Journal Title
XX(X):1–37
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DOI: 10.1177/ToBeAssigned
www.sagepub.com/
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The Total Costs of Seismic Retrofits: State of the Art

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Abstract

This article presents the current state-of-practice with respect to quantifying the total cost to retrofit an existing building. In particular, we combine quantitative, qualitative, and heuristic data to provide a taxonomy for understanding the direct and indirect costs associated with seismic risk mitigation. Much of the literature to date has focused on estimating *structural* retrofit costs, the costs of retrofitting the structural elements of a building. In contrast, there is very little research or data on the remaining cost components of the total cost. We propose using structural cost as the foundation for approximating the remaining cost components and the total cost itself. To validate our findings, we compare the proposed approximations with actual cost estimates developed by engineering professionals.

Keywords
Building economics, earthquake risk reduction, retrofit, resilience

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Prepared using sagej.cls *[Version: 2017/01/17 v1.20]*

Introduction

This article reviews what is known and unknown with respect to the total cost associated with the seismic retrofit of an existing building, in the spirit of Thomas et al. (2017). In particular, we combine quantitative, qualitative, and heuristic data to provide a taxonomy for understanding the components of the total cost.

Our review reveals that the literature on retrofit cost estimation to date has focused on the structural cost: the cost associated with retrofitting the structural elements of a building (see, e.g., Fung et al. (2020)). However, a retrofit project will typically incur other costs, such as the cost associated with *non-structural* mitigation, but also other direct and indirect costs that arise in any major construction project such as permit fees and relocation costs. Unfortunately, the literature on these other costs is much more limited.

We propose using structural cost as the foundation for approximating the remaining components of the total cost. Assuming that estimating the structural cost is feasible, we provide heuristics for approximating the contribution of the remaining components to the total. This is especially useful when estimating such costs is more challenging than estimating structural cost. As a result, our heuristics provide a foundation for approximating the total cost itself based on an estimate of the structural cost.

Naturally, such approximations are subject to imprecision. A certain degree of variability is inherent in cost estimation and thus any approximation for the total cost is only as precise as the underlying estimate for the structural cost. Regardless of the cost-estimation method available to a decision maker, such approximations can provide order of magnitude information that is invaluable for planning and budgeting in the early stages of a project. For instance, an owner of a building portfolio can plug cost estimates into a benefit-cost analysis tool. The difference between tens of thousands and hundreds of thousands of dollars can be the difference between allocating funds for a seismic evaluation and declining to pursue seismic risk mitigation.

A taxonomy for the components of total retrofit cost

In this article, we define the total retrofit cost, C_T, as the sum of direct, C_D, and indirect, C_I, costs: $C_T = C_D + C_I$. FEMA 156 (FEMA 1994) defines direct costs, C_D, as "those costs incurred by the actual [retrofit] work, usually paid for by the owner," while Holland and Hobson Jr (1999) define direct costs as "costs that can be identified with the production of goods and/or services." We define direct costs analogously as any costs that directly support construction.

Indirect costs are more difficult to define precisely. In general, indirect costs consist of any costs incurred during construction that are not directly attributable to the actual retrofit work. Defining indirect costs in this way leaves ample room for interpretation (Holland and Hobson Jr 1999). In fact, the Construction Industry Institute (CII) found that "the categorization of indirect costs is not uniform across the industry" (Becker et al. 2012).

Further confusion arises with respect to who bears indirect costs. In the construction industry, indirect costs can refer to indirect *construction* costs borne by the building owner (Becker et al. 2012). FEMA 156 uses a broader definition of indirect costs that includes construction or non-construction costs that can be borne by any party, including tenants and neighbors, as a result of a construction project. In this article, we limit the scope of indirect costs to those costs borne by the building owner (e.g., the cost to rent temporary space during construction). This is consistent with our motivation of providing cost information for planning purposes.

Given existing research on estimating structural retrofit costs, we define direct costs, C_D, as the sum of structural costs, C_S, non-structural costs, C_N, and other direct costs, C_O:

$$C_D = C_S + C_N + C_O \tag{1}$$

The components of total cost are summarized in Table 1.

Table 1. Components of total retrofit cost discussed in this article, definitions, and examples.

Category	Cost	Definition	Example
Direct	Structural, C_S	Cost to retrofit the structural elements of the building	Increasing lateral strength
	Non-structural, C_N	Cost to reduce risk of failure of certain non-structural elements	Reinforcing partitions
	Other, C_O^c	Non-seismic construction costs that directly support the retrofit work	Demolition
	Other, C_O^n	Non-seismic, non-construction costs incurred that directly support the retrofit work	Permit fees
Indirect	Indirect, C_I	Costs incurred that do not directly support the retrofit work	Relocation costs; financing costs

Consistent with FEMA 156, structural retrofit cost, C_S, is defined as "the cost of the construction of the structural elements necessary to [retrofit] the building...[and] includes the contractor's overhead and profit" (FEMA 156). Note that this definition of C_S does not include items such as demolition and the replacement costs for architectural finishes or mechanical, electrical, and plumbing (MEP). Examples of structural costs include the costs of increasing the lateral strength of beams, columns, joints, and walls (Jafarzadeh et al. 2014).

On the other hand, non-structural cost, C_N, is defined as the "cost to reduce the risk of failure of certain non-structural elements of the building" (FEMA 156). Other direct costs, C_O, are defined as costs paid by the owner in order to complete the project and can include both other construction costs, C_O^c, such as demolition, as well as non-construction costs, C_O^n, such as permit fees. In particular, C_O are any other costs that *directly support construction* (in this case, the retrofit work). As a consequence, we define indirect costs, C_I, more precisely as costs borne by the building owner that *do not directly support construction.*

How much do structural costs contribute to the total cost?

We assume that structural cost, C_S, is proportional to the total cost, C_T, that is,

$$C_S = \alpha C_T, \alpha \in (0, 1). \tag{2}$$

Thus, to the extent that estimating C_S is feasible, structural cost can provide the foundation for approximating the total cost to an order of magnitude.

Eq. (2) embodies two assumptions. First, we assume that a retrofit project requires *some* structural mitigation, i.e., $\alpha > 0$. While this may not always be the case, it is consistent within the current context of defining the components of total retrofit cost as arising from a construction project. Purely non-structural mitigation will not incur many of the costs that arise in a construction project. Second, we assume that the total retrofit cost includes other costs besides structural cost, i.e., $\alpha < 1$. As evidenced by the preceding discussion, a complex construction project that includes structural mitigation will incur a myriad of costs.

Background on estimating structural retrofit costs

In a series of papers, Fung et al. (2017, 2018b,a, 2019, 2020) develop a predictive modeling approach to estimate structural retrofit costs. The predictive models are trained on a historical retrofit cost database collected for FEMA 156. The data is freely available online. In particular, the data can be found as part of FEMA's archived Seismic Rehabilitation Cost Estimator (SRCE) software (FEMA 2013–2014).

The predictive modeling approach uses a set of predictors that includes building characteristics, such as building age, size, and type, as well as retrofit-specifc characteristics, including the target performance objective (typically life safety) and status of occupants during the retrofit, in order to predict structural retrofit cost. Table 2 presents a summary of the predictors as well as the outcome of interest, structural retrofit cost. Importantly, the SRCE data does not include information on building occupancy or use (e.g., residential, office, industrial).

Table 2. Definition of outcome, Y, and set of predictors, X, used in Fung et al. (2020).

Variable	Definition
Y	Structural retrofit cost (in dollars per square foot)
s	Seismicity (e.g., peak ground acceleration)
p	Performance objective (e.g., life safety)
b	Building type (e.g., unreinforced masonry, wood frame)
Area	Building area (in square feet)
Age	Building age (in years)
Stories	Number of above and below ground stories
Occup	Occupancy during retrofit (e.g., vacate occupants from building)
Historic	Is building deemed historic? (yes or no)

Building characteristics may be correlated with the other components of total cost, as well. In particular, non-structural cost, C_N depends on building type to the extent that building type determines retrofit technique. Unfortunately, there is very little research relating the remaining components of total cost to such characteristics. Thus, our discussion of the components of total cost does not cover such considerations, with the caveat that in practice, total cost as well as its components may vary with building characteristics.

Table 3 summarizes the total retrofit costs reported in the SRCE data, as well as structural, non-structural, and other components of total cost. All costs in this article are presented in 2019 US Dollars (USD), with the exception of tables reproduced from published papers where it is unlcear what base year is being reported. Costs in the SRCE data are normalized using the Engineering News Record's Building Construction Index (BCI) (ENR 2017). It is worth noting that retrofit engineering practice has evolved since the SRCE data was collected, likely decreasing the rate of growth in retrofit costs relative to the growth in the material and labor costs represented by the BCI.

Total construction costs in the SRCE data include costs of structural mitigation, as well as additional costs triggered by the retrofit, including: (1) costs associated with compliance with the Americans with Disabilities Act of 1990 (ADA 1990), labeled "Disabled" in Table 3; (2) costs associated with removal of asbestos and other hazardous material, labeled "Asbestos;" (3) costs associated with repairing damage or deterioration, labeled "Repair;" (4) non-structural mitigation costs,

Table 3. Total cost and cost components appearing in SRCE data, in millions of 2019 USD.

Cost	Category	Mean	sd	Percent reported
Total		3.362	11.055	100 %
Structural	Direct	2.092	6.858	100 %
Nonstructural	Direct	0.546	3.437	29 %
Architectrual/engineering fees	Other	0.394	1.624	17 %
Project management	Other	0.283	0.530	9 %
Repair	Other	0.175	0.834	14 %
Asbestos	Other	0.120	0.787	13 %
Disabled	Other	0.039	0.185	13 %
System improvements	Other	0.695	3.309	20 %
Relocation	Indirect	0.256	0.689	1 %

labeled “Nonstructural;” and (5) other costs typically associated with construction projects, including architectural and engineering fees, project management, and system improvements.

Finally, we note that the SRCE data includes information on retrofit technique. In principle, the predictive modeling approach of Fung et al. (2020) can be used to compare C_S for a range of retrofit techniques. However, because the data was collected in the 1990s, it is not reflective of current engineering practice.

Approximating C_T based on SRCE data

As Table 3 illustrates, total costs have much higher variability than structural costs. Moreover, it should be noted that while every building in the SRCE data has values for both structural and total cost, the other cost components are often missing. While the SRCE data on other costs shown in Table 3 may not be useful for predicting other costs, it can nevertheless serve as a reference for developing heuristics for $\alpha \equiv \frac{C_S}{C_T}$.

In the SRCE data,

$$\alpha \simeq E[\frac{C_S}{C_T}] = 0.87. \tag{3}$$

That is, on average structural costs account for roughly 87 % of total costs. On the other hand, based on the averages in Table 3,

$$\alpha \simeq \frac{E[C_S]}{E[C_T]} = \frac{2.092}{3.362} = 0.62. \tag{4}$$

That is, average structural costs are approximately 62 % of average total costs in the SRCE data. The caveat to these heuristics is that C_T as reported in the SRCE data significantly underestimates the total cost. As we discuss in the next section, C_T in the SRCE data more closely approximates C_D.

The remainder of this article is organized as follows. The next section presents each component of the direct cost, C_D broken down as in Equation (1). The discussion begins with structural costs in order to better understand the contribution of C_S to C_D and, consequently, C_T. The third section discusses indirect costs, C_I, including definitions of C_I as well as three major contributors to C_I. The fourth section validates our findings using actual retrofit cost data. Finally, we summarize our results and discuss limitations and directions for future research.

Direct costs

This section summarizes the components of direct costs, C_D, which include: (1) structural costs, C_S; (2) non-structural costs, C_N; and (3) other costs, C_O. In the construction industry, direct and indirect costs can be distinguished by one of three ways Holland and Hobson Jr (1999):

- final placement: direct costs are part of the completed work (e.g., materials and labor), while indirect costs are not (e.g., overhead);
- accountability: direct costs can be identified with a specific unit of production within a construction project;
- quantity survey: direct costs are “incurred for material, labor, and production equipment for items measured during the preparation of the quantity survey.”

A quantity survey refers to the estimation and management of costs for a construction project, as conducted by a quantity surveyor.

Holland and Hobson Jr (1999) find that industry professionals do not categorize direct costs consistently. The final placement approach is closest to the one we take in this article: direct costs are costs incurred by the actual retrofit work (FEMA 156). Thus, C_S, C_N, and C_O as defined in Table 1 are considered components of direct costs. Relocation, financing, and loss of revenue during construction, on the other hand, are considered to be indirect costs. Note that based on this approach, "indirect construction costs" as defined in the construction literature (e.g., Becker et al. (2012)) are considered to be part of C_O—other direct non-construction costs—rather than indirect costs.

As shown in Table 3, some of the components of C_D are included in the SRCE data. However, none of the other components besides C_S are reported for more than 30 % of buildings. Moreover, as Table 17 in the Appendix illustrates, even when reported a majority of these cost components has a median of 0—that is, 50 % of the buildings in the SRCE data report a value of 0 for the other cost components. Finally, note the large amount of dispersion for the unit costs presented in Tables 3 and 17.

Structural costs

The literature on estimating seismic retrofit costs is limited. In many cases the retrofit cost being studied is actually the structural retrofit cost, as in Fung et al. (2017, 2018b,a, 2019, 2020).

Jafarzadeh et al. (2014) collect a comprehensive database of retrofit projects for 158 schools in Iran. In subsequent papers, the database is used to predict retrofit costs (Jafarzadeh et al. 2013a,b). The authors compiled the database by collecting primary retrofit documents for each school, including a detailed seismic retrofit design study. By law in Iran, the retrofit studies are rigorously validated by consulting professionals. This yielded highly reliable retrofit cost estimates from the tender (i.e., project bid) documents prepared by the consulting firm.

This cost, which the authors call the Seismic Retrofit Construction Cost (SRCC), includes markups that are highly variable across retrofit projects and are largely unrelated to the actual construction cost (Jafarzadeh et al. 2014). As a result, the authors focus on the Retrofit Net Construction Cost (RNCC), which does not include markups. The RNCC is defined as the sum of *structural* cost, SC, and "clean-up cost," CC, which is the cost of restoring architectural elements (e.g., carpentry) and finishes after the retrofit work has been completed. Summary statistics for the data are reproduced below in Table 4. Based on the minimum, mean, and maximum values, structural cost accounts for between 73 to 80 % of RNCC, suggesting about 20 to 25 % of the retrofit cost is due to clean-up costs. Note that the data in Jafarzadeh et al. (2014) is reported in USD/sq m using a conversion rate of 1 USD=10 000 Iranian Rials.

Table 4. Summary statistics for costs in Jafarzadeh et al. (2014)'s retrofit cost database in USD/sq m.

Variable	Min	Mean	Max	sd
RNCC	20.41	53.60	226.24	20.25
SC	15.07	41.11	181.34	16.65
CC	2.92	12.49	44.90	6.52

Nasrazadani et al. (2017) collect their own database of 167 retrofits of school buildings in Iran. The authors use Bayesian linear regression in order to predict retrofit costs. The main difference is that Nasrazadani et al. (2017)'s objective is to compare retrofit costs for three retrofit actions for a given level of expected *gain in performance*, measured as the change in lateral strength after retrofit.

While the authors do not publish their data (or descriptive statistics for cost), the source of their data is the same as Jafarzadeh et al. (2014)'s, namely retrofit study documents including tender documents prepared by a consulting firm. Thus, although not explicitly stated, the cost under study is the structural retrofit cost (there is no mention of separating out markups or "clean-up costs" from the structural cost as in Jafarzadeh et al. (2014)).

Finally, FEMA 227 (FEMA 1992a) and FEMA 228 (FEMA 1992b) compile retrofit cost data from various sources, largely reports and case studies prepared for cities in California, Utah, and others in the West Coast and the Midwest in the 1980s. The cost data predominantly covers what FEMA 227 calls "hard costs," defined as including the structural cost as well as the clean-up costs, similar to the definition of RNCC in Jafarzadeh et al. (2014). In particular, hard costs are "the bid cost for labor and materials for the seismic portion of the work, including a component for restoring architectural finishes." Based on these sources, FEMA 227 presents a range of "typical" hard costs, reproduced in Appendix Table 18.

Other papers in the literature on retrofit costs do not collect cost databases, but nevertheless provide some guidelines on cost. For instance, Smyth et al. (2004) develop a benefit-cost methodology for evaluating seismic retrofits of apartment buildings in Istanbul, Turkey. To illustrate the methodology, the authors conduct a benefit-cost analysis for a prototype building. The cost inputs for the analysis are "based on information provided by a well-known retrofitting contractor in Istanbul"

(Smyth et al. 2004, p. 191) and represent the mitigation costs for three retrofit alternatives. These costs are reproduced in Table 5 below.

Table 5. Costs of seismic mitigation alternatives in Smyth et al. (2004) in thousands of USD.

Mitigation alternative	Cost
Status Quo	0
Braced	65
Partial (shear wall)	80
Full (shear wall)	135

Note that these are not unit costs. To obtain unit costs, floor area for the prototype building can be approximated from the footprint × number of stories, which is $(28.14 \times 11.3)\text{m} \times 5 = 1589.91$ sq m. Moreover, since no further information on these costs is given, we assume mitigation costs refer to the structural cost.

Formulas and heuristics, typically a function of the estimated building replacement cost (that is, the cost of new construction for a replacement building), are also used to approximate retrofit costs. For example, Hopkins and Stuart (2003) use a formula based on improved performance: Retrofit cost = $(0.08 + \frac{1}{3}\sqrt{DR_{ex} - DR_{ret}}) \times RC$ where DR_{ex} is the damage ratio for an existing building, DR_{ret} is the damage ratio after retrofit, and RC is the replacement cost. The authors use the formula to input retrofit costs into a benefit-cost analysis of buildings across 32 cities and towns in New Zealand. Hopkins and Stuart (2003) report that retrofit costs for these buildings range from \$120/sq m to over \$500/sq m.

Kappos and Dimitrakopoulos (2008) use a heuristic based solely on replacement cost: the “direct cost” of the retrofit (per square meter) is 12 % of the building’s replacement value (per square meter). In the definition of direct cost, the authors include “all expenses for materials and rehabilitation work, [which] obviously depends on the type of the strengthening method.” This definition and heuristic approximates structural cost. The heuristic is applied to conduct both benefit-cost and life-cycle cost analyses for seismic risk mitigation of buildings in Thessaloniki, Greece. Chrysostomou et al. (2015) employ a similar heuristic in the study of school buildings in Cyprus. The authors also define direct cost as “captur[ing] all expenses for materials and the rehabilitation work” and approximate its value as 20 % of the building’s replacement value (per square meter of floor area). With an average replacement cost of €750/sq m, the authors' heuristic estimates direct retrofit cost at €150/sqm, or about \$180/sq m in 2019 USD (assuming a base year of 2015).

Finally, Liel and Deierlein (2013) use FEMA 156 to estimate retrofit costs for non-ductile concrete buildings. They find structural retrofit cost estimates to be between 40 % and 70 % of the buiding replacement value. Moreover, Liel and Deierlein (2013) argue that their estimates are consistent with estimates "obtained from practicing engineers."

Table 6 summarizes the replacement-cost based heuristics for computing "direct retrofit cost." As the discussion illustrates, direct cost typically means *structural* cost. The heuristics approximate structural cost as a fraction of the building's replacement cost. Note that the heuristic reported in Hopkins and Stuart (2003) also depends on the change in the damage ratio. Assuming the change in the damage ratio is between 0 and 1 implies a lower bound for retrofit cost at $0.08 \times RC$ and an upper bound for retrofit cost at $0.08 + \frac{1}{3} \simeq 0.4133 \times RC$.

Table 6. Summary of heuristics in the literature to compute retrofit cost as a fraction of replacement cost.

Fraction of Replacement cost	Source
$[0.08, 0.41]$	Hopkins and Stuart (2003)
0.12	Kappos and Dimitrakopoulos (2008)
0.20	Chrysostomou et al. (2015)
$[0.40, 0.70]$	Liel and Deierlein (2013)

Non-structural costs

In contrast to the literature on structural retrofit costs, the literature on non-structural costs is very limited. As a result, data on non-structural retrofit costs is relatively rare.

Jafarzadeh (2012) provides a taxonomy of the components of total retrofit cost that defines non-structural cost as including both non-structural mitigation costs, C_N in this article, as well as the "clean-up costs" associated with structural mitigation. Moreover, Jafarzadeh (2012) argues that non-structrual mitigation costs, C_N, have "decreased to just a small fraction of the cost of retrofitting structural components," though no explicit fractions are given.

Chapter 2 of FEMA 156 provides a similar taxonomy of costs, in which non-structural cost is defined as the "cost to reduce the risk of failure of certain non-structural elements of the building." This includes MEP and "equipment required to enable the building to fulfill its primary mission" (e.g., medical equipment in a hospital), in addition to the typical non-structural elements addressed by mitigation (e.g., cladding). We apply this definition to the non-structural costs reported in the SRCE data.

Recall from Table 3 that non-structural cost is only reported for roughly 29 % of buildings in the SRCE data. Moreover, the total cost reported in the SRCE data does not always include the reported non-structural cost. This produces inconsistencies when comparing the reported non-structural cost to the reported total cost, as the sum of structural and non-structural costs often exceeds the reported total. In order to better capture the contribution of non-structural cost to the total cost, we re-calculate the total cost as the sum of all the cost components reported for that building. To avoid confusion, we call this the *sum total of costs* and denote it as C_{T^*}.

Table 7 summarizes structural and non-structural costs, the sum total of all reported costs in the SRCE data, as well as the ratio of structural and non-structural cost, respectively, to the sum total of costs. Since we cannot distinguish between unreported C_N and $C_N = 0$, we present summaries conditional on $C_N > 0$. Note that, on average, non-structural retrofit costs account for 13 % of the sum total of costs in the SRCE data. However, as the median ratio shows, non-structrural costs account for 7 % or less of the sum total of costs for half of the buildings in the SRCE data. Also note that the mean and median of $\frac{C_N}{C_T}$ coincide with the mean and median of $\frac{C_N}{C_{T^*}}$.

Figure 1 illustrates the relationship between this ratio, $\frac{C_N}{C_{T^*}}$, and the sum total of costs C_{T^*}. For ease of presentation, the figure omits three outliers for which $C_{T^*} > 50$. Consistent with Table 7, the figure shows that the sum total of costs for many buildings is on the order of millions. However, there are cases for which the sum total of costs is in the tens of millions and, for two buildings, in the hundreds of millions. Moreover, as the regression curve fit to the points suggests, non-structural costs are typically no more than 25 % of the total cost, though in some cases can account for almost 90 % of the total cost.

Table 7. Mean, median, and standard deviation (sd) for the sum total of all costs, C_{T^*}, as well as structural cost, C_S, non-structural cost, C_N, and the ratios of each to the sum total of all costs in the SRCE data. Values in millions of 2019 USD.

Cost	Mean	Median	sd
Sum total of costs, C_{T^*}	4.577	1.280	18.082
Structural cost, C_S	3.306	1.042	12.953
C_S/C_{T^*}	0.798	0.870	0.195
Non-structural cost, C_N	0.797	0.063	4.131
C_N/C_{T^*}	0.133	0.070	0.161

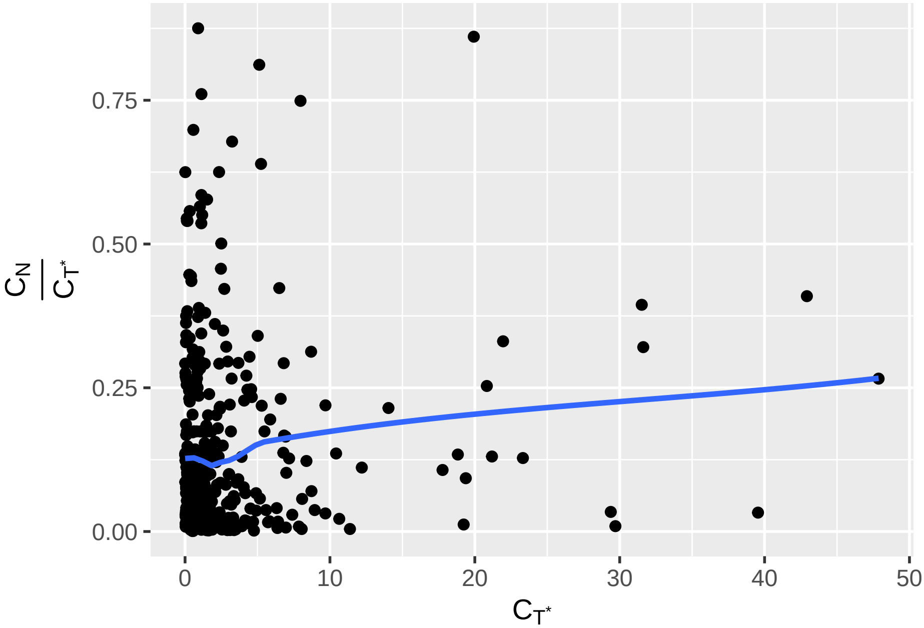

Figure 1. Scatter plot of the ratio of non-structural costs, C_N, to the sum total of costs, C_{T^*}, as a function of the sum total of costs (in millions of USD), with non-parametric regression curve fit.

Figure 2 compares non-structural cost to structural cost. For ease of presentation, the figure omits two outliers for which $\frac{C_N}{C_{T^*}} > 5$ (and the three for which $C_{T^*} > 50$). Unlike the ratio $\frac{C_N}{C_{T^*}}$, the ratio $\frac{C_N}{C_S}$ can be greater than 1. On average, however, the ratio is roughly 0.3, while the median ratio is only 0.09.

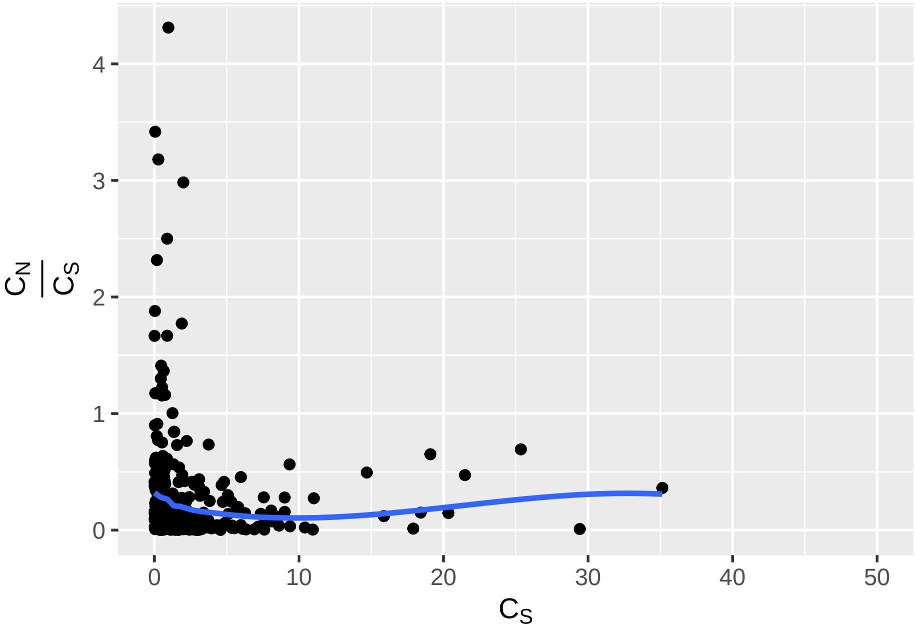

Figure 2. Scatter plot of the ratio of non-structural costs, C_N, to structural costs, C_S, as a function of structural cost (in millions of USD), with non-parametric regression curve fit.

Given $C_{T^*} \geq C_T$, we obtain another heuristic for α conditional on $C_N > 0$. Analogous to Eqs. (3) and (4), we have two approximations for α based on C_{T^*}:

$$\alpha \simeq E[\frac{C_S}{C_{T^*}}] = 0.798 \tag{5}$$

$$\alpha \simeq \frac{E[C_S]}{E[C_{T^*}]} = 0.722 \tag{6}$$

With additional information on the contribution of C_N to total cost, we obtain an alternative heuristic for α. Based on Table 7, on average we have that $C_N = 0.31C_S$ and $C_N = 0.13C_{T^*}$, which implies that, on average,

$$\alpha \equiv \frac{C_S}{C_{T^*}} \simeq 0.43. \tag{7}$$

Table 8 summarizes what we know from the literature about non-structural cost, C_N, and its relationship to structural cost, C_S, and total retrofit cost.

Table 8. Summary of relationship of non-structural cost, C_N, to structural cost, C_S, and the sum total of costs, C_{T^*}, based on SRCE data.

Ratio	Mean	Median	Standard deviation
C_N/C_S	0.31	0.09	1.13
C_N/C_{T^*}	0.13	0.07	0.16

Other direct costs

Finally, we define other direct costs, C_O, as either construction or non-construction costs that directly support construction. Other direct costs typically include replacement costs for MEP, project management, and non-seismic structural costs triggered by construction, such as providing disability access, removing asbestos, or other system improvements, as shown in Table 3. In addition, FEMA 156 discusses other direct non-construction costs, including:

- Design fees: “costs of design professionals such as structural engineers, architects, geotechnical engineers, civil engineers, surveyors, and cost estimators required to perform the studies and design work necessary for structural work and architectural refinishing work.”
- Testing and inspection fees: “[to] verify that the contractor is performing the work in general conformance with the design documents and to perform tests and inspections required by the building codes.”
- Permit fees: “[paid] to the building department to cover their plan checking, field inspection, and recording costs.”

Direct non-construction costs are typically paid to someone other than the contractor. Unfortunately, these costs are not provided in the SRCE data.

Note that FEMA 156 categorizes relocation costs associated with relocating occupants and equipment due to construction as direct costs. In this article, we depart from this definition and categorize relocation costs as indirect costs. This is consistent with our definition of indirect costs as costs that do not directly support construction. FEMA 156 argues that cost of relocation is “an extension of premium construction costs,” while “ongoing rental from relocation...is considered similar to the loss of business” and is therefore considered indirect. In the case of a retrofit, occupants may be left in place, temporarily relocated to a different part of the building, or vacated to another building. As a result, *initial* relocation cost (as defined in FEMA 156) could be difficult to disentangle from the *recurring* relocation cost. We discuss this further in the next section on indirect costs.

Although the SRCE data contains very little information on other direct costs, C_O may be approximated by a heuristic. In particular, FEMA 227 suggests computing the total cost by doubling the hard cost, defined as the structural cost plus clean-up costs. According to FEMA 227, this rule of thumb covers the remaining components of the total cost, which are called "soft costs" and include "architecture and engineering fees, permit fees, legal fees, construction financing and other [costs] typically associated with renovation."

This rule of thumb provides yet another heuristic for α. Suppose that structural cost, C_S, accounts for about 75 % of hard costs and clean-up costs, CC, for the remaining 25 %, as in Jafarzadeh et al. (2014). This implies that $CC = \frac{1}{3}C_S$. Letting C_H denote hard costs, we have that $C_H = C_S + CC = \frac{4}{3}C_S$. Applying the heuristic for total cost in FEMA 227, $C_T = 2 \times C_H = 2 \times \frac{4}{3}C_S$, which implies that

$$\alpha \equiv \frac{C_S}{C_T} \simeq 0.375. \tag{8}$$

If we then define C_O loosely as $C_O = C_T - C_S - C_N$, and we approximate $C_N = 0.13C_T$ as in Table 8, we obtain a heuristic for approximating C_O as a fraction of C_T, namely, $C_O = C_T - C_S - C_N = 0.495C_T$.

One challenge in applying this heuristic is that the definition of total cost is ambiguous. The heuristic in FEMA 227 is meant to approximate "total project costs," which is undefined but likely means total *direct* costs. In general, indirect costs such as relocation and financing costs are not included in typical cost estimates as these are non-project costs borne by the owner. Thus, if we approximate total cost as $C_T = 2 \times C_D$ and $C_D = 2 \times C_S$, we have $C_T = 4 \times C_S$, which implies that

$$\alpha \equiv \frac{C_S}{C_T} \simeq 0.25. \tag{9}$$

Kappos and Dimitrakopoulos (2008) use a heuristic for C_O as a fraction of the replacement cost, similar to their heuristic for C_S. In particular, they assume C_O includes engineering and permit fees and compute it as $C_O = 0.2\times$ Replacement cost, which is larger than the fraction for C_S. On the other hand, Chrysostomou et al. (2015) assume engineering and permit fees are lower, using the heuristic $C_O = 0.15\times$ Replacement cost. It should be noted that Kappos and Dimitrakopoulos (2008) and Chrysostomou et al. (2015) call engineering and permit fees *indirect* costs.

Table 9 summarizes the heuristics for computing C_O. Although data on other costs, C_O is not readily available specifically for seismic retrofit projects, many of the costs included in C_O are common to construction projects in general. Thus, a building owner or manager can consult the larger construction cost literature to shed more light on other direct costs.

Table 9. Summary of heuristics in the literature to compute other costs, C_O. The heuristics based on C_T follow from FEMA 227 and Jafarzadeh et al. (2014) and average values in the SRCE data.

Heuristic	Source
$\frac{C_O}{C_T} = 0.495$	Implied by $C_O = C_T - C_S - C_N$
$C_O = 0.2\times$ Replacement cost	Kappos and Dimitrakopoulos (2008)
$C_O = 0.15\times$ Replacement cost	Chrysostomou et al. (2015)

For instance, Nurul Zahirah and Abidin (2012) review the elements of “soft costs” associated with green buildings. They define soft costs project,” which may include design costs, commissioning, and green certification. They find that design costs can range from an additional 0.5 % to 10 % of “hard” or structural costs. Commissioning, which involves inspections for compliance with green standards, can cost an additional 1 %, while the actual green certification cost can be anywhere from 0 to 5 % of the strutural cost.

Indirect costs

This section summarizes indirect costs, C_I, which comprise the remaining component of total retrofit cost, C_T. Indirect costs are typically defined as any costs that are not direct. Defining indirect costs in this way provides a lot of flexibility for professionals. This flexibility, however, results in a lack of consistency that makes indirect costs more challenging to pin down.

Defining indirect costs

The definition and categorization of indirect costs varies greatly among construction industry professionals. Holland and Hobson Jr (1999) conduct a survey of construction contractors and find inconsistencies in how indirect costs are defined and in how professionals categorize cost components as direct or indirect. Such inconsistencies can be partially explained by variations in construction projects that sometimes allow contractors to more confidently assign costs to the project and, therefore, as direct costs.

CII (Becker et al. 2012), defines indirect costs as "supporting functions that cannot be attributed readily to a part of the final product." Moreover, CII divides indirect costs into two sub-components: indirect construction costs (IDCC), which contractors and project managers may have more control over, and indirect *non-construction* costs. Although definitions typically used in the construction industry, such CII's, are rooted in accounting and make sense from a billing perspective (especially for a contractor), a lack of consistency makes it difficult to distinguish between IDCC and other direct costs, C_O. For the purposes of this article, we define indirect costs, C_I, as costs that do not directly support construction, that is, are not directly attributable to a retrofit project.

Becker et al. (2012) also reviews how much indirect costs contribute to total project costs. As a result of the variability in the practice of assigning indirect costs, Becker et al. (2012) find indirect costs can account for as little as 10 % of the total cost and as much as 40 % of the total cost, with 20 % of the total cost being typical. Thus, a reasonable approximation for total cost is the "conservative" heuristic given in the previous section, $C_T = 4C_S$.

Definitions of indirect costs, C_I, in the retrofit cost literature, while just as vague, are supported by examples that align with the definition we adopt. FEMA 156 defines indirect costs as "costs which come about as a result of the rehabilitation work and affect the owner, the tenants, the community, or other related groups." The following examples of indirect costs are given:

- financing
- occupant interruption/relocation
- increased rents
- change in property value

Moreover, FEMA 156 argue that quantifying indirect costs is more challenging than direct costs. Quoting Comerio (1989): “indirect costs [are] those costs difficult to measure as a result of rehabilitation, mainly the loss of income and opportunity costs.”

Finally, Jafarzadeh et al. (2014) define indirect costs as “the cost[s] coming about as a result of undertaking a seismic retrofit project” and potentially including “loss of revenue due to business interruption during the construction period, relocation cost, and temporary accommodation cost.”

The broad message that emerges is that indirect costs tend to be the most idiosyncratic components of total cost with respect to a project. In the remainder of this section, we discuss three components of indirect costs that are more salient and relatively easy to quantify: relocation costs, the cost of downtime (as a proxy for loss of income during construction), and financing costs. These costs are also likely to be the most typical indirect costs facing a building owner during a retrofit.

Relocation of occupants

FEMA 156 and the SRCE data describe three options for relocating occupants during a retrofit:

- Occupants left in place: “work is scheduled around normal hours of occupancy;”
- Occupants temporarily relocated within building: “occupants are moved to another room in the building during construction;” and
- Occupants vacated from building: “the building is completely vacated during construction.”

Relocation costs are only incurred in the last two cases.

In this article, we distinguish between *initial* relocation costs (e.g., moving costs) and *recurring* relocation costs (e.g., rental costs for temporary space). Note that in the second case—temporary relocation within building—both initial and recurring relocation costs can be negligible, if not zero, relative to vacating occupants from the building. Vacating occupants from a building will require both professional movers and temporary space.

Moving costs will vary significantly by the type of move (e.g., small vs large office). Building owners can easily obtain moving cost estimates from moving companies. For instance, we consulted an online price aggregating tool to obtain best guesses of moving costs for offices (CostHelper, Inc. 2019). Office moves can cost as little as $750 for a small office to well over $30 000 for a large office. Such moving cost estimates typically do not include additional costs, such as disconnecting and reconnecting IT and telecom equipment, delays caused by elevators, and tipping.

Recall from Table 3 that only 1 % of buildings in the SRCE data have information on relocation costs. Moreover, FEMA 156 categorizes these costs as *direct*, suggesting they consist of initial rather than recurring relocation costs. In order to approximate recurring relocation costs, i.e., the costs to rent temporary space, we obtain rental rates for office space, shown in Table 10. In particular, we use the Building Owners and Managers Association (BOMA) International's Office Experience Exchange Reports (EER) to obtain information on rental rates for commercial space in the United States for 2016 (BOMA 2018) (note that access to BOMA's EER requires a paid subscription). While the buildings in the data set rent office, retail, parking, and storage space, this does not cover all potential commercial building uses (BOMA International also offers a subscription for Industrial building reports, which we did not consult).

Table 10. Year-end mean annual rental rates for office space per square foot (per square meter) in 2019 USD. Source data: BOMA Office Experience Exchange Reports (BOMA 2018).

Building size: sq ft	Mean rent/sq ft	Building size: sq m	Mean rent/sq m
$<$ 50 000	22.06	4645	237.48
[50 000, 100 000)	23.69	[4645, 9290)	255.02
[100 000, 300 000)	30.5	[9290, 27 870)	328.29
[300 000, 600 000)	36.38	[27 870, 55 740)	391.59
$\geq$ 600 000	37.72	$\geq$ 55 740	406.03
US Average	29.83		321.07

Downtime

From a building owner's perspective, the primary cost associated with downtime due to a retrofit is the loss of rent and other income. If a building owner is renting temporary space for tenants, the net loss is the amount paid by the building owner to relocate occupants (i.e., rent for temporary space), minus any rent the building owner charges for temporary space.

Table 11 presents mean and median annual income from rent by source, as well as total income, for 2016. Sources of rental income include office, retail, and other (e.g., parking, storage), while sources of non-rental income include tenant services (e.g., cleaning, security) and miscellaneous services (e.g., vending machines, special events) (Source: BOMA's Office EER (BOMA 2018)). Note that, on average, rental income accounts for roughly 93 % of total income.

Table 11. Mean and median annual income from rent and other sources per square foot (per square meter) of rentable space in 2019 USD. Source data: BOMA's Office Experience Exchange Reports (BOMA 2018).

Income source	Mean/sq ft (sq m)	Median/sq ft (sq m)
Office rent	29.76 (2.77)	25.19 (2.34)
Retail rent	27.06 (2.51)	26.96 (2.50)
Other rent	5.44 (0.50)	8.77 (0.82)
Total rental income	29.44 (2.74)	25.00 (2.32)
Total income	31.76 (2.95)	25.80 (2.40)

Total costs depend on the time it takes to complete construction, or *downtime*. The SRCE database includes information on construction duration in days. Table 12 presents retrofit duration in days broken down by occupancy during construction. Note only 425 buildings, representing 21 % of the SRCE data, provide information on duration of retrofit. Thus, this duration data should not be taken as representative of how long a retrofit will take, but nevertheless can provide some guidance.

Table 12. Duration of retrofit (in days) by occupancy during retrofit. Source: SRCE data.

Occupancy during retrofit	Mean	Median	sd
In place	5.48	4	4.19
Temporary relocation within building	9.19	7	8.02
Vacated from building	11.50	10	8.65
No information	7.58	6	5.02

On average, retrofit duration in the SRCE data is 8.5 days, and may be as short as a single day or as long as 60 days. Moreover, the mean and median duration increase with relocation efforts, with leaving occupants in place being the shortest and vacating occupants from the building being the longest. This is likely because both what happens to occupants (a pre-construction decision) and construction duration are driven by the complexity of the retrofit.

To illustrate potential costs of downtime, Table 13 estimates mean and median losses of retrofit downtime by occupancy during retrofit. These losses are calculated by multiplying the duration in Table 12, measured in days, by daily income. Daily income is calculated by dividing total annual income in Table 11 by 365. The table assumes that the building owner does not charge rent for temporary space. If the building owner continues to charge the usual rent, there is no loss of *rental* income. Otherwise, the building owner can pass on the rental cost for temporary space, fully or partially, to the tenants in lieu of the usual rent. In this case, the cost of downtime is the difference between the lost income and the rent collected for temporary space.

Table 13. Mean and median losses from retrofit downtime, computed as total daily income × total duration in days. Total daily income is calculated from total annual income in Table 11, while total duration in days is obtained directly from Table 12.

Occupancy during retrofit	Mean cost/sq ft (sq m)	Median cost/sq ft (sq m)
In place	0.48 (0.04)	0.28 (0.03)
Temporary relocation within building	0.8 (0.07)	0.49 (0.05)
Vacated from building	1 (0.09)	0.71 (0.07)
No information	0.66 (0.06)	0.42 (0.04)

In the context of post-earthquake reconstruction, there is an established literature on estimating losses due to downtime, that is, the time to complete repairs following an earthquake. The seminal paper is Comerio (2006), which breaks downtime into two components: rational and irrational downtime. Rational downtime includes construction costs and the time to repair damage. As Comerio and Blecher (2010) note, the rational components of downtime are "more predictable and more easily quantifiable." Irrational downtime includes the time needed to "mobilize resources and make decisions." The irrational components consist of financing, relocation of functions, human resources, and economic and regulatory uncertainty, which may be more difficult to predict and quantify. The current state of the art methodology is developed in FEMA P-58 (FEMA 2018).

In contrast to post-earthquake reconstruction, pre-earthquake mitigation such as a seismic retrofit is planned. In this context, the relevant drivers of downtime due to retrofit are the specific retrofit action (the “rational” component), which varies by building, and delays that are typical of construction projects (the “irrational” component). Nevertheless, downtime due to post-earthquake repair may be useful in approximating downtime due to retrofit. Downtime due to repair can serve as upper bound for a retrofit assuming that: (1) a retrofit is planned, and (2) the building is at least as occupiable as a building damaged from an earthquake.

To estimate losses from downtime, Mitrani-Reiser (2007) computes expected monetary loss, which is the expected loss in rental income multiplied by the estimated downtime. Loss estimates are used to estimate the expected annualized losses from an earthquake. A similar approach could be used to compute the expected *avoided* losses from a retrofitted building relative to an un-retrofitted building.

It should be noted that the discussion of downtime in this article does not account for productivity losses incurred from the interruption of normal tenant activity, which will vary by the building’s primary use and are harder to quantify. For a building owner, the loss of rental income is the primary loss. If a building owner also occupies the building (for instance, a university), then another potential cost of downtime is due to interruption of the building owner’s other activities.

Financing

Financing costs are the costs incurred to secure funding for a retrofit project. Financing sources include federal agencies such as the Small Business Administraion (SBA), banks, revenue bonds, and other private lenders. Moreover, as FEMA 156 observes, if “external financing is required, the financial costs depend on the ability of the owner to secure financing as dictated by the marketplace.”

From the building owner’s perspective, this implies that financing costs should be easy to predict and quantify (for instance, by obtaining a commercial mortgage quote from a lender). On the other hand, from a research perspective, financing costs are more difficult to pin down because mortgage rates fluctutate daily, and vary by borrower’s credit risk, the property’s building use and value, and the purpose of the loan.

For illustrative purposes, we discuss one potential option for financing a seismic retrofit. The SBA 7(a) loan program offers financial assistance to small businesses for any purchase, including renovation of commercial property (SBA 2018). The program offers several different loan options, which differ in terms and eligibility. For instance, the Standard 7(a) loan offers a maximum loan amount of up to $5 million, with an SBA guarantee of 85% for loans below $150 000 and a guarantee of 75 % for larger loans. On the other hand, the 7(a) Small Loan offers a maximum loan amount of $350 000, with a similar SBA guarantee.

Both Standard and Small loan interest rates may be negotiated by the borrower and lender based on current market rates, but negotiated rates cannot exceed the maximum SBA rate. As an example of private lender rates, commercial loan rates from banks range from 5% to 7 % as of August 20, 2019 (Wood 2019). Maximum rates depend on the length of the loan and loan amount. For instance, the interest rate on a loan amount of more than $50 000, with a life of less than seven years, cannot exceed 2.25 %, based on published maximum SBA rates for Fiscal Year 2019 (SBA 2018).

The SBA offers many other loan programs, including the 504 loans, non-7(a) micro-loans, and CapLines, a loan program for short-term construction projects with a term of no more than 10 years.

Finally, note that financing costs are typically accounted for in standard benefit-cost analyses, which may be used in conjunction with total retrofit cost estimates for deciding whether to proceed with a potential retrofit. As noted in FEMA 156, “financing costs are normally included automatically [in benefit-cost studies] when considering the time value of money and are incorporated into the discount rate.” Thus, in general financing costs for building owners should not present a large source of uncertainty. (Of course, this is generally not the case in the event of post-disaster financing.)

Validating the approximations

In this section, we validate the approximations presented in this article. In particular, we collect retrofit cost estimates prepared by engineering consulting firms for actual retrofit projects and compare the contribution of each cost component to the total cost—$\frac{C_S}{C_T}$, $\frac{C_N}{C_T}$, and $\frac{C_O}{C_T}$—with the approximations based on the heuristics.

The data was shared with the authors by three engineering consulting firms in the United States. The estimates cover 12 projects for buildings in a high-seismicity region of the United States and were prepared between 2000 and 2019. To preserve confidentiality, we only present high-level summary statistics in the article. Table 14 presents summary statistics for building floor area (in thousands of square feet), total cost (in millions of dollars), and unit cost (in dollars per square foot), with costs adjusted to 2019 USD. The validation data covers building occupancies such as office buildings and hospitals, building structural types such as non-ductile concrete and reinforced masonry, a range of retrofit techniques including application of shotcrete and adding shear wall foundations, as well as both life safety and immediate occupancy performance objectives. We note that retrofit techniques are not mutually exclusive and often multiple techniques are implemented in a single project.

Table 14. Summary statistics for building floor area (in thousands of square feet), total retrofit cost (in millions of 2019 USD), and unit retrofit cost (total cost per square foot) in the validation data. The validation data is based on 12 building retrofit cost estimates prepared by three anonymous engineering consulting firms.

	Mean	Median	sd
Area	63.76	24.86	97.1
Total cost	5.53	1.34	10.4
Unit cost	65.81	55.18	50.2

The cost estimates include a breakdown of structural cost, C_S, non-structural cost, C_N, finish costs (including demolition, clean-up, and MEP replacement), and soft costs, as well as overhead, profit, and contingency. Table 15 presents the contribution of each cost component to total retrofit cost in the validation data.

Finish costs in the cost estimates align with our definition of other direct construction costs, C_O^c. Soft costs, on the other hand, align with our definition of other direct non-construction costs, C_O^n, with the caveat that the cost estimates exclude the typical fees included in C_D (e.g., architectural, design, and permit fees), repair costs, costs triggered by construction (e.g., ADA compliance), cost of removing hazardous material, and other costs outside of the scope of the work presented in

Table 15. Summary statistics for the contribution to total retrofit cost for four cost components in the validation data. The validation data is based on 12 building retrofit cost estimates prepared by three anonymous engineering consulting firms.

Cost component	C	Min	Mean	Median	Max	sd
Structural	C_S	0.068	0.282	0.239	0.653	0.173
Nonstructural	C_N	0.000	0.234	0.192	0.611	0.185
Other	C_O	0.320	0.484	0.450	0.736	0.133
Finish	C_O^c	0.032	0.251	0.222	0.506	0.145
Soft	C_O^n	0.175	0.232	0.231	0.315	0.028

the cost estimate. As such, C_O^n may be underestimated in the validation data. We combine finish costs, C_O^c, and soft costs, C_O^n, into other direct costs, C_O.

Finally, note that the the data does not include *indirect* costs as these are, by definition, beyond the scope of the construction work (they are costs faced by the building owner) and tend to vary significantly across projects. Thus, total cost in the data may be more accurately described as total *direct* cost, C_D.

Comparisons

We can now compare the contribution to the total cost from each cost component in the validation data to the approximations based on the heuristics presented in this article. We focus on the mean ratios in the validation as a point of departure, with the caveat that such estimates of the mean are highly noisy due to the small sample size.

$\mathbf{\frac{C_S}{C_T}}$: In the validation data, the average ratio is 0.282, with a standard deviation of 0.173. Based on Eq. (7), $\alpha \equiv \frac{C_S}{C_{T*}} \simeq 0.43$, which is one and a half times the average in the validation data. Note, however, that Eq. (7) assumes $\frac{C_N}{C_S} = 0.31$ and $\frac{C_N}{C_{T*}} = 0.13$, both of which are larger in the validation data. On the other hand, Eq. (8) combines heuristics from FEMA 227 with average values from Jafarzadeh et al. (2014) and implies $\alpha \simeq 0.375$. It should be noted that both approximations are within one standard deviation of the mean in the validation data.

$\mathbf{\frac{C_N}{C_T}}$: The validation data shows non-structural cost contributing 0.234 on average, with a standard deviation of 0.185. On the other hand, recall from Table 8 that $\frac{C_N}{C_T} = 0.13$ on average in the SRCE data, with a standard deviation of 0.16. This is the only heuristic for non-structural cost that we is available from the literature. The difference between the validation data and the heuristic is likely due to the nature of the validation data, which over-represents retrofits for an Immediate Occupancy (IO) performance objective, the retrofit of a historical building, or both. For the one non-historical building retrofitted for a Life Safety (LS) performance objective for which $C_N > 0$, we have $\frac{C_S}{C_T} = 0.34$ and $\frac{C_N}{C_T} = 0.14$, both much closer to our heuristics. However, we caution that these values are not intended to be representative.

$\mathbf{\frac{C_O}{C_T}}$: While our validation data provides a breakdown in terms of both C_O^c and C_O^n, we did not find any heuristics in the literature for these components. However, our heuristic $\frac{C_O}{C_T} = 0.495$, based on Eq. (8) and Table 8, closely approximates $\frac{C_O}{C_T}$ in our validation data, 0.484 (with standard deviation 0.133). Unlike our heuristics for C_S and C_N, this suggests that C_O may vary less across projects, which is reasonable if C_O does not depend on retrofit technique, performance objective, and building structural type to the same degree as C_S and C_N.

The validation data suggests an approximation to the total *direct* cost, $C_D = 2 \times (C_S + C_N)$, with indirect costs being highly variable across projects. Moreover, if estimating C_S is feasible (e.g., using the methods in Fung et al. (2020)), a conservative estimate for non-structural cost of $C_N = C_S$ based on the validation data would imply $C_D = 2 \times (C_S + C_N) = 4 \times C_S$.

Conclusion

Summary and key takeaways

In this article, we review the literature on seismic retrofits in order to characterize the total retrofit cost, C_T. In particular, we present a taxonomy that decomposes C_T into four major components:

- Structural cost, C_S: the most widely studied cost component and may be more feasible to estimate relative to the other cost components. As such, it can be used as the foundation to approximate total cost based on the heuristic $\alpha \equiv \frac{C_S}{C_T}$;
- Non-structural cost, C_N: while non-structrural mitigation is as important as structural mitigation, its cost is significantly

understudied. Assuming C_S can be estimated, the SRCE data suggests the approximation $C_N = 0.31 C_S$, while the validation data suggests to $C_N \simeq C_S$;
- Other direct costs, C_O: typical non-mitigation costs associated with major construction projects may vary less across projects and may be approximated as $C_O \simeq C_S + C_N$;
- Indirect costs, C_I: indirect costs cause the most confusion in both the literature and in practice, are highly variable and individualized to each project.

Our review reveals an absence of reliable data on C_N, C_O, and C_I. However, while C_I may be difficult to approximate in a generalizable way, a building owner may be able to reliably predict C_I due to their highly individualized nature. Given the challenges in estimating C_I, we find that heuristics used in the literature for approximating the total cost, C_T, should be used to approximate the total *direct* cost, C_D. In particular, the heuristic $C_O \simeq C_S + C_N$ reflected in our validation data suggests $C_D = 2 \times (C_S + C_N)$ as a reasonable approximation to the total direct cost.

A key takeaway from our review is that while C_S may be the more feasible cost to predict, the remaining cost components can be approximated as a function of C_S. The implication is that a reasonable approach to estimating C_T is to focus on estimating C_S, for instance, using a predictive model as in Fung et al. (2017, 2018b,a, 2019, 2020). Given an estimate of C_S, approximate $C_N \simeq C_S$ and $C_O \simeq C_S + C_N$, which implies $\frac{C_S}{C_D} = 0.25$. Absent more information, the total cost may then be approximated as $C_T \simeq \gamma C_D$, for some $\gamma > 1$. A good starting point could be $C_T = 2C_D$, which implies $\alpha \equiv \frac{C_S}{C_T} = 0.125$. Using $\gamma = 3$ provides a more risk averse approach, with the caveat that any approximation for C_T is likely associated with significant error as C_I will be highly individualized to each project. The approximations are summarized in Table 16.

Table 16. Summary of heuristics to approximate the contribution of structural cost to the total cost, $\alpha \equiv \frac{C_s}{C_T}$. Note that $\gamma \equiv \frac{C_D}{C_T}$.

Heuristic	Source
$\alpha = 0.125$	Assuming $C_N \simeq C_S, C_O = C_S + C_N$, and $\gamma = 2$
$\alpha = 0.25$	Assuming $C_T = 4 \times C_S$, Eq. (9)
$\alpha \simeq 0.375$	FEMA 227 and Jafarzadeh et al. (2014) Eq.(8)
$\alpha \simeq 0.43$	Based on $\frac{C_N}{C_S} = 0.31$ and $\frac{C_N}{C_{T*}} = 0.13$, Eq. (7)
$\frac{E[C_S]}{E[C_T]} = 0.62$	SRCE data, Eq. (4)
$\frac{E[C_S]}{E[C_T^*]} = 0.72$	SRCE data, Eq. (6)
$E[\frac{C_S}{C_{T*}}] = 0.80$	SRCE data, Eq. (5)
$E[\frac{C_S}{C_T}] = 0.87$	SRCE data, Eq. (3)

Remaining gaps and future directions

Construction cost estimation, especially in the planning stage, is bound to include a high degree of uncertainty. We propose heuristics to approximate C_T, as well as the components of C_T, using estimates of C_S as the foundation. We note that approximations based on the mean are subject to variability around the mean and are meant as a point of departure for approximating cost rather than as precise estimates of cost. Nevertheless, we hope that decomposing C_T as we have in this article provides a useful organizing principle for thinking about the components of retrofit cost. Moreover, our review highlights the gaps in the literature.

We note that the focus of this article is on retrofitting existing buildings as a form of pre-earthquake mitigation. This is in contrast to an active literature that studies costs associated with the repair, possibly coupled with retrofit, of damage from an earthquake. Several papers validate predictions of repair costs and losses (e.g., from FEMA P-58 (FEMA 2018)) with actual repair costs and losses following an earthquake (Di Ludovico et al. 2017a,b; Del Vecchio et al. 2018; Cremen and Baker 2019). An obvious direction for future research is to further validate the approximations for C_N, C_O,, and C_T based on C_S to actual retrofit costs. While our validation is illustrative, it is not intended to be statistically representative of actual costs.

Another potential direction is to evaluate how much C_N, C_O, and even C_I depend on structural properties such as building type, performance objective, occupancy, and retrofit technique. In particular, while C_S likely has the highest correlation with retrofit technique, it is unclear to what degree retrofit technique determines the remaining cost components. To the extent that such correlations are non-trivial, our approximations based on C_S may not be suitable. Moreover, data reflecting modern retrofit techniques is needed for predicting C_S.

Finally, a comprehensive accounting of total retrofit cost can contribute to benefit-cost analysis of seismic retrofits. Moreover, typical benefit-cost analyses do not include indirect benefits or co-benefits, which may be harder to quantify (Fung and Helgeson 2017). Thus, a more comprehensive accounting of potential benefits and costs of seismic retrofits for buildings is needed.

Acknowledgements

We are grateful to Jennifer Helgeson (NIST) and Christopher Segura (NIST) for their comments, as well as three anonymous sources for the validation data.

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Appendix: Supplemental materials

Table 17 presents the unit costs (that is, cost per floor area) for total retrofit cost as well as the other cost components that appear in the SRCE data.

Table 17 suggests that $\alpha \simeq \frac{E[C_S]}{E[C_T]} = 0.7$ in unit cost terms. Thus, average structural unit costs account for a slightly larger fraction of average total unit costs (recall that in terms of absolute cost, Table 3 suggests $\alpha \simeq 0.6$). Moreover, note that while the ratio of the minimums $\simeq 0.7$ as well, the ratio of the maximums $\simeq 0.4$, suggesting much higher dispersion of α in the upper tail.

Table 18 presents the range of typical costs given in FEMA 227 (FEMA 1992a), published April 1992. The range of typical costs represents a range of average unit costs by building type, based on several studies collected in FEMA 228 (FEMA 1992b). Original unit costs are assumed to be in 1990 USD and are updated to 2019 USD using the BCI. (We assume a base year of 1990 because the data presented in FEMA 227 is collected in the period 1979-1990.) Tables 1-8 in FEMA 228 present the data sources that inform the construction of Table 18. It should be noted that one of the sources is the first edition of FEMA 156, published in 1988, which is uperseded by the data collected in SRCE for FEMA 156 (FEMA 1994), published December 1994.

FEMA 227 and FEMA 228 do not define “typical” precisely. It is often used interchangeably with “consensus,” but for presenting the cost data likely refers to average, or mean, costs. It is worth noting that the cost data collected for FEMA 227 generally does not include the level of detail FEMA 156 provides for each building. At best, building type and/or square footage are provided.

Table 17. Summary statistics for the components of total retrofit cost in SRCE data, in 2019 USD/sq ft (USD/sq m).

Cost	Min	Mean	Median	Max	Standard deviation
Total	0.44 (4.78)	52.47 (564.81)	28.83 (310.3)	1835.42 (19756.89)	82.01 (882.79)
Structural	0.32 (3.41)	37.12 (399.53)	22.92 (246.7)	734.17 (7902.76)	46.16 (496.87)
Nonstructural	0.00 (0.00)	6.61 (71.15)	0.58 (6.19)	147.96 (1592.64)	17.53 (188.71)
Relocation	0.00 (0.00)	3.03 (32.63)	0.00 (0.00)	37.99 (408.94)	7.97 (85.81)
Arch/eng fees	0.07 (0.74)	8.15 (87.69)	2.99 (32.2)	155.79 (1676.95)	16.18 (174.13)
Project mgmt	0.00 (0.00)	4.66 (50.17)	2.83 (30.48)	69.21 (744.96)	7.56 (81.37)
Repair	0.00 (0.00)	1.95 (20.95)	0.00 (0.00)	148.08 (1594.02)	9.69 (104.31)
Asbestos	0.00 (0.00)	1 (10.72)	0.00 (0.00)	50.94 (548.31)	5.15 (55.45)
Disabled	0.00 (0.00)	0.9 (9.74)	0.00 (0.00)	24.92 (268.27)	3.41 (36.71)
System improvements	0.00 (0.00)	12.54 (134.96)	0.00 (0.00)	734.17 (7902.76)	46.99 (505.87)

Table 18. Typical hard unit costs (structural cost plus clean-up cost) by building type, in 2019 USD. Reproduced from Table 3-7 in FEMA 227 and updated using the BCI assuming a base year of 1990.

Building type	Cost/sq ft	Cost/sq m
Cast in Place Reinforced Concrete Frame	18 to 22	194 to 233
Cast in Place Reinforced Concrete Shear Walls	14 to 54	155 to 582
Cast in Place Reinforced Concrete Frame with URM Infill	36 to 45	388 to 485
Precast Concrete Tilt-Up	5 to 22	58 to 233
Precast Concrete Frame	14 to 54	155 to 582
Reinforced Masonry	14 to 31	155 to 330
Steel Frame (Moment or Braced)	14 to 36	155 to 389
Steel Frames & {Shear Walls or URM Infills}	9 to 22	97 to 233
Unreinforced Masonry Bearing Wall	18 to 45	193 to 484
Wood	13 to 31	136 to 336

For comparison, Table 19 presents mean and median structural costs by building type, in 2019 USD per square foot (per square meter). Note that for many of the building types that overlap both data sets, there is general agreement in the typical values for structural cost.

Table 19. Mean structural unit costs by building type, in 2019 USD. Based on structural costs reported in SRCE data and updated using the BCI with a base year of 1993.

Building type	Cost/sq ft	Cost/sq m
Concrete Frame with Infill Walls	39.9	430
Concrete Moment Frame	35.7	384
Concrete Shear Wall	31.5	339
Precast Concrete Frame with Infill Walls	47.1	507
Precast Concrete Tilt Up Walls	15.1	163
Reinforced Masonry with Metal or Wood Diaphragm	31.9	343
Reinforced Masonry with Precast Concrete Diaphragm	25.3	272
Steel Braced Frame	11.0	118
Steel Frame with Concrete Walls	31.6	340
Steel Frame with Infill Walls	54.4	586
Steel Light Frame	18.3	197
Steel Moment Frame	33.4	359
Unreinforced Masonry	35.5	382
Wood (Commerical or Industrial)	22.9	247
Wood Light Frame	20.9	225