

Supplementary Information to the Manuscript

Unveiling the Environmental Impact of Earthquakes in Europe

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Correlation between Embodied Carbon and Repair Cost Ratios

Computing the environmental consequences of earthquakes remains relatively uncommon in the scientific literature. We express these consequences in terms of average annual embodied carbon ratio (AAECR), which reflects the embodied carbon associated with repairing seismic damage (AAEC), normalised by the embodied carbon of building replacement (REC). To expand our analysis over diverse building types, we adopt the practical simplification of a one-to-one relation between embodied carbon and repair cost ratios, allowing us to consider that the average annual economic loss ratio (AALR) is equal to AAECR. We expand on existing literature and provide additional illustrative case studies to support the plausibility of this assumption.

Hasik et al.¹ identified repair-cost ratios as a valid means of translating seismic damage into environmental impacts. This approach has been employed in several studies²⁻⁴, which used repair-cost ratios to estimate earthquake-related environmental impacts, primarily for steel and reinforced concrete buildings and bridges in various regions. More recent studies^{5,6} confirmed the good correlation between economic and environmental loss ratios for reinforced concrete buildings in Italy, including cases of structural retrofitting⁷. Ping et al.⁷ drew similar conclusions for buckling-restrained and self-centring braced frames.

We provide extra analysis comparing the ratios of embodied carbon and repair cost for a clay-brick masonry wall subjected to different levels of seismic damage. This example is representative, as these walls are the main components in masonry structures, which, together with reinforced concrete structures, constitute up to 90% of the entire European building stock.

Supplementary Table 1 summarises the repair activities required for the masonry wall across different damage states (DSs), along with their unit costs in Euros, adapted from Del Gaudio et al.⁸. The unit embodied carbon for each activity is also reported. For masonry wall construction, the embodied carbon includes the emissions from the individual brick units and the cement mortar, composed of a sand-cement ratio of 3:1. Plastering uses a 5:1 sand-cement ratio, while paint volume is estimated based on a spread ratio of 6.5 m² per litre of water-based paints. To illustrate the correlation between embodied carbon and repair cost, we examine a typical masonry wall panel with a length (l_w) of 4.00 m and a height (h_w) of 2.75 m. The repair costs and embodied carbon associated with each DS of such a wall panel are summarised in the Supplementary Table 2, both in absolute and normalised terms. The results show a close alignment between repair cost and embodied carbon ratios, with a minor discrepancy for DS1 alone, where using the repair cost ratio as a proxy for embodied carbon may slightly overestimate emissions.

Supplementary Table 1. Repair actions and unit costs for masonry wall damage states (DSs), with corresponding embodied carbon estimates calculated using the current study's database. Table adapted from Del Gaudio et al.⁸, Empirical Drift-Fragility Functions and Loss Estimation for Infills in Reinforced Concrete Frames under Seismic Loading, [Bulletin of Earthquake Engineering](#) 17 (2019), Springer Nature. Reproduced with permission from SNCSC. Copyright © 2018, Springer Nature B.V.

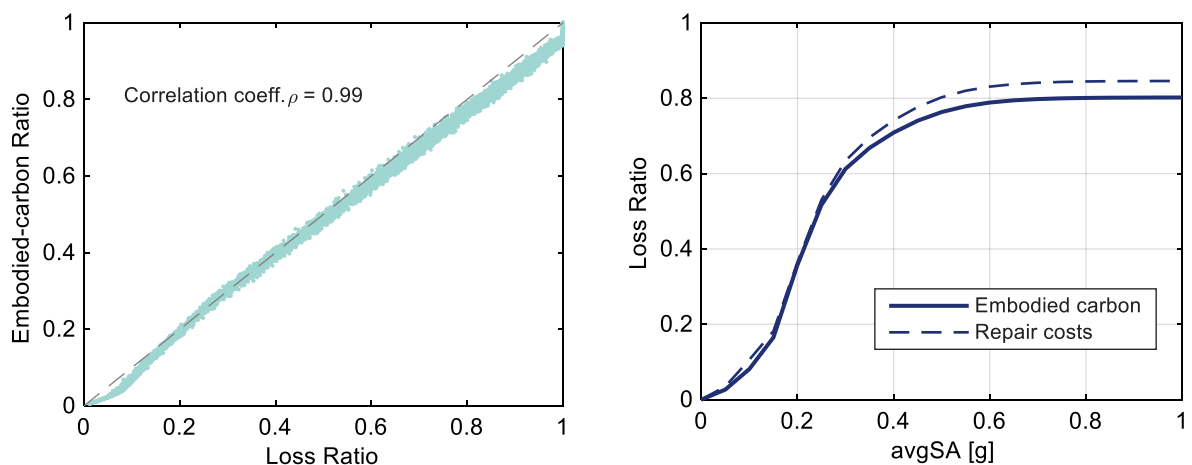
Repair category	Description of repair actions	Repair extent for each damage state (DS)			Unit cost	Embodied carbon
		DS1	DS2	DS3		
Preliminary operations	Install steel scaffolding with ring-lock rosettes and fibreglass netting for enclosure	$0.5(h_w l_w)$	$0.5(h_w l_w)$	$h_w l_w$	25.72 €/m ²	N.A.
Demolition activities	1. Demolition of single-leaf masonry bricks	N.A.	$0.1(h_w l_w)$	$h_w l_w$	13.84 €/m ²	3.4
	2. Removal of plaster up to 5-cm thickness	$(0.2m)d^*$	$0.3(h_w l_w)$	$h_w l_w$	8.58 €/m ²	kgCO ₂ e/m ²
Construction activities	1. Construction of a double-leaf masonry wall with 12x25x25 cm hollow clay bricks for external leaf and 8x25x25 cm for internal one	N.A.	$0.1(h_w l_w)$	$h_w l_w$	72.58 €/m ²	88.56 kgCO ₂ e/m ²
	2. Thermal insulation of cavities with mineral glass wool for external walls	N.A.	$0.1(h_w l_w)$	$h_w l_w$	22.78 €/m ²	7.02 kgCO ₂ e/m ²
Finishings	1. 3-layer plastering with cement mortar	$(0.2m)d^*$	$0.4(h_w l_w)$	$h_w l_w$	23.86 €/m ²	23.10 kgCO ₂ e/m ²
	2. Application of water-based primer	$h_w l_w$	$h_w l_w$	$h_w l_w$	2.53 €/m ²	7.70 kgCO ₂ e/m ²
	3. Water-based painting with 3 layers	$h_w l_w$	$h_w l_w$	$h_w l_w$	13.19 €/m ²	12.40 kgCO ₂ e/m ²
Landfill operations	1. Transportation to landfill	$(0.2m \times 0.1m)d^*$	$0.3(h_w l_w)(0.1m) + 0.1(h_w l_w)(t_w + 0.1m)$	$(h_w l_w)(t_w + 0.1m)$	26.24 €/m ³	N.A.
	2. Landfill disposal				15 €/tonne	13.4 kgCO ₂ e/tonne
Labour	Technical efforts and labour				8% of total cost	N.A.

*d: infill wall diagonal

Supplementary Table 2. Total repair costs and embodied carbon associated with various damage states (DSs) of the masonry wall panel.

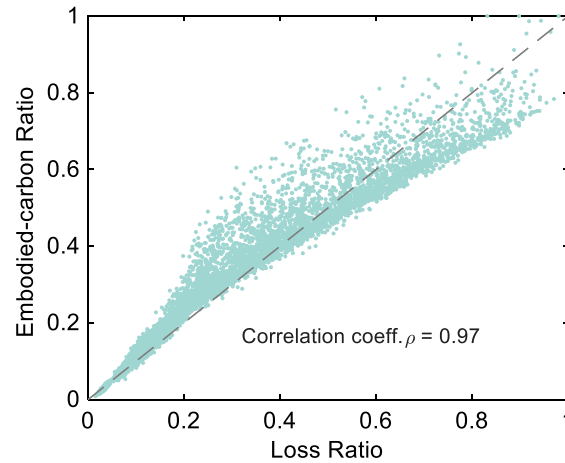
Damage state (DS)	Repair costs [€]	Embodied carbon [kgCO ₂ e]	Normalised repair costs	Normalised embodied carbon
DS1	381	173	0.16	0.12
DS2	648	409	0.27	0.26
DS3	2,351	1,580	1.00	1.00

A similar pattern is observed in the Supplementary Fig. 1 (left), adapted from Aljawhari et al.⁹, which shows the relationship between repair cost and embodied carbon ratios for a low-code 5-storey reinforced concrete frame with unreinforced masonry infills located in Italy. These results were obtained through a detailed component-based seismic loss assessment under a wide range of ground-shaking intensities, following the state-of-the-art FEMA P-58 approach¹⁰. Consistent findings are also indicated in Supplementary Fig. 1 (right), showing the vulnerability functions expressing both the repair cost and embodied carbon ratios as functions of ground-shaking intensity in terms of spectral acceleration values over a range of periods (avgSa).



Supplementary Fig. 1. Environmental and economic loss ratios, and corresponding vulnerability functions, for a case-study concrete frame. Realisations of embodied carbon and economic loss ratios for a reinforced concrete infilled frame (left); and vulnerability functions for repair costs and embodied carbon (right). Figure on the left adapted from Aljawhari et al.⁹, Earthquake-induced environmental impacts for residential Italian buildings: Consequence models and risk assessment, Journal of Building Engineering 84 (2024), licensed under a Creative Commons Attribution 4.0 International License, <http://creativecommons.org/licenses/by/4.0/>.

We also run additional analysis using the same methodology for a 3-storey steel office building, considering a variety of structural and non-structural components. Their fragility, repair cost, and embodied carbon information are obtained from the default component library of the FEMA P-58 guidelines¹⁰, originally developed for the United States. Although the embodied carbon estimates in these guidelines are compiled using economic input-output data rather than environmental product declarations, the results still reveal a clear correlation between embodied carbon and economic loss ratios as shown in Supplementary Fig. 2. The observed dispersion is greater than that of the previous example due to the use of repair cost models in FEMA P-58 that vary prices based on the quantity of the materials being repaired.



Supplementary Fig. 2. Environmental and economic loss ratios for a case-study steel frame. Realisations of embodied carbon and economic loss ratios for a steel frame, derived using the FEMA P-58 methodology.

In general, the main limitation of using repair cost ratios as proxies for embodied carbon arises from the inclusion of cost elements, such as labour, technical services, shoring, and scaffolding, which contribute significantly to repair costs but negligibly to emissions. Typical reconstruction cost breakdowns indicate that materials account for approximately 60-80% of total repair expenditures, with the remainder attributed to labour and other services. The material share also varies with the severity of damage: in minor repair cases, labour dominates, whereas in severe or near-collapse scenarios, where most structural and non-structural components are replaced, both embodied carbon and repair costs are driven primarily by materials. Under these conditions, the correlation between the two metrics strengthens, supporting the validity of using repair cost ratios as proxies for embodied carbon in seismic risk assessments.

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