Multihazard Analysis: Integrated Engineering and Social Science Approach

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Abstract: Reducing the potential impacts from a future disaster can be accomplished through decreasing the hazard exposure and reducing the community's vulnerability. Moreover, communities have both physical and social vulnerabilities that deserve attention; however, most engineering studies focus on assessing and mitigating the physical infrastructure without fully considering the social infrastructure. This paper offers a more holistic examination of vulnerability. Specifically, a two-stage analytical approach is presented that treats both an earthquake and a community's socioeconomic and demographic makeup as hazards. The first stage addresses the physical vulnerability of a community through retrofitting the residential building stock using an inventory of woodframe building archetypes. The second stage incorporates the social characteristics of a community through modeling six social vulnerability variables. A social disaster factor (SDF) is introduced to offer a quantifiable approach for understanding the intersections between physical and social vulnerabilities. Case studies are presented for three communities: a middle-class ZIP code, the poorest ZIP code, and the wealthiest ZIP code, all in Los Angeles County, California. The SDF is computed and compared for the case studies during both stages of the analysis. The analyses demonstrate that when only physical vulnerabilities are modeled, one might incorrectly conclude that the impacts of the event are virtually eliminated. However, when social vulnerabilities are modeled as a hazard alongside the physical vulnerabilities, the projected impacts of the disaster are severe, especially for the most vulnerable populations, in terms of injuries, fatalities, posttraumatic stress disorder diagnoses, and number of dislocated households. In the combined model, these impacts run along racial and economic fault lines, with the most marginalized communities experiencing the most extreme projected losses. These results may have implications for both theory and practice. **DOI: 10.1061/(ASCE)ST.1943-541X.0001846.** *© 2017 American Society of Civil Engineers.*

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Introduction

McFarlane and Norris (2006, p. 4) define a disaster as "a potentially traumatic event that is collectively experienced, has an acute onset, and is time-delimited; disasters may be attributed to natural, technological, or human causes." It is common practice for the impacts of disasters to be measured in terms of economic or insured loss, fatalities, injuries, emotional distress, evacuation and population dislocation, and loss in quality of life (Weber and Peek 2012). In addition, social scientists often measure other community-level impacts, such as business closures and job loss; reduced access to healthcare services, childcare services, and schools; and diminished access to lifeline services such as water and power, to name a few (Peacock et al. 1997).

Social scientists have long-argued that *natural* disasters are actually social events that occur as a result of a natural hazard agent affecting human settlements (O'Keefe et al. 1976; Quarantelli 1986). From this perspective, disaster risk is conceptualized as the product of exposure and vulnerability, in which vulnerability includes both the physical infrastructure and the diverse persons who make up any given community. As decades of research have clearly illustrated, disasters are not *equal opportunity events*, because risks are not equally distributed before the event (Erikson 1976; Hartman and Squires 2006). Instead, the most socially vulnerable persons tend to have the most limited resources, power, and social networks, while also living in the lowest-quality building stock located in the most hazard-prone regions (e.g., Pastor et al. 2006).

Whereas social scientists have offered many empirical cases of how social vulnerability translates into higher levels of risk and disproportionate disaster impacts, engineers have simultaneously documented how unsafe physical environments can cause widespread loss of life, injury, and other negative impacts (e.g., Porter et al. 2006; Foulser-Piggott et al. 2016; DesRoches et al. 2011). In an effort to aid in predisaster planning, researchers in engineering have developed community-level loss estimation models, such as HAZUS (DHS 2003) and MAEViz (Elnashai et al. 2008), and a community-level seismic retrofit optimization model in which Sutley et al. (2016a, b) modeled the physical infrastructure and incorporated specific social and economic metrics. In addition, to prevent, or at least reduce, widespread negative impacts, engineers have also developed new and enhanced design methodologies that improve structural performance and can explicitly account for life safety goals (e.g., Pang et al. 2010; Bass and Koumoudis 2012; Herseth et al. 2012; van de Lindt et al. 2013, to name a few).

This article merges these theoretical perspectives from the social sciences and engineering and presents a multihazard two-stage approach in which the natural hazard is an earthquake; the social hazard is the socioeconomic and demographic (SED) makeup of the community; the vulnerabilities are the physical infrastructure and

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the community's social inequality characteristics; and the impacts include building damage, population dislocation, injuries, fatalities, and posttraumatic stress disorder (PTSD) diagnoses within affected populations. Physical infrastructure was modeled as the residential woodframe building stock, and social inequality at the community level was modeled using 2010 U.S. Census data. A social disaster factor (SDF) was developed and examined for three earthquake-prone neighborhoods (defined herein as ZIP codes) in the United States. The three case studies used data from a middle-class ZIP code and the poorest and wealthiest ZIP codes, all in Los Angeles County, California, at two earthquake hazard levels. The first stage considers the physical hazard only. The second stage additionally incorporates the social hazard through the application of SED modification factors developed as empirically based odds ratios. This work demonstrates that social vulnerability should be included in engineering loss estimation and hazard analysis studies conducted at the household, neighborhood, and community levels.

Modeling Physical Infrastructure

Residential building damage and housing relocation are responsible for a significant portion of economic loss generated by disasters (Peacock et al. 2015). For example, the 1994 Northridge earthquake caused an estimated $40 billion in property loss, approximately $20 billion of which was due to damage to residential woodframe buildings (Reitherman and Cobeen 2003). Hurricane Andrew caused an estimated $26.5 billion in total losses, of which nearly $11 billion was distributed to homeowners through insurance settlements for housing reconstruction (Zhang and Peacock 2009). Because woodframe construction comprises approximately 90% of residential buildings in the United States (Ellingwood et al. 2008), the present study only modeled residential woodframe buildings in an effort to control the size of the analysis while focusing attention on the most common residential building type in the nation. Additionally, the present study focuses on the residential sector because it is where the intersection of physical and social vulnerabilities is more apparent. In 2016, (Sutley and van de Lindt 2016) modeled and analyzed a suite of 37 woodframe building archetypes to quantify the evolution of seismic risk. A portion of the woodframe building archetypes from the prior study was selected for the present study: a one-story single-family house, a two-story single-family house, a two-story multifamily townhome, and a three-story multifamily apartment building. Table 1 provides more specific descriptions and the livable floor area for each of the archetypes used in the present study.

In Sutley and van de Lindt (2016), each of these four building types was designed following multiple seismic provisions to model the variety in the existing building stock. Many residential structures in the United States were built prior to current locally adopted residential building codes and seismic design standards, and, therefore, it is important to accurately capture the range of anticipated structural performance. The present study adopts three levels of seismic design: (1) low-code, (2) code, and (3) high-code, based on changes and updates in the state of the art in seismic design over time. To model these three levels, the selection of seismic provisions used in Sutley and van de Lindt (2016) included the 1978 National Earthquake Hazard Reduction Program (NEHRP) provisions, 2006 International Building Code (IBC) using ASCE 7 (ASCE 2005) load modeling, and a performance-based seismic retrofit (PBSR) using the simplified direct displacement design (SDDD) procedure (Pang et al. 2010), respectively. The PBSR was designed to an immediate occupancy limit state defined as not exceeding 1% peak interstory drift given a maximum considered earthquake (MCE) ($Sa = 2.5$ g, $T \approx 0.2$ s) with a 50% probability of nonexceedance (PNE). In all cases, the building archetypes were designed using the seismic hazard for Los Angeles, California.

Table 1. Descriptions of Building Archetypes

Archetype number	Description	Livable floor area [m^2 (sf)]
1	One-story single-family house	131.0 (1,410)
2	Two-story single-family house with garage	262.0 (2,820)
3	Two-story three-unit townhome with garages	674.5 (7,260)
4	Three-story 10-unit apartment building with tuck-under parking	655.7 (7,057)

Modeling Social Characteristics

As a step toward integrating social science and engineering, the community's social characteristics were modeled in the second stage of the analysis using U.S. Census data to capture differential predisaster circumstances. Various studies indicate that socially marginalized groups are more likely to suffer adverse consequences following disaster. For example, the elderly are at higher risk of injury and fatality (Jia et al. 2010; Cenat and Derivois 2014; Altindag et al. 2005; Priebe et al. 2009; Flores et al. 2014). Ethnic and racial minorities are more susceptible to sustaining physical injuries and to developing PTSD following an earthquake (Kun et al. 2013; Jia et al. 2010; Liu et al. 2010). Single parents and their children are at higher risk for shorter-term and longer-term displacement and they may be more prone to developing mental health distress after disaster (Fothergill and Peek 2015; Tobin-Gurley et al. 2010; Weber and Peek 2012). Females, particularly in developing countries, are more vulnerable to injury and fatality (generally, fatality counts have been low in the United States), and women exposed to earthquakes in the United States and in developing countries are more likely to develop PTSD relative to their male counterparts following an earthquake disaster (Chou et al. 2004; Dell'Osso et al. 2011; Enarson et al. 2007; Flores et al. 2014; Jin et al. 2014; Kuo et al. 2007; Mahue-Giangreco et al. 2001; Peek-Asa et al. 1998; Ramirez et al. 2005; Sharan et al. 1996; Shoaf et al. 1998). Those in low-income households, racial and ethnic minorities, and single mothers are also among those most likely to be renters (Pardee 2012). Renters may not have the legal authority to make retrofits to their living space, but even if they were allowed to make such retrofits, the cost would likely be prohibitive. There are, of course, many other factors that also have significant influence on social vulnerability and it is critically important to understand how these factors intersect [e.g., how do poverty, minority status, and age cluster together or lead to what Fothergill and Peek (2015) refer to as *cumulative vulnerability*?]; however, demonstrating this intersection is quite complex, it requires data that do not presently exist, and it is therefore outside of the scope of this paper.

Low-income households and households with low education levels (i.e., low socioeconomic status) are the most vulnerable groups to injury, fatality, displacement, and PTSD (Fothergill and Peek 2004; Cutter et al. 2003; Weber and Peek 2012). Widespread building damage to a community and damage to personal property have been linked to higher rates of PTSD in affected populations (Sharan et al. 1996; Ramirez et al. 2005; Peek-Asa et al. 1998; Shoaf et al. 1998). The majority of deaths and injuries resulting from earthquakes are due to building damage or building collapse (Shoaf et al. 1998). This vulnerability is exacerbated if the infrastructure is older and/or of poor quality (Cutter et al. 2003).

To capture who is at risk to these negative impacts, census data were used to obtain the case study communities' distributions of age, ethnicity and race, family structure, gender, socioeconomic status, and age and density of the built environment. Each of these variables was divided into subgroups based on the Census data subgroups. These subgroups were then used to empirically develop SED modification factors (discussed later in more detail). Specifically, age was divided into six meaningful categories, ranging from age 0 to 65+ [see Peek (2012) for a discussion of age-specific variation in disaster impacts]. Two ethnicity/race groups were modeled. The first is white, non-Hispanic, which consists of persons identifying with the white race that do not identify with the Hispanic ethnicity. The second is termed racial-ethnic minority, and encompasses Blacks, Hispanics/Latinos, Asians, Native Americans, and all other racial-ethnic minorities in the United States [see Dash et al. (2007) for an explanation of the influence of racial and ethnic majority or minority status across the disaster lifecycle]. The term *partnered family structure* encompasses married couples and unmarried couples in cohabiting relationships. It does not include households with housemates and roommates. Single-person households were captured in family structures as well. Socioeconomic status (SES) was divided into three subgroups that aggregated income and education level. The year the structure was built and the number of units in the structure were used to determine the overall age and density of the built environment.

Natural Hazard

The natural hazard considered in this study is a seismic hazard exemplified through an earthquake scenario in the case study analyses. The seismic hazard was modeled using the seismic performance of the building archetypes, in which performance was measured by a single engineering demand parameter: peak interstory drift (ISD). To demonstrate the difference in seismic performance gained between the three seismic design levels, the results of an extensive nonlinear time history analysis for the four archetypes (Table 1) is provided in Fig. 1 for the first story of each building at all three seismic design levels and two seismic intensities. The nonlinear time history analysis used a suite of 22 biaxial ground motion records (FEMA 2009). The seismic intensities were calculated as the design basis earthquake (DBE) and MCE for a specific location in Los Angeles, California. These seismic intensity levels were based on ASCE 7 (ASCE 2005) seismic maps, in which MCE corresponds to a spectral acceleration of 2.5 g ($T \approx 0.2$ s), and the spectral acceleration of DBE is two-thirds MCE.

As illustrated in Fig. 1(a), the difference in performance based on seismic design level for the one-story house was only significant at MCE. Figs. 1(b and c) demonstrate a moderate reduction for the two two-story archetypes. As shown in Fig. 1(d), a large reduction in peak ISD can be obtained by improving the design level for the three-story building. Given a MCE event, the performance of all four archetypes can be enhanced by increasing the seismic design level.

Social Hazard

The social hazard was modeled by considering six SED variables. The six variables, as previously described, are age, ethnicity/race, family structure, gender, socioeconomic status, and the age and density of the built environment. As the brief review previously

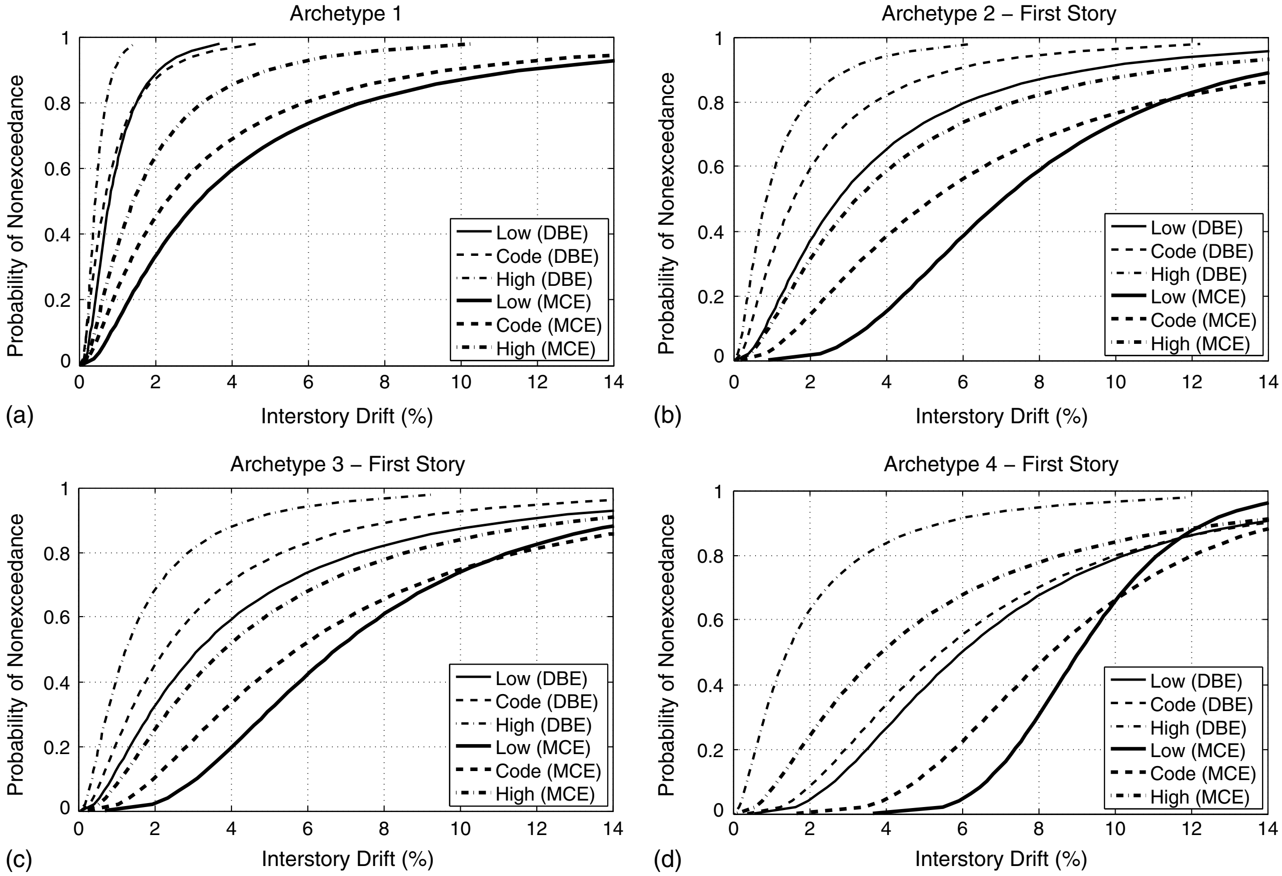

Fig. 1. Probability of nonexceedance of peak interstory drift for DBE and MCE: (a) Archetype 1; (b) Archetype 2; (c) Archetype 3; (d) Archetype 4

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Table 2. Damage State Description

Damage state	Level	Mean peak ISD (%)	Description
1	Slight	1.20	Structure can be immediately occupied, minor drywall repairs required
2	Moderate	2.75	Shelter in place allowed, drywall replacement required
3	Severe	5.50	Shelter in place prohibited, structural damage incurred
4	Collapse	10.0	Structure is not safe for entry, must be reconstructed

indicates, these six variables have been shown to have a significant effect on social vulnerability, which is associated with susceptibility to injury, fatality, PTSD, and other undesirable consequences (Cutter et al. 2003; Wisner et al. 2004).

The six SED factors were developed as odds ratios from empirical data. Generally, the studies used to develop the SED factors reported postearthquake disaster injury, fatality, and/or PTSD diagnosis counts for distinct groups by socioeconomic status and demographic characteristics. Those reported values were used in Sutley et al. (2016a) to develop odds ratios between subcategories of groups providing the quantity of how much more likely one subcategory was to suffer from one of the morbidities when compared to another subcategory. The SED factors each represent a category divided into subcategories, in which, for example, the factor for the category gender has two subcategories, male and female. Thus, the subcategory factors for gender might indicate that females are twice as likely as males to experience postearthquake disaster PTSD ($f_{\mathrm{PR,Female}} = 2$; $f_{\mathrm{PR,Male}} = 1$). The six SED factors, $F_{\mathrm{MR,cat}}$, were computed by multiplying the subcategory odds ratios, $f_{\mathrm{MR,subs}}$, by the percentage of the population in the respective subcategory, $p_{\mathrm{sub},j}$, determined through Census data, and summing over all n_{sub} subcategories. The six SED (category) factors were analytically expressed as

$$F_{\mathrm{MR,cat}} = \sum_{j=1}^{n_{\mathrm{sub}}} f_{\mathrm{MR,sub}(j)} \cdot p_{\mathrm{sub},j} \tag{1}$$

Additional details of the empirical formulation of the subcategory factors and category factors from odds ratios are available in Sutley et al. (2016a).

Physical Impacts

Physical impacts modeled in this study included the range and extent of structural damage and collapses to the residential woodframe building stock. Physical damage to woodframe buildings is correlated with interstory drift, and has been demonstrated in experimental tests (Filiatrault and Folz 2002). Damage states can be defined based on those drifts, in which damage states are descriptive categories of physical damage. Generally, four damage states are used for woodframe buildings, and those used herein are provided in Table 2; they are based on Sutley and van de Lindt (2016). As shown in Table 2, the two measures of physical impacts occur in Damage States 3 and 4. The extent of structural damage is computed as the collective number of buildings in Damage States 3 and 4 after an earthquake scenario. Similarly, the extent of collapse is computed as the number of buildings in Damage State 4 after an earthquake scenario. These calculations are done using the performance curves presented in Fig. 1.

The 50th percentile probability of structural damage given a MCE ground motion was extracted from Fig. 1 and is provided for all four archetypes and seismic design levels in Fig. 2. Fig. 2 demonstrates that improving the seismic design level of the three-story apartment building will reduce the probability of structural damage from 100% to effectively zero probability given a MCE ground motion. The two two-story buildings reduce from 95% (low-design level) to 68% [multi-family dwelling (MFD)] and 46% [single-family dwelling (SFD)] (code-design level) to effectively a zero percent probability of structural damage for the high seismic design level. No real difference is observed for the one-story house.

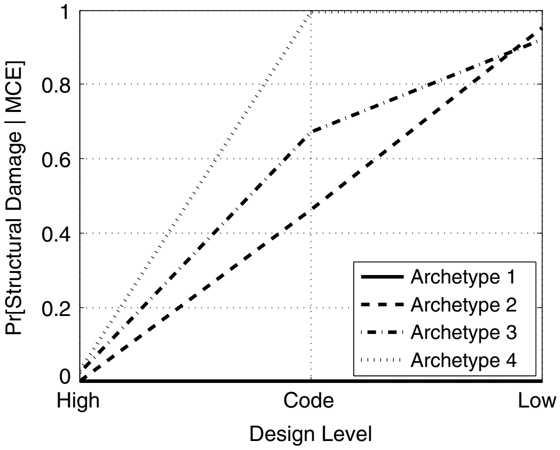

Fig. 2. 50th percentile probability of structural damage given a MCE ground motion versus seismic design level

The 50th percentile probability of collapse give a MCE ground motion was extracted from Fig. 1 and is provided in Fig. 3 for all four archetypes and seismic design levels. Fig. 3 illustrates that in the model, only one of the four archetypes is prone to collapse: the three-story apartment building, with a 35% probability of collapse at the low seismic design level. A code-level design of the apartment building has a reduced probability of collapse of 20%. A high-design level of the apartment building has an approximately zero probability of collapse. Tables 3 and 4 present the 50th and 84th percentile values for the archetypes' probabilities of both physical impacts at DBE and MCE, respectively.

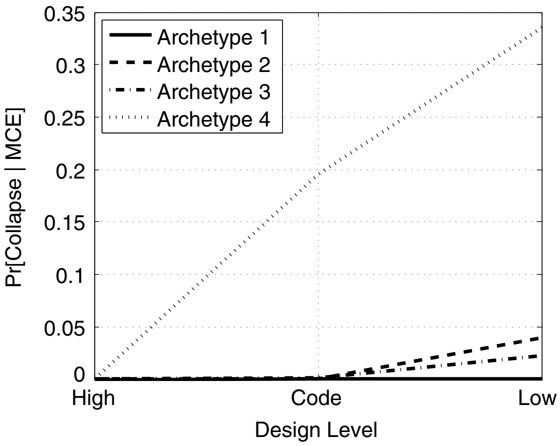

Fig. 3. 50th percentile probability of collapse given a MCE ground motion versus seismic design level

Table 3. Archetype Probabilities of Physical Impacts at DBE

		Probability of structural damage		Probability of collapse	
Archetype number	Design level	50th percentile	84th percentile	50th percentile	84th percentile
1	Low	0.00	0.00	0.00	0.00
	Code	0.00	0.00	0.00	0.00
	High	0.00	0.00	0.00	0.00
2	Low	0.00	0.00	0.00	0.00
	Code	0.00	0.08	0.00	0.00
	High	4.0×10^{-5}	0.93	0.00	2.7×10^{-2}
3	Low	0.0	1.4×10^{-3}	0.00	0.00
	Code	0.0	0.77	0.00	1.4×10^{-3}
	High	9.0×10^{-4}	0.99	0.00	0.20
4	Low	0.00	0.03	0.00	0.00
	Code	0.55	1.00	7.0×10^{-4}	0.75
	High	0.75	1.00	3.9×10^{-3}	0.76

Table 4. Archetype Probabilities of Physical Impacts at MCE

		Probability of structural damage		Probability of collapse	
Archetype number	Design level	50th percentile	84th percentile	50th percentile	84th percentile
1	Low	0.00	0.01	0.00	0.00
	Code	0.00	0.93	0.00	0.02
	High	7.0×10^{-4}	0.99	0.00	0.22
2	Low	1.5×10^{-3}	0.99	0.00	0.20
	Code	0.46	1.00	3.0×10^{-4}	0.91
	High	0.95	1.00	0.04	0.88
3	Low	0.02	0.99	0.00	0.49
	Code	0.67	1.00	2.0×10^{-3}	0.93
	High	0.92	1.00	0.02	0.89
4	Low	0.03	0.99	0.00	0.48
	Code	0.99	1.00	0.19	0.92
	High	0.99	1.00	0.33	0.80

Social Impacts

Based on the previous review, four social impacts were estimated. The first of these, household dislocation, was computed using the damage categories in Table 2, which required sheltering out of place. Using the mean peak ISD values in Table 2, the probability of household dislocation may be determined for a given seismic intensity as the combined probability of a building being in Damage State 3 or 4. This implies that the household dislocation is caused by the home being damaged in an event exceeding a mean peak ISD of 5.5%. Of course, this is not a comprehensive description, because dislocation is dependent on many factors other than physical building damage to the home. For example, a building may only experience a peak ISD of 1%, yet if the power and/or water supply are lost for a long enough period of time, then temporary dislocation becomes more likely. Business closure, school closure, building abandonment, socioeconomic status, access to nearby relatives to shelter with, new zoning laws, neighborhood vitality, experience with previous disasters, and myriad other social, economic, political, and environmental factors may influence temporary and permanent dislocation in any given population (Sapat and Esnard 2016; Weber and Peek 2012). However, measuring household dislocation in this simplified way allowed the model to account for potential dislocation as connected to housing damage.

Additional social impacts included the three morbidities that have all been measured and demonstrated in the literature to be significant potential outcomes of disasters. Again, these are critical injury, fatality, and posttraumatic stress disorder diagnosis rate. Although various mental health indicators have been used across a variety of disasters to assess population mental health, PTSD was selected for this study due to its ability to be systematically measured and the fact that it is the most-often-measured mental health outcome after disaster (Norris 2006).

Social Disaster Factor

A two-stage approach is presented to determine the impacts of an earthquake-induced disaster by considering a subset of physical and social impacts commonly observed after disasters. A SDF was developed to quantify and communicate the impacts and severity of the disaster. The composite SDF can be expressed as

$$\mathrm{SDF} = H \times S_i \times \sum I_i \tag{2}$$

$$\sum I_i = \sum \begin{pmatrix} \text{Injuries} \\ \text{Fatalities} \\ \text{PTSD diagnoses} \\ \text{Dislocated households} \end{pmatrix}_i \tag{3}$$

where H = natural hazard; S_i = social hazard; and I_i = impacts. To avoid double counting, collapse is not explicitly counted in the SDF, because household dislocation encompasses both severe and collapse damage. As shown in Eq. (2), if there is no earthquake, then there are no earthquake-related impacts (if $H = 0$, then $I = 0$ and $\mathrm{SDF} = 0$). If there is no community population, and thus no SED makeup of the community, then there will be no impacts regardless of the earthquake hazard (if $S = 0$, then $I = 0$, regardless of the value of H, and $\mathrm{SDF} = 0$). If the SED makeup exists but is neglected (if $S = 1$ and $H \neq 0$ or 1, then $I > 0$ and $\mathrm{SDF} > 0$) in the analysis, then the impacts are due to a natural hazard only. If the earthquake hazard is neglected, or if there is no earthquake hazard (if $H = 1$ and $S \neq 0$ or 1, then $I > 0$ and $\mathrm{SDF} > 0$) in the analysis, then the impacts are not disaster related, but instead are a consequence of normal daily life. If H is not equal to 0 or 1, and S is not equal to 0 or 1, then the impacts are the result of the intersection of the natural and social hazards, thereby combining to form a disaster. Eq. (2) demonstrates how the social hazard will act as an amplifier on the impacts caused by the natural hazard. Eq. (3) weights all four impacts equally. If a decision maker prioritizes one or more of the impacts higher than the others, weights can be applied as multipliers on each impact within Eq. (3). Furthermore, additional impacts can be included in Eq. (3) as data become available.

Multihazard Analysis

In this section, three community-level analyses are presented and compared. The three case study neighborhoods are represented by ZIP codes in Los Angeles County, California: the poorest ZIP code (90011), the wealthiest ZIP code (90077), and a middle-income ZIP code (90019). Fig. 4 presents the generalized approach followed for Stage 2; Stage 1 follows the same approach except that it excludes the socioeconomic and demographic factors and the community social inequality characteristics (gray boxes). In both cases, the residential building stock is modeled and exposed to an earthquake, and all buildings are exposed to identical seismic intensity. The resulting physical and social impacts are computed and communicated via the SDF. In both stages, the only mitigation approach investigated is retrofit of the residential building stock.

The two-stage approach is used to capture the differences in losses when the SED factors and community social inequality characteristics are included in the analysis. This is done through an analogy of the SED factors acting as a hazard and amplifying the losses to attain more realistic values. Table 5 presents the U.S. Census and American Community Survey data used in both stages of the analysis. Table 6 presents the additional U.S. Census data needed in Stage 2 of the analysis to capture the community social inequality characteristics.

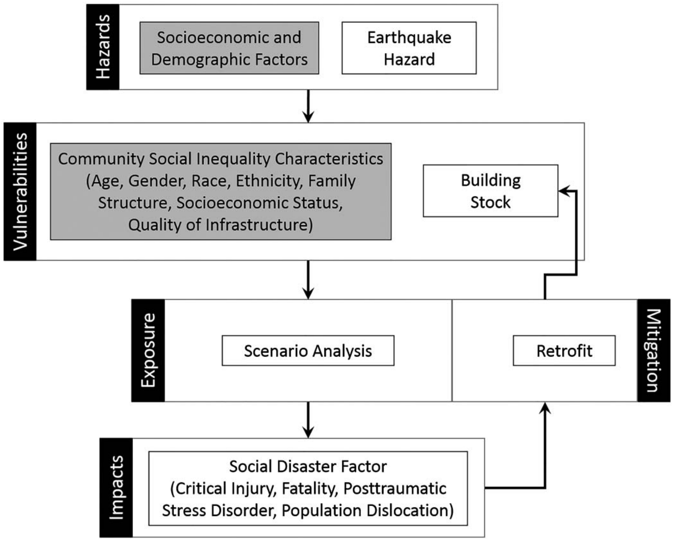

Fig. 4. Two-stage multihazard integrated approach

Table 5. Stage 1: Case Study Community Characteristics

Variable	Subcategory	ZIP code 90011	ZIP code 90019	ZIP code 90077
Total population size		100,882	65,408	8,506
Mean annual income		\$39,043	\$66,176	\$284,834
Mean household size		4.57	2.70	2.53
Total number of housing units		23,625	25,373	3,806
Year structure built	Built 2010 or later	0.2%	0.0%	0.0%
	Built 2000–2009	4.0%	2.5%	4.6%
	Built prior to 1999	95.8%	97.4%	95.4%
Units in structure	1 unit detached	46.1%	24.2%	88.4%
	3 or 4 units	10.9%	15.5%	1.1%
	10 to 19 units	4.6%	13.6%	0.0%

For the analyses, rather than using the total number of housing units for each ZIP code as provided in Table 5, this variable was set at 2,000 households for each of the ZIP codes to maintain some consistency for analyzing and comparing the results. Using the housing data from the American Community Survey, which operates under the U.S. Census Bureau (2012), an approximate distribution of the 12 building archetypes scaled for only 2,000 households may be determined for each ZIP code, and it is provided in Table 7. The American Community Survey data used to develop the data in Table 7 are provided as the bottom two variables in Table 5. Table 7 provides the Census distribution for archetypes in this study. There are other building types in the Census not represented in this study; therefore, the columns in Table 7 do not add up to 100%. It is interesting to point out that nearly 100% of the housing stock was captured for the wealthy ZIP code (90077), but there were many other multifamily dwellings not captured for the middle-class and poor ZIP codes.

The archetype distribution presented in Table 7 was used as the initial building stock distribution for the three communities based on structure type and the year of the seismic provisions, which correspond to the built prior to year in Table 5. The actual number of each of the modeled building structures can be determined by multiplying the values in Table 7 by 2,000 for each ZIP code. To determine the total number of households in each ZIP code, the number of each archetype must be multiplied by the number of residential units per archetype, $N_{\text{unit},i}$, and then multiplied by 2,000. Archetypes 1 and 2 are single family, and therefore only have one residential unit. Archetypes 3 and 4 are multifamily, and have 3 and 10 units, respectively. The analyses were conducted at two seismic intensity levels, DBE and MCE, for Los Angeles, California, as described previously.

Stage 1: Measuring the Physical and Social Impacts from the Natural Hazard

As discussed previously, the social impacts are measured through a count of the number of households required to either temporarily or permanently dislocate, and the number of persons experiencing each of the three morbidity impacts. Recall, to determine the number of households dislocated, N_{HD}, the total number of archetypes

Table 6. Stage 2: Case Study Community Characteristics for Social Inequity

Variable	Subcategory	ZIP code 90011	ZIP code 90019	ZIP code 90077
Age	Child (0–9 years old)	18.8%	11.8%	11.1%
	Adolescent (10–19 years old)	18.7%	12.4%	12.2%
	Young adult (20–29 years old)	16.7%	14.7%	8.60%
	Middle-aged adult (30–45 years old)	23.5%	24.1%	13.4%
	Older adult (46–64 years old)	17.6%	25.7%	30.3%
	Elder (65 + years old)	4.60%	11.2%	24.4%
Ethnicity/race	White, non-Hispanic	0.60%	14.9%	84.3%
	Racial-ethnic minorities	99.4%	85.1%	15.7%
Family structure	Single	59.8%	67.0%	35.4%
	Partnered	40.2%	33.0%	64.6%
	Child <18 years old in household	62.8%	32.0%	27.3%
Gender	Female	49.8%	48.5%	46.8%
	Male	50.2%	51.5%	53.2%
Socioeconomic status	Low	52.9%	49.2%	7.60%
	Moderate	42.1%	33.8%	16.8%
	High	5.10%	17.0%	75.7%

Table 7. Case Study Initial Building Stocks

Archetype	90011 (poor)	90019 (middle)	90077 (wealthy)
Archetype 1, Low	17.7%	5.70%	46.0%
Archetype 1, Code	0.74%	0.15%	2.22%
Archetype 1, High	0.05%	0.00%	0.00%
Archetype 2, Low	17.7%	5.70%	46.0%
Archetype 2, Code	0.74%	0.15%	2.22%
Archetype 2, High	0.05%	0.00%	0.00%
Archetype 3, Low	8.37%	7.30%	1.14%
Archetype 3, Code	3.44%	0.19%	0.06%
Archetype 3, High	0.00%	0.00%	0.00%
Archetype 4, Low	3.54%	6.42%	0.00%
Archetype 4, Code	0.15%	0.16%	0.00%
Archetype 4, High	0.00%	0.00%	0.00%

in Damage States 3 and 4 were multiplied by their respective number of units, and summed. This is expressed as

$$N_{\mathrm{HD}} = 2{,}000 \cdot \sum_{ds=3}^{4} \sum_{i=1}^{12} (N_{\mathrm{unit},i} \cdot N_{ds,i}) \tag{4}$$

In this first stage, the three morbidity counts (critical injury, fatality, and PTSD diagnosis) were computed based on building damage alone. The mean value for each morbidity rate is provided in Table 8. The critical injury rate and fatality rate were adopted from HAZUS (DHS 2003). The PTSD diagnosis rate was taken as the severe injury rate in HAZUS (in which severe injury is less serious than critical injury) due to a similar rate being observed in the empirical literature (see PTSD references discussed previously). The total population size was 9,140, 5,506, and 5,062 persons for ZIP codes 90011 (poorest), 90019 (middle), and 90077 (wealthiest), respectively. This was determined using the 2,000-household analysis size and the mean household size, HS, for each ZIP code as provided in Table 5 (4.57, 2.70, and 2.53, respectively). The morbidity counts, N_M, were determined by multiplying the morbidity rates, $R_{M,ds}$, in Table 8 by the total population size for each ZIP code and the total number of households in each damage state, expressed as

$$N_M = (2{,}000 \cdot \mathrm{HS}) \cdot \sum_{ds=1}^{4} \left[R_{M,ds} \cdot \sum_{i=1}^{12} (N_{\mathrm{unit},i} \cdot N_{ds,i}) \right] \tag{5}$$

Stage 1 reduces the physical and social impacts through mitigating the physical infrastructure. To do this, three building stocks were analyzed for each ZIP code to investigate the impacts of different mitigation levels. The first building stock was the initial unretrofitted building stock for each ZIP code, as presented in Table 7. The second building stock retrofitted 50% of the low-code buildings to high-code, and the third building stock retrofitted 100% of the low-code buildings to high-code. The mean values from Table 8 were modeled as lognormally distributed random variables by assigning a standard deviation equal to one-fifth of the mean to capture the variability in these rates.

Table 8. Morbidity Rates by Damage State (Mean Values)

Damage state	Critical injury rate	Fatality rate	PTSD diagnosis rate
1	0.0000005	0.0000005	0.000005
2	0.0000003	0.0000003	0.0003
3	0.00001	0.00001	0.001
4	0.03	0.05	0.2

McFarlane and Norris (2006) note that the American Red Cross classifies an event as a disaster when it affects 100 or more people, causes 10 or more fatalities, triggers an appeal for international help, and/or leads to a declaration of a state of emergency. With this in mind, the 100 persons affected and 10 fatalities threshold can be used to measure the scale of the disaster. The 50th percentile values for the number of fatalities and the total number of morbidities (which includes fatalities) are plotted in Figs. 5(a and b) for the DBE and MCE analyses, respectively, of Stage 1.

Fig. 5(a) demonstrates that the wealthiest ZIP code, 90077, will not experience more than 10 fatalities, and actually not more than 10 morbidities, given a design basis earthquake. This is due to the very low number of multifamily buildings in that community. Additionally, Fig. 5(a) shows that the middle-class ZIP code (90019) is more vulnerable to fatalities and morbidities than the poorest ZIP code (90011) for the initial building stock and 50% retrofit cases. This finding is due to the fact that it has a higher percentage of Archetypes 3 and 4 designed to the low-code level. Fig. 2 demonstrated these two archetypes to be the most vulnerable to structural damage, and thereby subject to household dislocation. Fig. 5(a) illustrates that when retrofitting 100% of the low-code structures to high-code, the affected number of persons is reduced to well below 100 affected persons for all three ZIP codes. However, for both the poorest and the middle-class ZIP codes, the initial building stock and the 50% retrofitted building stock exceed 100 persons affected.

Fig. 5(b) demonstrates the poorest ZIP code is the most vulnerable and experiences the most impacts for the higher intensity earthquake, and the wealthiest ZIP code is the least vulnerable for all three building stocks. When 100% of the low-code buildings were retrofitted to high-code, the impacts from both the middle-class and wealthy ZIP codes were reduced to below 100 persons affected. Only the wealthiest ZIP code experiences fewer than 10 fatalities under this highest retrofit level at MCE.

Figs. 6(a and b) provide the 50th percentile values for the number of households dislocated at DBE and MCE, respectively. Looking at Fig. 6(a), less than 100 households were dislocated for all three building stocks for the wealthiest ZIP code, 90077, and for all three ZIP codes at the 100% retrofitted building stock. The initial building stock of the middle-class ZIP code, 90019, had the highest number of displaced households, followed by the poorest ZIP code (90011).

At MCE [Fig. 6(b)], a significant reduction was obtained at each increase in retrofit level; however, only at 100% retrofit do the middle-class and wealthiest ZIP codes have fewer than 100 households dislocated. In fact, the high-intensity earthquake caused dislocation of nearly every single household (1,864 out of 2,000) in the initial building stock for the middle-class ZIP code (90019). This is similar to the poorest ZIP code (90011) as well, which had 1,682 displaced households out of 2,000 in the initial building stock.

The SDF may be computed for the DBE and MCE analyses using Eq. (2) and the 50th percentile values determined previously. Table 9 presents these values for the number of households dislocated, the number of morbidities, and the SDF at MCE. In this case, the SDF reduced to being less than 100 for the wealthiest ZIP code, 90077, at the 100% retrofitted building stock. The poorest ZIP code, 90011, had the highest SDF, demonstrating that this area had the most physically vulnerable building stock.

Stage 2: Measuring Social Impacts Considering Earthquake and Social Hazards

For the second stage of the analysis, the morbidity rates were modified using the six SED (category) factors, expressed as

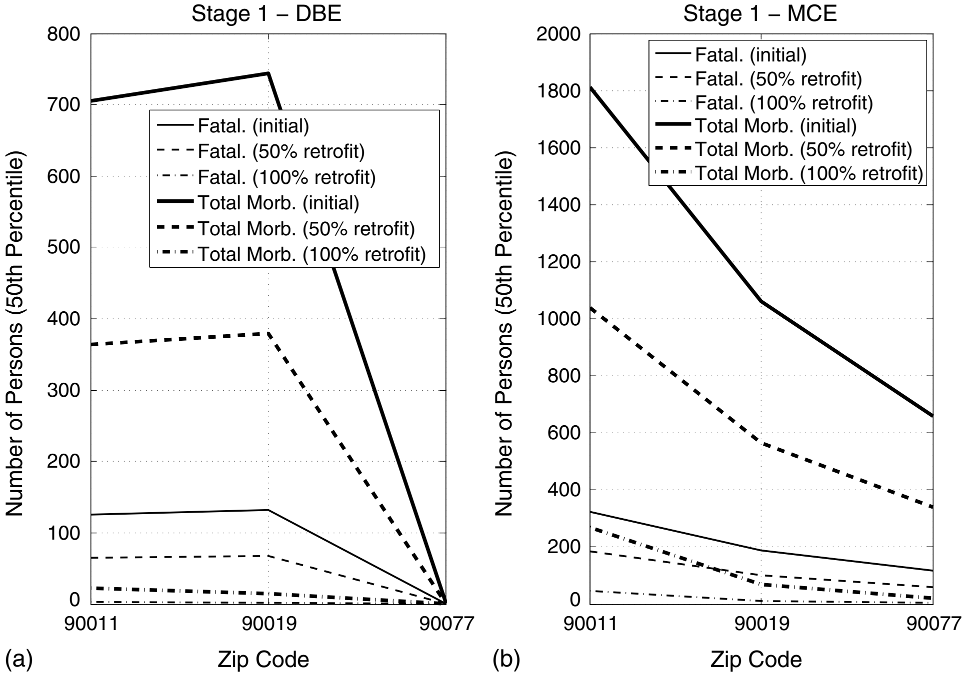

Fig. 5. Stage 1—50th percentile value for the number of fatalities (Fatal.) relative to total morbidities (Morb.): (a) DBE; (b) MCE

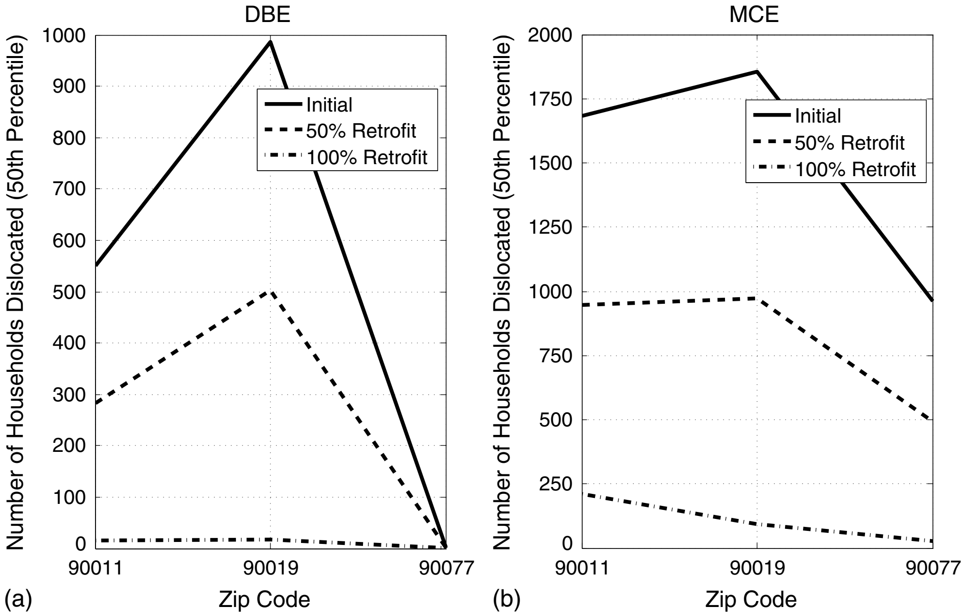

Fig. 6. 50th percentile value for number of households dislocated: (a) DBE; (b) MCE

$$MR_{is,ds} = (F_{\text{MR,age}} \cdot F_{\text{MR,gen}} \cdot F_{\text{MR,ses}} \cdot F_{\text{MR,env}}) \cdot IS_{is,ds} \quad (6)$$

for injury and fatality, and the morbidity rate for PTSD was modified as

$$\text{MR}_{pr,ds} = (F_{\text{MR,age}} \cdot F_{\text{MR,eth}} \cdot F_{\text{MR,fam}} \cdot F_{\text{MR,gen}} \cdot F_{\text{MR,ses}} \cdot F_{\text{MR,env}}) \cdot PR_{ds} \quad (7)$$

where F_{age}, F_{eth}, F_{fam}, F_{gen}, F_{ses}, and F_{env} are the SED (category) factors for age, ethnicity/race, family structure, gender, socioeconomic status, and the age and density of the built environment, respectively, as developed in Eq. (1), and where the MR subscript refers to the category factor value for the specific morbidity rate (either injury, fatality, or PTSD diagnosis). The term $IS_{is,ds}$ refers to the rates of injury and fatality is, and PR_{ds} is the rate of PTSD diagnosis for damage state ds due to building damage, respectively. Note that the category factors F_{eth} and F_{fam} were not used in Eq. (6) for determining the morbidity rates for injury and fatality. This is due to the lack of empirical data on these two variables for injury and fatality (Sutley et al. 2016a). Similar to Stage 1, previous engineering frameworks set all of these factors equal to unity, and base the loss and recovery estimations wholly on the physical infrastructure ($MR_{is,ds} = IS_{is,ds}$ and $\text{MR}_{pr,ds} = PR_{ds}$).

Table 9. Stage 1: Reduction in SDF through Reducing Physical Vulnerabilities at MCE

ZIP code	Building stock	Households dislocated	Morbidities	SDF
90011 (poor)	Initial	1,682	1,810	3,492
	50% retrofit	947	1,039	1,986
	100% retrofit	211	269	480
90019 (middle)	Initial	1,864	1,061	2,915
	50% retrofit	973	565	1,638
	100% retrofit	92	70	162
90077 (wealthy)	Initial	963	657	1,620
	50% retrofit	494	339	833
	100% retrofit	26	21	47

Table 10. Morbidity Rate Factors

		Stage 2		
Morbidity rate factor	Stage 1	90011	90019	90077
Critical injury	1.0	3.67	3.61	2.15
Fatality	1.0	3.66	3.60	2.14
PTSD diagnosis	1.0	8.87	5.72	2.37

To incorporate the social hazard of the three ZIP codes, Eqs. (6) and (7) were applied: the morbidity rates were modified by multiplying the rates presented in Table 8 by the factors developed using Eq. (1) and using the community inputs in Tables 5 and 6. The resulting morbidity rate factors are provided in Table 10 and compared across the two-stage approach. The factors in Table 10 are multiplied by the morbidity rates provided in Table 8 for each specified stage of the analysis. Just as stronger shaking may lead to greater losses, more social inequity may also lead to greater losses.

The product of the SED factors provides one number with which to compare the social inequity for communities for each morbidity and demonstrates how the SED makeup of a community acts as a social hazard in that it amplifies the impacts. As shown in Table 10, the poorest ZIP code, 90011, has the highest values for all three morbidity rates, indicating that it has the highest social hazard of the three communities. The wealthiest ZIP code, 90077, consistently has the lowest factors for all three morbidity rates, indicating that it has the lowest social hazard of the three communities. These findings are in line with social science disaster vulnerability theory, because 90011 is the poorest ZIP code, it has a very high population of minorities, and it has mostly multifamily dwellings, and 90077 is the wealthiest ZIP code, it has a very low population of minorities, and it has mostly single-family dwellings. The most significant difference between the three communities is the factor developed for the rate of PTSD diagnosis, which is nearly four times higher for 90011 than for 90077.

Fig. 5 was reproduced for the second stage using the factors in Table 10, and it is presented as Fig. 7. As shown in Fig. 7(a), at DBE the number of fatalities was less than 10 at 100% retrofit for the middle-class (90019) and wealthiest (90077) ZIP codes. In fact, the number of fatalities and morbidities was below 10 for all three building stocks for the wealthiest ZIP code. Conversely, the poorest ZIP code had higher impacts for all three building stocks. In the Stage 1 analysis at DBE, the middle-class ZIP code was shown to be the most vulnerable to high impacts. In Stage 2, the poorest ZIP code was shown to be the most vulnerable to high impacts at both DBE and MCE. It should be noted that the total number of morbidities in Fig. 7(b) exceeds the total population size for the poorest ZIP code (90011) for the initial building stock. The total number of morbidities nearly exceeds the total population size for the initial building stock for the middle-class ZIP code (90019) as well. Having more morbidities than population members implies that some people would have experienced multiple morbidities. This has been documented in postdisaster field studies that demonstrate that people experiencing physical injuries are more susceptible to adverse mental health impacts such as PTSD (Norris et al. 2002).

Following the second stage does not change the performance of the building stock, and, therefore, Fig. 6 does not change between stages. Table 9 was reproduced for the second stage and the results are presented as Table 11. As shown, when taking the social hazard into account, the number of morbidities increases substantially,

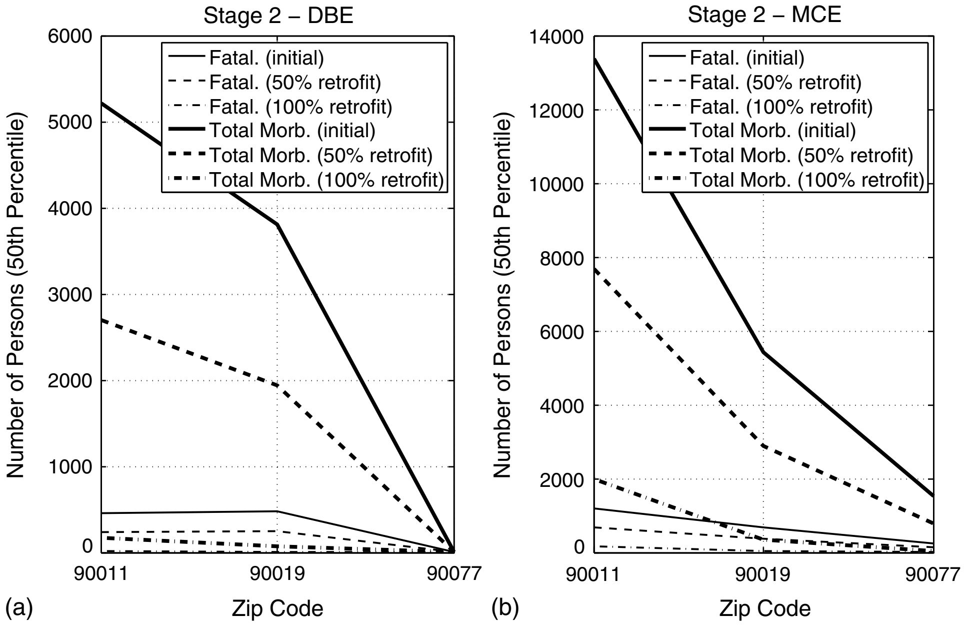

Fig. 7. Stage 2—50th percentile value for number of fatalities: (a) DBE; (b) MCE

Table 11. Stage 2: Reduction in SDF through Reducing Physical Vulnerabilities at MCE

ZIP code	Building stock	Households dislocated	Morbidities	SDF
90011 (poor)	Initial	1,682	13,360	15,042
	50% retrofit	947	7,677	8,624
	100% retrofit	211	1,993	2,204
90019 (middle)	Initial	1,864	5,425	7,279
	50% retrofit	973	2,892	3,865
	100% retrofit	92	359	451
90077 (wealthy)	Initial	963	1,515	2,478
	50% retrofit	494	782	1,276
	100% retrofit	26	49	75

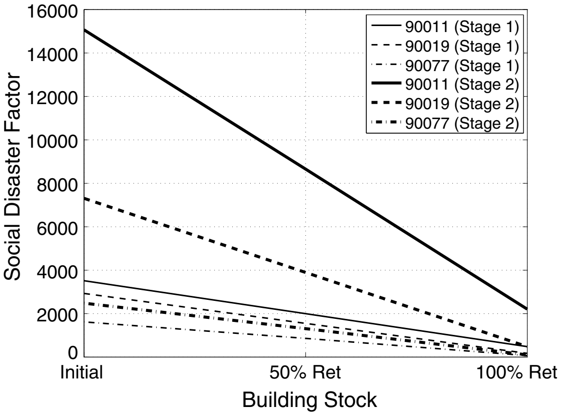

Fig. 8. Social disaster factor versus building stock for each retrofit (Ret.) given a MCE ground motion

and, hence, so does the SDF. However, even in this case, the number of households dislocated is less than 100 for the middle-class and wealthiest ZIP codes at the 100% retrofit level. The SDF is also less than 100 for the wealthiest ZIP code at the 100% retrofit level.

The SDF values presented in Tables 9 and 11 are plotted in Fig. 8 for each community and building stock. A clear trend is seen with the change in building stock: as more low-code buildings are retrofitted to high-code, the SDF decreases by two-fold or more. The SDF is much larger in the second stage than it was in the first stage for all three building stocks and ZIP codes. The second stage includes the social hazard and gives a more accurate estimate of disaster impacts.

Discussion and Conclusion

The multihazard methodology presented here demonstrated that social inequity and social vulnerability are important and should be included in loss estimation and hazard studies. By incorporating these factors, decision makers can have a richer picture of the potential benefits of any retrofit decisions. The first stage modeled the natural hazard and captured the differences in the building stock of various communities, but it did not include social inequity or the social hazard. Based on the differences in values for the number of morbidities, and specifically the number of fatalities, across the neighborhoods, the unequal social consequences were apparent. However, relying on the building stock alone may be misleading if other social vulnerability measures are not considered. The middle-class ZIP code, 90019, had the largest percentage of multifamily buildings, which created a higher physical vulnerability for that ZIP code. Therefore, at DBE, the 90019 ZIP code had the highest number of morbidities and highest number of dislocated households. The differential building stocks across the communities dictated the differential impacts in the first stage.

The second stage considered the people within the community by modeling six socioeconomic and demographic factors. Previous engineering frameworks set these factors equal to unity, and base the loss and recovery estimations strictly on the physical infrastructure. When social inequity was included, the poorest ZIP code, 90011, experienced the highest impacts at both earthquake intensities and for the initial building stock and both retrofit levels due to its combined physical vulnerability and social inequity. Comparing the two stages demonstrates the importance of including social inequity and SED factors in loss estimation and hazard analyses. Without this more complete estimation, community leaders may not feel the urgency to invest in mitigation activities to reduce these potential impacts across diverse population groups.

When modeling the SED factors, the most significant difference between the three neighborhoods was the factor developed for the rate of PTSD diagnosis. This factor was nearly four times higher for the poorest ZIP code (90011) than for the wealthiest ZIP code (90077). This finding underscores the importance of pre-event mitigation and postevent interventions in the most socially vulnerable communities.

As with any study, there are limitations to this work. The adverse impacts for these population groups is not due to one characteristic in isolation, but instead it is the result of many intersecting and overlapping social factors, including the fact that marginalized individuals and households tend to have less access to financial resources and political power, while also having more limited social networks. These groups often live in riskier areas with lower-quality housing, which sustains more damage during extreme loadings. An intersectional analysis with more robust data would be ideal, and it is anticipated future work of the authors. Additionally, the SED factors were used to modify the morbidity rates, and not population dislocation. This is also considered a limitation and future work of the authors. Last, tenure status is a significant source of social vulnerability, but it was not included as a SED factor in this study. Currently, the state of the art in understanding and available data prevents all three of these limitations from being included.

The three-story apartment building at a low-code level was susceptible to collapse. At code level and high-code level, the probability of collapse was substantially reduced. These results have significant life-safety implications when considering the number of persons that might be saved by preventing building collapse due to a higher performing building stock given a very large earthquake. The analyses also illustrate how pre-event planning and mitigation could speed postevent recovery when considering the reduced number of emergency shelters and short-term housing needed by increasing the number of households allowed to shelter in place.

A plan that consists of retrofitting 50% or 100% of all low-code buildings to high-code warrants the question "Who pays for the retrofits?" The three-story apartment building is a soft-story woodframe building that is covered by the Los Angeles (Council of the City of Los Angeles 2015) and San Francisco (Board of Supervisors 2013) soft-story retrofit mandates. Both ordinances mandate the retrofit of 100% of the soft-story woodframe buildings built to the standard represented by the low-code level with the floor and elevation plan matching this archetype, which could cost upward of $130,000 per building (Xia and Lin 2015). The California Senate passed a tax credit on September 8, 2015, that provides a 30% tax break on the cost of seismic retrofitting of at-risk buildings (Xia 2015). The bill is not specific to wood buildings or apartment buildings. Other retrofit programs and tax incentive programs, such as the California Residential Mitigation Program, which gives up to $3,000 toward retrofitting an older home, have promoted the retrofit of single family and multifamily homes. At this time, there is no example of a policy that mandates the retrofit of 50% or 100% of all low-code designed woodframe buildings. The authors' hope is that this article will provide motivation through demonstrating the effect that such a retrofit plan has on reducing morbidities and population dislocation. Even still, when considering the results of the second stage, it is clear that only retrofitting buildings will not stop a disaster, and that some communities are more vulnerable than others. Addressing both the physical and social vulnerabilities of a community is likely the only way to effectively reduce the risk and impacts of a natural or social disaster. Of course, this will take political leadership, social will, and financial investment.

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