Measuring and enhancing resilience of building portfolios considering the functional interdependence among community sectors

Kairui Feng, Naiyu Wang, Quanwang Li, Peihui Lin

Abstract

Resilience is an attribute of communities, and is supported by community building sectors (occupancy types) with different functionalities. Evaluating community resilience and functionality requires the establishment of new metrics and their quantification. This study introduces a methodology to consider how the interdependencies in functionality among different building sectors impact community resilience. Four building sectors that provide essential functions to a community, i.e. housing, education, business and public services, are considered. The percentage of people in a community who dislocate following a disaster as a result of the physical damages to buildings is selected as the resilience metric in this conceptual study. A framework is further developed to determine the optimum strategies for retrofitting community building portfolios as a whole in order to achieve an overall community resilience objective expressed in terms of the threshold value of the community resilience metric identified above. Finally, the methodology to quantify community functionality and the associated retrofit optimization algorithm are illustrated using a simplified hypothetical community building portfolio in China exposed to potentially severe earthquakes, in which the objective is to achieve a predetermined functionality level when financial constraints may be present.

1. Introduction

Natural hazards, such as earthquakes and hurricanes, can damage the built environment, making it difficult for a community to function normally. The aftermath of recent hazard events has highlighted the need for a community to be prepared for and be able to recover rapidly from a sudden potentially disastrous event. Over the past two decades, the concept of community resilience has evolved and received considerable attention from researchers and policymakers. Many studies have considered definitions of resilience and the metrics necessary to measure it [5,28,38,12,30]. Presidential Policy Directive 21 [32] defines resilience as “the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions.” More specifically, a resilient system should demonstrate the following characteristics: reduced failure probability, reduced consequence from failure, and reduced time to recovery [7].

Resilience is often regarded as an attribute of communities rather than a property of individual infrastructure components or systems [26,24,30]. A resilient community requires a resilient building portfolio that consists of different building sectors, such as residential, commercial, education, government, etc., the functionalities of which are interdependent in maintaining the well-being of a community. For example, if a large percentage of housing in an urban area becomes unusable after an earthquake, a significant outmigration of residents may occur, which will impact the local businesses and the delivery of public services [27]. Therefore, an important aspect of community resilience assessment involves quantifying the interdependencies between building sectors in terms of their functionalities within the community and developing a methodology to determine the performance targets for each sector needed to support the overall community resilience goals [22]. Although research studies to date have considered numerous aspects of community resilience evaluation [5,7,2,12,31,4,24], the quantitative linkage between the overall community resilience and the functionalities of its building sectors has received only limited attention [27,22]. Moreover, a search of the resilience literature has failed to reveal methodologies to account for the interdependencies among building sectors in assessing community resilience, as well as in designing community building inventory retrofit plans.

This paper proposes a methodology to establish the linkage between the overall community resilience goals and the...
functionalities of its supporting building sectors in which the performance of individual sectors as well as their intrinsic functional interdependencies are considered. A methodology to determine the optimal community inventory retrofit plans is developed to enable an existing community to achieve an overall community resilience goal that is supported by the above-mentioned functionalities facilitated by different building sectors. Finally, this methodology and the associated retrofit optimization algorithm are illustrated using a simplified hypothetical community in China that is composed of four building sectors exposed to scenario earthquake hazards.

2. Community functionality considering the functional interdependency among building sectors

To quantify community resilience, the measure of community functionality (performance) shown by the vertical axis of Fig. 1 must be defined [39,29,11,8,14]. Conceptually, the community resilience can be measured in terms of the probability of its “undesired outcome”, the occurrence of which would adversely impact a community’s ability to function normally, as suggested in Mieler et al. [27]. For instance, if the residential building sector is seriously damaged by an earthquake, the building occupants may be forced to relocate to temporary housing some distance away, which leads to a decline in retail customers and school students, affecting local business and the operation of the education system. Local businesses therefore lose both employees and customers and some businesses might close permanently or their owners might decide to relocate, taking additional employees with them [27]. Such effects can further ripple throughout a community and its economy [10,20,23,34,40]. As businesses and residents relocate, tax revenues decline, forcing cuts to essential public services and further layoffs, causing more residents to leave and making community recovery extremely difficult. [This, in fact, is what happened following Hurricane Katrina in 2005; see Girard and Peacock [16] for a comprehensive discussion.] Accordingly, significant population outmigration as one undesired outcome following a hazard event can be used as an overall community resilience metric, which is highly dependent on the damage to each community building sector and the interdependent functionalities among them. These interdependencies are highly complex in nature. Furthermore, what is “significant” is different from community to community; ultimately, it is up to a community to determine the goals that are most appropriate, and such goals ideally should be developed by a diverse group of community stakeholders in a transparent public process to properly address a potentially wide range of competing objectives and considerations [SPUR, 2009; 35,27].

Certain essential community functions must be maintained to prevent the occurrence of significant population outmigration [27]. The essential community functions considered in this conceptual study are housing, employment, education, and public services [37,38,33,12]: failure to maintain one or more of these functions may result in significant population outmigration following an earthquake (or other major natural hazard). The buildings supporting each of these four essential community functions are referred herein as residential building sector (RBS), business building sector (BBS), education building sector (EBS) and public service building sector (PBS), respectively.

For a community in which the building portfolio consists of the above-mentioned four building sectors, let \( p_{o,i} \) denote the percentage of population outmigration (PO) conditional on the loss of only sector \( i \). Similarly, \( p_{o,i,j} \) and \( p_{o,j,h,i} \) denote the percentage of PO, conditioned on the loss of two, three or four sectors simultaneously. Let \( P_i \) represent the probability of losing functionality of sector \( i \). Since structural types and preparedness to hazards of different sectors are generally different, losing the function of sector \( i \) and that of sector \( j \) conditional on the same hazard event, are assumed statically independent. Then according to the theorem of total probability, the expected percentage of PO, \( P_{io} \), is:

\[
P_{io} = \sum_{i=0}^{4} \left( \sum_{j=1}^{4} \left( 1 - P_i \right) \right) + \sum_{j=1}^{4} \left( \sum_{k=1}^{4} \left( 1 - P_j \right) \right) + \sum_{k=1}^{4} \left( \sum_{l=1}^{4} \left( 1 - P_k \right) \right) + \sum_{l=1}^{4} \left( \sum_{m=1}^{4} \left( 1 - P_m \right) \right) \]

Considering that \( P_i \) typically is small for engineered building sectors, the last two higher order terms in Eq. (1) (representing the loss of three or four essential functions simultaneously) can be neglected, and Eq. (1) simplifies to:

\[
P_{io} = \sum_{i=0}^{4} \left( \sum_{j=1}^{4} \left( 1 - P_i \right) \right) + \sum_{j=1}^{4} \left( \sum_{k=1}^{4} \left( 1 - P_j \right) \right) + \sum_{k=1}^{4} \left( \sum_{l=1}^{4} \left( 1 - P_k \right) \right) \]

which can be expressed in matrix form:

\[
\begin{bmatrix}
P_{o,1} \\
P_{o,2} \\
P_{o,3} \\
P_{o,4} \\
\end{bmatrix} = \begin{bmatrix}
P_{o,1} & P_{o,1} & P_{o,1} & P_{o,1} \\
P_{o,1} & P_{o,2} & P_{o,2} & P_{o,2} \\
P_{o,1} & P_{o,2} & P_{o,3} & P_{o,3} \\
P_{o,1} & P_{o,2} & P_{o,3} & P_{o,4} \\
\end{bmatrix} \begin{bmatrix}
P_1 \\
P_2 \\
P_3 \\
P_4 \\
\end{bmatrix}
\]

The probability that building sector \( i \) is lost \( (P_i) \) can also be interpreted as the percentage of buildings in sector \( i \) that are lost \( (l) \). With this interpretation, we further define community functionality loss \( (L_c) \) and the residual post-disaster functionality level \( (F_c) \), measured herein by the percentage of PO for a considered scenario event, as:

\[
1 - F_c = L_c = I_{1,4} \text{DAM} \left[ \begin{bmatrix} 1 \end{bmatrix} \right] \]

in which \( F_c \) and \( L_c \) are the overall community functionality and loss, normalized on the interval from 0 to 1; \( I = [l_1, l_2, l_3, l_4]^T \), in which \( l \) ranging from 0 to 1 reflects the fraction of functionality loss of the individual building sector \( i \), and \( i = 1, 2, 3 \) and 4 denotes RBS, BBS, EBS and PBS, respectively. We define \( \text{DAM} \) as a Damage Augmentation Matrix (DAM), which accounts for the interdependencies among the essential functionalities provided by the four building sectors. According to Eq. (3), the \( \text{DAM} \) takes the form:

\[
\begin{bmatrix} \text{DAM} \end{bmatrix} = \begin{bmatrix}
a_{11} & a_{21} & a_{31} & a_{41} \\
a_{12} & a_{22} & a_{32} & a_{42} \\
a_{13} & a_{23} & a_{33} & a_{43} \\
a_{14} & a_{24} & a_{34} & a_{44} \\
\end{bmatrix}
\]
in which the parameter \( a_{ij} \) (\( i = 1–4 \)) denotes the fraction loss of \( L_{c} \) that can be attributed to the loss of the \( ith \) essential function, \( l_{i} \). Parameter \( a_{ij} \) (\( i = 1–4, j = 1–4 \)) reflects the additional loss to the essential function \( i \) due to the loss of essential function \( j \), counting for the functional interdependencies among different sectors. The assumption regarding the independence among the structural performances of building sectors \( (P_{i}) \) can be eliminated, if necessary, by considering the site-to-site and structure-to-structure correlations among buildings in different sectors \([21]\). It should be noted that \( F_{c} \) actually is a function of time, and how the community’s social infrastructure responds to hazard events has a significant impact on the actual community outmigration rate. Although in this study, we only illustrated the DAM-approach to model interdependency among building sectors with a “snapshot” in time, i.e. immediately following the hazard, this approach could be extended in the time dimension as methods to quantify the stochastic recovery of different building sectors being developed. Moreover, uncertainties should be propagated from hazard intensity to damage estimation, and to DAM metrics in order to obtain a probabilistic estimation of the metric, \( F_{c} \); in the rest of the paper, however, we use the mean \( F_{c} \) as the metric for building portfolio retrofit decisions.

The above illustration provides a reasonable format for [DAM], but for a real community, the [DAM] can only be determined by analyses of data from previous hazard events or, in the absence of empirical data, by computational models for physical damage and social-economic impact assessments coupled with economic analysis and the best judgment of expert team including social scientists, economists, engineers and stakeholders, which reflects the unique features of different communities and depends on the level of preparedness of community to hazard events. For case study presented later in this paper, we use the DAM calibrated according to the study presented in Mieler et al. \([27]\), in which four functional states (FSs) – Green, Yellow, Orange and Red – are defined for each of the community sectors. The fractional losses \( (l) \) of each sector correspond to each of the FSs are tabulated in Table 1, reflecting the relative importance of the four sectors to preserve the overall community function (i.e. preventing significant population outmigration, in this case). While there are 44 (i.e. 256) possible community function levels resulted from the exhaustive combinations of the 4 FSs of the 4 sectors, significant PO was assumed to occur only when two or more community sectors are “in red” or three or more are “in orange or red”, which represent 104 combinations out of the 256 cases. We calibrated Eq. (4) by optimizing the DAM and the value of \( L_{c} \) against the above scenario presented in \([27]\), the calibration resulted in a \( L_{c} \) of 13% (i.e. 13% probability of PO) and a DAM:

\[
[DAM] = \begin{bmatrix}
0.13 & 0.30l_{1} & 0.37l_{1} & 0.27l_{1} \\
0.30l_{2} & 0.04 & 0.28l_{2} & 0.10l_{2} \\
0.37l_{2} & 0.28l_{3} & 0.13 & 0.28l_{3} \\
0.27l_{4} & 0.10l_{4} & 0.28l_{4} & 0.05
\end{bmatrix}
\]  

(6)

This [DAM] is adopted later to represent the functional interdependencies of the four building sectors considered in the case study. The \( L_{c} \) of 13% is adopted as the threshold value (or resilience objective), beyond which the resilience of the community is regarded as unacceptable. It should be noted that the [DAM] in Eq. (6) depends on how FSs (i.e. Green, Yellow, Orange and Red) are defined for each sector (e.g. Table 1).

3. Seismic performance of building sectors

It is common to describe the seismic hazard in terms of either a scenario earthquake (e.g., a \( M_{w} = 7 \) event with an epicentral distance \( R = 50 \) km from the community) or the probability of exceeding a ground motion intensity, \( (IM) \), measured by a peak ground acceleration (PGA) or spectral acceleration at the fundamental period of the building \( (S_{a}) \) \([3,9,19]\). Earthquake ground motions may cause structural damage to occur once the structural response \( (\theta) \) in the form of a maximum force or maximum displacement, exceeds a predetermined threshold value that depends on the nature of the building construction. The relationship between structural response and seismic intensity is established by performing nonlinear dynamic analyses of the structural system model for a suite of appropriate ground motions at different levels of intensity. This relationship can be expressed in a power-law form \([9]\)

\[
\theta = a \cdot IM^{b} \cdot \varepsilon
\]  

(7)

where \( a \) and \( b \) are parameters determined by regression analysis and \( \varepsilon \) is the random error associated with the power-law form. If \( \varepsilon = 1.0 \), Eq. (7) defines the relation between the median of \( \theta \) and the IM. If the structural response \( \theta \) represents the maximum inter-story drift angle (ISDA, in radians) of a moment frame building, \( b \) typically lies between 0.8 and 1 when the building period is greater than about 1 s. The logarithmic standard deviation of \( \varepsilon \), which approximates the coefficient of variation (COV) in \( \theta \) when \( IM \) is known, is typically 0.30–0.40 \([25,18]\).

The structural capacity of a system is the maximum force or deformation that it can sustain without reaching a prescribed limit state, which depends on the type of construction, structural material properties and the limit state under consideration. For example in ASCE Standard 41-13 \([1]\), three performance/damage levels are identified: immediate occupancy (IO), life safety (LS) and collapse prevention (CP). Each performance level is related to a structural response level described by a connection rotation or drift limit. For example, for concrete frame buildings, the structural system is deemed to maintain its overall stability (CP state) if the plastic rotation angles (PRA) for beams and columns are less than 0.040 and 0.034, respectively \([1, \text{chap. 10}]\). The deformation limit for continued occupancy is much less; IO requires that there be essentially no permanent deformation in the structural system, which requires maximum PRAs or ISDAs on the order of 0.005–0.01. In this study, it is assumed that once the performance level of a building is beyond an ISDA or PRA of 0.01, its functionality of providing immediate occupancy to the community is lost.

The building structural response conditioned on \( IM \), i.e. building fragility, is uncertain and is often assumed to be modeled by a log-normal distribution \([25]\):

\[
F_{\theta}(IM) = P(\theta > \theta_{cr}|IM = im) = 1 - \Phi \left( \frac{\ln(\theta_{cr} - \lambda_{i})}{\sigma_{\theta}} \right)
\]  

(8)

in which \( \theta_{cr} \) is the structural performance limit state of interest, expressed in terms of PRA or ISDA and \( \lambda_{i} \) and \( \sigma_{\theta} \) are the lognormal mean and standard deviation of structural response, \( \theta \), when \( IM = im \). For individual buildings, this fragility function describes the probability that an individual building is unsafe for continued occupancy, conditioned on \( IM = im \). For building sector \( i \) as a whole, the fragility function simply represents the ratio of buildings that are not safe to occupy \( (l) \) as:

\[
l_{i} = 1 - \Phi \left( \frac{\ln(\theta_{cr} - \lambda_{i})}{\sigma_{\theta_{i}}} \right)
\]  

(9)

We refer to \( l_{i} \) as the loss index, and \( f_{i} = 1 - l_{i} \) as the functionality index of building sector \( i \). The \( \lambda_{i} \) and \( \sigma_{\theta_{i}} \) can be obtained through simulation-based methods introduced in Lin and Wang \([21]\) provided that fragility information on individual buildings in the sector are available.
4. Optimization of retrofit strategies to achieve community resilience goals

A community is usually developed over a period of several decades. Therefore, buildings in a community are likely to have been constructed at different times and according to different design standards and construction practices. Newly constructed buildings must meet the performance objectives specified in current design codes, while older buildings may not be compliant with the current building codes [21]. Consequently, the overall condition of an existing building portfolio may not be sufficient for the community to achieve its overall resilience objectives. In this situation, building retrofits may be stipulated to enhance the performance of those buildings that do not meet modern seismic design standards. A method is required to establish retrofit priorities, considering the functional interdependence among different building sectors in a community. An effective retrofit plan at the community scale should specify [21]: (1) the performance objective for the community that the retrofit plan is trying to achieve; (2) the target building performance level for retrofitting of each building sector; (3) the number of buildings to be retrofitted in each building sector; and (4) the overall cost associated with the retrofit strategy. These are the decision variables discussed in the subsequent optimization formulation.

The retrofit cost associated with upgrading a building to a target performance level depends on building characteristics, site conditions and retrofit options, which can either be determined based on construction cost data [36] or estimated empirically when cost data are not available. For example, Kanda and Ellingwood [17] suggested that the retrofit cost for an individual building may be approximated by a linear function of retrofitted resistance. In this study, we adopt their approach and assume that the retrofit cost, \( C \), for individual building is:

\[
C = C_0 \cdot k \cdot \left( \frac{\mu_s}{\mu_o} - 1 \right)
\]

(10)

in which \( C_0 \) is the building replacement cost; coefficient \( k \) is associated with the building construction type and site conditions; \( \mu_s \) and \( \mu_o \) are pre- and post-retrofit mean seismic performance of the building in terms of ISDA computed from Eq. (7); and \( \mu_o \) reflects the improvement in seismic performance by retrofitting. Accordingly, the retrofit cost for building sector \( i \) is:

\[
C_i = n_i \cdot C_0 \cdot i \cdot \left( \frac{\mu_s}{\mu_o} - 1 \right)
\]

(11)

in which the subscript \( i \) indicates that all terms in Eq. (10) pertain to building sector \( i \). \( n_i \) is the total number of buildings retrofitted in sector \( i \). Note that Eq. (11) presumes that the retrofit cost of each building in sector \( i \) is the same; this simplifying assumption can be easily relaxed, as will be illustrated in later in the case study. Accordingly, the cost efficiency to increase the functionality index \( f_i \) can be evaluated as:

\[
\frac{df_i}{dc_i} = \frac{df_i}{d\mu_o} \cdot \frac{d\mu_o}{dc_i}
\]

(12)

Eq. (12) can be evaluated according to Eqs. (7)–(9). Naturally, cost efficiency is inversely related to the investment in retrofitting.

Suppose that the community is composed of four building sectors, i.e. RBS, BBS, EBS and PBS. According to Eqs. (4) and (5), the sensitivity of community functionality, \( F_c \), to the functionality of building sector, \( f_i \), is:

\[
\frac{dF_c}{df_i} = a_i + \sum_{j=1, j \neq i}^m (a_j + a_i)l_j
\]

(13)

which depends on the loss indices of all building sectors. For example, if building sector \( k \) is retrofitted, then the loss index of the sector \( l_k \) becomes smaller, which will result in a decrease in \( dF_c/df_k \).

Finally, the cost efficiency of retrofitting sector \( i \) to enhance the overall functionality of the community as a whole is:

\[
z_i = \frac{dF_c}{dc_i} \cdot \frac{df_i}{dc_i}
\]

(14)

\( z_i \) can be evaluated according to Eqs. (12) and (13), and is a key parameter to determine the retrofit strategy because the building sector associated with the largest value of \( z_i \), \( i = 1, \ldots, 4 \), has the highest priority for retrofitting. Note from Eq. (14) that the cost efficiency \( z_i \) decreases monotonically with the number of buildings being retrofitted. For example, if the entire budget is used to retrofit building sector \( i \), \( z_j \) will decrease because the term \( dF_c/df_i \) remains constant while \( df_i/dc_i \) decreases. Meanwhile, the cost efficiency of other building sectors, \( Z_j (j \neq i) \) also decreases because the term \( dF_c/df_i \) decreases while \( df_i/dc_i \) remains constant. In a typical retrofit decision process (to be illustrated in the next section), it was found that \( df_i/dc_i \) usually decreases faster than \( dF_c/df_i \); thus \( z_i \) decreases faster than \( z_j \) and eventually becomes equal to \( Z_j \) as more buildings in sector \( i \) are retrofitted to a higher performance level.

In summary, the optimum retrofit strategy is determined by the following steps: building sector \( i \) associated with the largest cost efficiency \( z_i \) is selected first for retrofit. As more buildings in sector \( i \) are retrofitted to a higher performance level, \( Z_i \) decreases to the point where \( Z_i = Z_j \) (is the second largest cost efficiency among all building sectors prior to retrofits). Building sectors \( i \) and \( j \) are then both retrofitted using the remaining budget, keeping \( Z_i \) and \( Z_j \) equal, until \( Z_i = Z_2 = Z_3 (Z_k \) is the third largest cost efficiency among all building sectors prior to retrofit). Subsequently, building sectors \( i, j \) and \( k \) are all retrofitted until the overall retrofit budget is exhausted. The decision variables, i.e. which building sector(s) will be retrofitted (\( i \)), how many buildings within each sector will be retrofitted (\( n_i \)), and to what level will they be retrofitted (\( \mu_o \)) all depend on the total retrofit budget. In the next section, this optimization method will be illustrated utilizing a hypothetical community exposed to earthquake hazard.

5. Optimal retrofit strategies to achieve community resilience goals

We consider a simplified hypothetical community in China in which four building sectors are considered: RBS, BBS, EBS and PBS. Each building sector includes three building categories
designed for different seismic intensity levels\(^1\) (SIL), i.e. SIL6, SIL 7 or SIL 8, corresponding to PGAs of 0.06 g, 0.13 g and 0.25 g, respectively [15]. For example, the RBS includes 40 buildings (designated as R6) designed to SIL 6, 50 buildings (R7) to SIL 7, and 10 buildings (R8) to SIL 8. Similar notation is used for the other building sectors identified in Table 2. For simplicity, we assume that all buildings are reinforced concrete frames, which is a practical assumption for most communities in China.

The seismic response, in terms of inter-story drift, of individual buildings is estimated by Eq. (7), in which the parameter \(a\) is tabulated in Table 2 and the parameter \(b\) is assumed to be 0.85 for all buildings [6]. Within a sector, there may be substantial variation in construction (e.g., different building heights, plan dimensions and bay sizes, and foundation conditions), thus the parameter \(a\) is assumed to be a lognormally distributed random variable with COV of 0.3. The mean and standard deviation of the seismic structural response of the individual buildings were obtained by Monte Carlo simulation, and the fragility of each building category designed to SIL 6, 7 and 8 in each sector is assessed using Eq. (8) to SIL 6, 7 and 10 buildings (R8) to SIL 8. Similar notation is used for the other building sectors identified in Table 2. For simplicity, we assume that all buildings are reinforced concrete frames, which is a practical assumption for most communities in China.

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This level of uncertainty for building groups is larger than the uncertainties of 0.30–0.40, which are associated with individual building. Note that under earthquake intensities that are one level higher than those used for the design, e.g. a building designed by seismic intensity of 7 (PGA = 0.13 g) exposed to an earthquake with intensity of 8 (PGA = 0.25 g), the probability that the building is unsafe to occupy is approximately 20%, which is consistent with the survey results on the seismic performance and fragility of existing buildings of China [41]. The basic retrofit costs for different building categories and sectors are presented in Table 2.

<table>
<thead>
<tr>
<th>Building Sector</th>
<th>Building Category</th>
<th>Number of Buildings</th>
<th>(a)</th>
<th>Design Seismic Intensity Level (SIL)</th>
<th>Retrofit cost per building, (C_0) (million RMB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential buildings (RBS)</td>
<td>R6</td>
<td>40</td>
<td>0.040</td>
<td>6 (0.07 g)</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>R7</td>
<td>50</td>
<td>0.024</td>
<td>7 (0.13 g)</td>
<td>1.89</td>
</tr>
<tr>
<td></td>
<td>R8</td>
<td>10</td>
<td>0.013</td>
<td>8 (0.25 g)</td>
<td>2.06</td>
</tr>
<tr>
<td>Business buildings (BBS)</td>
<td>B6</td>
<td>8</td>
<td>0.046</td>
<td>6 (0.07 g)</td>
<td>5.15</td>
</tr>
<tr>
<td></td>
<td>B7</td>
<td>10</td>
<td>0.026</td>
<td>7 (0.13 g)</td>
<td>5.66</td>
</tr>
<tr>
<td></td>
<td>B8</td>
<td>2</td>
<td>0.015</td>
<td>8 (0.25 g)</td>
<td>6.17</td>
</tr>
<tr>
<td>Education buildings (EBS)</td>
<td>E6</td>
<td>2</td>
<td>0.036</td>
<td>6 (0.07 g)</td>
<td>2.57</td>
</tr>
<tr>
<td></td>
<td>E7</td>
<td>2</td>
<td>0.021</td>
<td>7 (0.13 g)</td>
<td>2.92</td>
</tr>
<tr>
<td></td>
<td>E8</td>
<td>1</td>
<td>0.012</td>
<td>8 (0.25 g)</td>
<td>3.26</td>
</tr>
<tr>
<td></td>
<td>P6</td>
<td>10</td>
<td>0.044</td>
<td>6 (0.07 g)</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>P7</td>
<td>10</td>
<td>0.025</td>
<td>7 (0.13 g)</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>P8</td>
<td>5</td>
<td>0.014</td>
<td>8 (0.25 g)</td>
<td>1.20</td>
</tr>
</tbody>
</table>

\(^1\) In the Chinese code for seismic design of buildings, the ground motion intensity for design is given in terms of Peak Ground Acceleration (PGA). For example, in Beijing, China, PGAs of 0.06 g, 0.13 g and 0.25 g are associated with exceedance probabilities of 63%, 10% and 2% in 50 years respectively.

in which \(m\) is the number of different design categories, in this example \(m = 3\), associated with SIL6, 7 and 8. Parameter \(n_k\) denotes the number of category \(k\) buildings in sector \(i\); \(l_k\) is the functionality loss index of category \(k\) buildings in sector \(i\) which can be obtained by Eq. (9) and plotted in Fig. 2. Since the building portfolio as tabulated in Table 2 is small (consist of only 150 buildings), the PGAs for all buildings are assumed to be identical (spatial variation in earthquake demand is neglected for simplicity) in the following analysis.

The overall community functionality \(C_0\) as defined in Eq. (4), using the DAM defined in Eq. (6) as a function of seismic intensity expressed by PGA, is plotted in Fig. 3. The community functionality, \(F_0\), decreases with increase in the PGA intensity, reaching 0.87 (the threshold of the acceptable functionality, as discussed in Section 2) as the PGA reaches 0.16 g. At this intensity, the functionalities for RBS, BBS, EBS, and PBS drop to 0.83, 0.80, 0.88 and 0.85, respectively.

Now suppose that the community is to be retrofitted to achieve the target community functionality, i.e. \(F_{T} = 0.87\), under seismic intensity level 8 (PGA = 0.25 g). The optimum retrofit strategy is shown in Table 3. The education buildings with design seismic intensities of 6 and 7 are all retrofitted to the seismic design level of 8, while those with design seismic intensity of 8 are retrofitted to the level of 9 (PGA = 0.50 g and the parameter \(a = 0.009\)). For public service buildings, except for those with seismic design intensity of 8, all must be retrofitted; among the 25 public service buildings, 20 are retrofitted to achieve the seismic design intensity of 8 and 5 to achieve the level of 7. The cost associated with this retrofit policy is 70.7 million RMB (approximately 10.9 M $US). The optimum retrofit strategy mainly enhances education buildings and public service buildings, because these buildings are fewer in number as well as lower in retrofit costs, resulting in higher cost efficiencies (2) than those of residential and business buildings.

The solid red line in Fig. 4 illustrates the optimum retrofit strategy graphically. Initially, the initial investment is aimed at increasing the functionality of EBS (to Point A). At point A, the cost efficiencies of EBS and PBS become equal (and are still greater than the cost efficiencies of other building groups), so additional resources are targeted to retrofit EBS and PBS (point A to D) simultaneously. At point D, the cost efficiencies of EBS, PBS and BBS become equal, so additional resources are targeted to retrofit these three building sectors simultaneously. Finally, the community functionality reaches 0.87 at point E. The equal cost curves [green dash line, obtained from Eqs. (7)–(9)] and the equal functionality curves [solid black line, obtained from Eq. (4)] show that the optimum strategy line passes through points of tangency, indicating the retrofit strategy is indeed optimum in terms of both cost efficiency and functionality enhancement.
It should be noted that the improvement of seismic behavior of an individual building is stepwise, while the increase in functionality of a building sector, \( f_i \), is continuous because \( f_i \) is the average of the functionalities of all buildings in the sector. Thus, \( f_i \) is assumed to increase continuously as a function of retrofit cost.

Suppose that the community is to be retrofitted to a higher level, e.g., a target community functionality, \( F_{C,T} = 0.92 \). Clearly, such decisions to enhance community resilience above and beyond current levels depend on the resources available to support such enhancements, typically involving some mixture of public and private funds and credits. The optimum retrofit for this case is shown in Table 4. Here, some residential buildings originally designed for seismic design levels of 6 are retrofitted to level 7 while education and public service buildings with original seismic design level of 8 are retrofitted to level 9. The retrofit cost associated with this policy increases from 70.7 to 122.6 million RMB (from 10.9 M to 18.8 M US$). Compared with the retrofit strategy to achieve the target community functionality of 0.87 summarized in Table 2, the strategy to achieve the target community functionality of 0.92 includes all buildings that were retrofitted to achieve the target of 0.87; furthermore, additional residential and commercial/retail buildings also must be retrofitted. Fig. 4 shows the points where the residential buildings are to be retrofitted (point F), and where the target community functionalities of 0.92 and 0.95 are achieved (points G and H).

The overall distribution of retrofit resources among the four building sectors is shown in Fig. 5. The resources are targeted firstly to education buildings; after the community functionality of 0.71 is achieved (with retrofit cost of 8.3 M RMB), the resources are targeted to both education and public service buildings; after the community functionality of 0.82 is achieved (with retrofit cost of 31.6 M RMB), the commercial buildings are targeted; and the resident buildings are the last to be targeted after the community functionality of 0.88 is achieved with retrofit cost of 77.8 M RMB. If the community is to be retrofitted to achieve the target community functionality under a higher seismic intensity level of 9 (the community functionality achieves 0.87 under the earthquake excitation of \( \text{PGA} = 0.5 \) g, while in the last case shown in Table 4, the target functionality is 0.92 exposed to an \( \text{PGA} \) of 0.25 g), the optimum retrofit strategy is shown in Table 5. Most residential buildings and commercial/retail buildings must be retrofitted to seismic level 8, while most education buildings and public service buildings must be retrofitted to seismic level 9.

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![Fig. 2. Probabilities that buildings in each category become unoccupiable.](image-url)
scenario earthquake from 8 to 9 leads to an increase in retrofit cost from 70.7 to 398.4 M RMB (10.9–61.4 M $US), an increase of nearly 4.6 times.

Finally, we consider a case in which the resources available for building retrofit are limited to 100 M RMB (15.4 M $US). Two alternative earthquake scenarios leading to seismic intensity level 9 (PGA = 0.5 g) and seismic intensity level 8 (PGA = 0.25 g) are considered. The optimum retrofit strategies to maximize the community functionalities for these two earthquake scenarios are compared in Table 6. The earthquake scenario considered has a significant impact on the optimum retrofit strategy because the optimum strategy generally is to ensure that as many buildings as possible have a seismic capacity matching the seismic intensity level under consideration after retrofit. Thus for the target seismic design level of 8, many buildings in the community must be retro-

Table 3
The retrofit strategy to achieve functionality 0.87 at a seismic intensity of 8 (PGA = 0.25 g).

<table>
<thead>
<tr>
<th>Building sector</th>
<th>Building category and No. of buildings</th>
<th>Seismic behavior, a</th>
<th>Sector functionality, f</th>
<th>Retrofit strategy</th>
<th>Cost (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential buildings (RBS)</td>
<td>R6, 40</td>
<td>0.040</td>
<td>0.040</td>
<td>0.584</td>
<td>0.584</td>
</tr>
<tr>
<td></td>
<td>R7, 50</td>
<td>0.024</td>
<td>0.024</td>
<td>0.831</td>
<td>0.831</td>
</tr>
<tr>
<td></td>
<td>R8, 10</td>
<td>0.013</td>
<td>0.013</td>
<td>0.952</td>
<td>0.952</td>
</tr>
<tr>
<td>Business buildings (BBS)</td>
<td>B6, 8</td>
<td>0.046</td>
<td>0.026</td>
<td>0.506</td>
<td>0.803</td>
</tr>
<tr>
<td></td>
<td>B7, 10</td>
<td>0.026</td>
<td>0.026</td>
<td>0.803</td>
<td>0.803</td>
</tr>
<tr>
<td></td>
<td>B8, 2</td>
<td>0.015</td>
<td>0.015</td>
<td>0.936</td>
<td>0.936</td>
</tr>
<tr>
<td>Education buildings (EBS)</td>
<td>E6, 2</td>
<td>0.036</td>
<td>0.012</td>
<td>0.619</td>
<td>0.962</td>
</tr>
<tr>
<td></td>
<td>E7, 2</td>
<td>0.021</td>
<td>0.012</td>
<td>0.860</td>
<td>0.962</td>
</tr>
<tr>
<td></td>
<td>E8, 1</td>
<td>0.012</td>
<td>0.009</td>
<td>0.962</td>
<td>0.991</td>
</tr>
<tr>
<td>Public service buildings (PBS)</td>
<td>P6, 10</td>
<td>0.044</td>
<td>0.020</td>
<td>0.533</td>
<td>0.882</td>
</tr>
<tr>
<td></td>
<td>P7, 10</td>
<td>0.025</td>
<td>0.014</td>
<td>0.820</td>
<td>0.943</td>
</tr>
<tr>
<td></td>
<td>P8, 5</td>
<td>0.014</td>
<td>0.014</td>
<td>0.943</td>
<td>0.943</td>
</tr>
</tbody>
</table>

Fig. 4. Graphical depiction of optimum retrofit strategy.

The overall strategy for the target of additional resources.

Table 4
Optimal retrofit strategy to reach community functionality of 0.92 at a seismic intensity level of 8 (PGA = 0.25 g).

<table>
<thead>
<tr>
<th>Building Sector</th>
<th>Building category</th>
<th>Amount</th>
<th>Seismic behavior, a</th>
<th>Sector functionality, f</th>
<th>Retrofit strategy</th>
<th>Cost (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential buildings (RBS)</td>
<td>R6, 40</td>
<td>0.028</td>
<td>0.775</td>
<td>29 buildings are retrofitted to level 7</td>
<td>37.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R7, 50</td>
<td>0.024</td>
<td>0.831</td>
<td>Not retrofitted</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R8, 10</td>
<td>0.013</td>
<td>0.952</td>
<td>Not retrofitted</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Business buildings (BBS)</td>
<td>B6, 8</td>
<td>0.026</td>
<td>0.803</td>
<td>All are retrofitted to level 7</td>
<td>30.96</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B7, 10</td>
<td>0.026</td>
<td>0.803</td>
<td>Not retrofitted</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B8, 2</td>
<td>0.015</td>
<td>0.936</td>
<td>Not retrofitted</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Education buildings (EBS)</td>
<td>E6, 2</td>
<td>0.012</td>
<td>0.962</td>
<td>All are retrofitted to level 8</td>
<td>10.95</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E7, 2</td>
<td>0.012</td>
<td>0.962</td>
<td>All are retrofitted to level 8</td>
<td>4.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E8, 1</td>
<td>0.009</td>
<td>0.991</td>
<td>Retrofitted to level 9</td>
<td>3.43</td>
<td></td>
</tr>
<tr>
<td>Public service buildings (PBS)</td>
<td>P6, 10</td>
<td>0.014</td>
<td>0.943</td>
<td>All are retrofitted to level 8</td>
<td>18.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P7, 10</td>
<td>0.014</td>
<td>0.943</td>
<td>All are retrofitted to level 8</td>
<td>8.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P8, 5</td>
<td>0.009</td>
<td>0.991</td>
<td>All are retrofitted to level 9</td>
<td>8.73</td>
<td></td>
</tr>
</tbody>
</table>
fitted to level 8; while for the target level of 9, many buildings in the community must be retrofitted to level 9. In both earthquake scenarios, most education buildings and public service buildings are retrofitted because their cost efficiencies are relatively larger while their functions are assumed to be as equally important as those of residential buildings and commercial/retail buildings.

If an earthquake does, indeed, occur with a level of 8, the community functionality decreases to 0.90 if the building inventory was retrofitted with a target seismic intensity of 8, while decreases to 0.88 if the retrofit was done considering intensity level of 9. This analysis reveals that if the retrofit budget is limited to a fixed amount, which is a common situation in an urban community because of limitations in the tax base, subsidies and insurance coverage, retrofitting to withstand more intense earthquake scenarios may not lead to increased functionality following a less severe earthquake because usually fewer buildings can be retrofitted to

Table 6
Optimum retrofit strategies considering different seismic intensity levels.

<table>
<thead>
<tr>
<th>Building sector</th>
<th>Building category and amount</th>
<th>Considered seismic intensity level: 8 (PGA = 0.25 g)</th>
<th>Considered seismic intensity level: 9 (PGA = 0.5 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost</td>
<td>Strategy</td>
<td>Cost</td>
</tr>
<tr>
<td>Residential buildings (RBS)</td>
<td>R6 40</td>
<td>26.76</td>
<td>21 buildings are retrofitted to level 7</td>
</tr>
<tr>
<td></td>
<td>R7 50</td>
<td>0</td>
<td>Not retrofitted</td>
</tr>
<tr>
<td></td>
<td>R8 10</td>
<td>0</td>
<td>Not retrofitted</td>
</tr>
<tr>
<td>Business buildings (BBS)</td>
<td>B6 8</td>
<td>30.96</td>
<td>All are retrofitted to level 7</td>
</tr>
<tr>
<td></td>
<td>B7 10</td>
<td>0</td>
<td>Not retrofitted</td>
</tr>
<tr>
<td></td>
<td>B8 2</td>
<td>0</td>
<td>Not retrofitted</td>
</tr>
<tr>
<td>Education buildings (EBS)</td>
<td>E6 2</td>
<td>10.95</td>
<td>All are retrofitted to level 8</td>
</tr>
<tr>
<td></td>
<td>E7 2</td>
<td>4.71</td>
<td>All are retrofitted to level 8</td>
</tr>
<tr>
<td></td>
<td>E8 1</td>
<td>3.43</td>
<td>Retrofitted to level 9</td>
</tr>
<tr>
<td>Public service buildings (PBS)</td>
<td>P6 10</td>
<td>14.98</td>
<td>2 buildings are retrofitted to level 7</td>
</tr>
<tr>
<td></td>
<td>P7 10</td>
<td>8.21</td>
<td>All are retrofitted to level 8</td>
</tr>
<tr>
<td></td>
<td>P8 5</td>
<td>0</td>
<td>Not retrofitted</td>
</tr>
</tbody>
</table>
the higher level in such cases. The comparison of sector functionalities can be seen in Fig. 6, which shows the sensitivity of the sector functionalities to different retrofit levels, expressed by seismic design level.

6. Summary and conclusions

This paper presented a quantitative framework to measure the community functionality of building inventories immediately following the occurrence of an earthquake event. The interdependencies in the functions of building sectors were considered in the calculation of community functionality. A methodology was also developed to determine the optimum retrofit strategy for buildings in an existing community to achieve a required measure of community functionality, based on limiting the outmigration of the population.

Examples were provided to illustrate how the proposed methodology can be used to obtain the optimum retrofit strategy to achieve the target community functionality or the necessary target seismic retrofit level at minimum total cost. In general, the number of buildings in a building sector, the unit cost for retrofit and the seismic scenario intensity for retrofit each may have a significant impact on the optimal retrofit policy. The optimum strategy has three distinct features: (1) many, but not necessarily all, buildings should have a seismic capacity matching the considered seismic intensity following retrofit; (2) the building sectors with high cost efficiency (e.g. education and public service buildings) should be retrofitted to higher performance level; and (3) when maximizing community functionality when resources are fixed, the scenario event on which to base retrofit policy must be selected carefully because the optimal strategy is scenario-dependent.

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References