buildings: Vulnerability of Current Buildings*.

MunichRe (n.d.) *Earthquake Risk: A Deadly Threat*, Available from: https://www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards/earthquakes-a-deadly-threat.html [Accessed 21st June 2022].

Polese, M, Di Ludovico, M, Marcolini, M, Prota, A and Manfredi, G (2015) Assessing reparability: simple tools for estimation of costs and performance loss of earthquake damaged reinforced concrete buildings, *Earthquake Engineering and Structural Dynamics*, **44**(10), 1539-1557.

Ramirez, C, Liel, A, Mitrani-Reiser, J, Haselton, C, Spear, A, Steiner, J, Deierlein, G and Miranda, E (2012) Expected earthquake damage and repair costs in reinforced concrete frame buildings, *Earthquake Engineering and Structural Dynamics*, **41(**11), 1455-1475.

Ramirez, C, Miranda, E (2009) *Building-Specific Loss Estimation Methods and Tools for Simplified Performance-Based Earthquake Engineering, Report No 171*, Stanford CA: The John A Blume Earthquake Engineering Centre.

Roca, A, Goula, X, Susagna, T, Chávez, J, González, M and Reinoso, E (2006) A simplified method for vulnerability assessment of dwelling buildings and estimation of damage scenarios in Catalonia, Spain, *Bulletin of Earthquake Engineering*, **4**(2), 141-158.

Scholl, R E, Kustu, O, Perry, C L and Zanetti, J M (1982) *Seismic Damage Assessment for High-Rise Building Technical Report*, Stanford CA: The John A Blume Earthquake Engineering Centre.

Spence, R, Bommer, J, del Re, D, Bird, J, Aydinoğlu, N and Tabuchi, S (2003) Comparing loss estimation with observed damage: A study of the 1999 Kocaeli earthquake in Turkey, *Bulletin of Earthquake Engineering*, **1(**1), 83-113.

Stojadinovic, Z, Kovacevic, M, Marinkovic, D and Stojadinovic, B (Eds) (2017) *In*: *Proceedings of the 16th World Conference on Earthquake Engineering (16WCEE)*, January 09-13**,** Santiago, Chile**.**

SwissRe (2021) *Sigma Explorer- Earthquakes (Total)*, Swiss Re Institute.

The Australian Business Roundtable for Disaster Resilience and Safer Communities (2016) *The Economic Cost of the Social Impact of Natural Disasters*, The Australian Business Roundtable.

Vitiello, U, Asprone, D, Di Ludovico, M and Prota, A (2017) Life-cycle cost optimisation of the seismic retrofit of existing RC structures, *Bulletin of Earthquake Engineering*, **15**(5), 2245-2271.

Vona, M, Manganelli, B, Tataranna, S and Anelli, A, 2018 An optimised procedure to estimate the economic seismic losses of existing reinforced concrete buildings due to seismic damage, *Buildings*, **8**(10), 144.

Wanigarathna, N, Jones, K, Morga, M, Pascale, F and Meslem, A (2022) Cost-benefit analysis for liquefaction disaster mitigation interventions, *Journal of Financial Management of Property and Construction,* [ahead of print].