Evaluating the role of transportation system in the community resilience assessment

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Abstract: The performance of transportation system has significant impact on the recovery rapidity of damaged communities after the occurrence of hazard events, because most of the necessary materials, machines and workmanship are shipped by transportation system from the suppliers to the building site. This paper analyses the supporting of transportation system to the recovery process of built environment, and proposes an indicator for evaluating this effect, which relates the capacity of transportation system to the recovery speed of built environment. The approach is demonstrated through the performance evaluation of the simplified transportation system of Beijing city, and the effects of retrofitting transportation system on improving the resilience of built environment are analysed.

Key words: Community resilience; Transportation system; Built environment; Retrofit strategy; Recovery; Earthquake.

1 Introduction

Natural hazards, such as earthquake and hurricanes, impose great risk to the residents in communities of all sizes, and impair the normal function of built environment. Consequently, increasing attention has been cast on the emergency capacity of communities and the rapidity of their recovery process following a hazard event. The concept of community resilience has been raised, accepted and valued by researchers and policy makers and significant efforts have been conducted to define and quantify the community resilience [2,7,9,14,16]. The gist of community resilience is reflected by four characters: robustness, rapidity, redundancy and resourcefulness [2], as shown in Figure 1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Schematic representation of community resilience}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Map of Beijing city}
\end{figure}
Resilience is often regarded as an attribute of communities rather than a property of individual infrastructure components or systems [13,16]. A resilient community requires a resilient built environment that consists of different building sectors, such as residential, commercial, education, government, etc., which are interdependent in their functionalities in maintaining the well-being of a community. Hence, it becomes meaningful to account for the interdependency between building sectors in the resilience assessment of the whole community [8].

Following a hazard event, the resilient of a community depends not only on the robustness of building sectors but also on the performance of transportation system, which affects significantly the rapidity of recovery process. From the viewpoint of system and network, the performance of transportation system following hazard events has been discussed in terms of the connectivity and travel time, and several case studies have been presented [5,10,15]. However, none of the existing literature analyzes the supporting role of transportation system for the recovery of damaged buildings, which is, however, a key issue because the repairing of damaged buildings needs the delivery of resources by transportation system, including materials, machines and workmanship.

Firstly, the paper introduces the measurement for community functionality considering the inter-dependency among building sectors, which is then illustrated using a simplified model of Beijing city. Secondly, an indicator for the performance of transportation system following hazard events is defined, and the network flow algorithm is introduced to find the optimal logistics plan and rapidest recovery process of the community functionality. Finally, a case study is carried out to demonstrate the application of the proposed method and evaluate the supporting effect of transportation system to the recovery of built environment after an earthquake.

2 Community functionality and retrofit optimization

2.1 Measurement for community functionality

The measure of community functionality, as seen in Fig. 1, is required to quantify the community resilience. Conceptually, the community functionality can be defined by the probability of an ‘undesired outcome’. In light of this, the degree of population out-migration following a hazard event is chosen as an overall community resilience metric. The occurrence of population out-migration highly depends on the damage conditions of different building sectors, and certain community functionality should be maintained to avoid it [3].

Four essential community functions are considered including housing, business, education and public service, and the buildings supporting each of these four essential community functions are respectively referred as residential building sector (RBS), business building sector (BBS), education building sector (EBS) and public service building sector (PBS). The community functionality, $F_C$, is defined as [8]:

$$F_C = 1 - L_C = 1 - \mathbf{1}_{4 \times 4}[\text{DAM}][\mathbf{1}]_{4 \times 1}$$

in which $F_C$ and $L_C$ are the overall community functionality and its loss, ranging from 0 to 1; $l_i$ is the percentage of buildings in sector $i$ becoming unoccupiable; The $[\text{DAM}]$ is Damage Augmentation Matrix accounting for the interdependency among the essential functionality provided by the four buildings sectors, which is
The threshold value for acceptable functionality, $F_C$, is 0.87. The detailed derivation for the $[DAM]$ and the threshold of $F_C$ can be found elsewhere [8].

### 2.2 Seismic response and retrofit optimization strategy

The relationship between structural response, $\theta$, and seismic intensity, $IM$, can be expressed in a power-law form [6,11].

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

where $a$ and $b$ are parameters determined by regression analysis and the logarithmic standard deviation $\varepsilon$ is the error associate with the power-law form. For building sector $i$ as a whole, the ratio of buildings that are not safe to occupy ($l_i$) can be written as:

\[ l_i = 1 - \phi \left( \frac{\ln(\theta_{cr,i}) - \lambda_{\theta,i}}{\xi_{\theta,i}} \right) \]  

where $\lambda_{\theta,i}$ and $\xi_{\theta,i}$ can be obtained through simulation-based methods introduced in [12] provided that fragility information on individual buildings in the sector are available. And $f_i = 1 - l_i$ is the functionality index of building sector $i$.

The retrofit cost for sector $i$, $c_i$, depending on building characteristics, site conditions and retrofit options, can be determined by a hyperbolic function of retrofitted resistance.

\[ c_i = \sum_{i=1}^{n_i} c_{oi} \cdot k_i \cdot \left( \frac{\mu_{\theta,i}^*}{\mu_{\theta,i}} - 1 \right) \]  

in which $c_{oi}$ is the individual building replacement cost; coefficient $k_i$ is associated with the building construction type and site conditions; $\mu_{\theta,i}^*$ and $\mu_{\theta,i}$ are the post- and pre-retrofit mean seismic performance of the building.

The Cost Efficiency, $Z_i$, of retrofitting sector $i$ to enhance the overall functionality of the community as a whole is:

\[ Z_i = \frac{\partial F_C}{\partial f_i} \cdot \frac{df_i}{dc_i} \]  

where

\[ \frac{\partial F_C}{\partial f_i} = a_{ii} + \sum_{j=1,j\neq i}^{m} (a_{ij} + a_{ji})l_j \]  

\[ \frac{df_i}{dc_i} = \frac{df_i}{d\lambda_{\theta,i}} \cdot \frac{d\lambda_{\theta,i}}{d\mu_{\theta,i}} \cdot \frac{d\mu_{\theta,i}}{dc_i} \]

$Z_i$ is a key parameter to determine the retrofit strategy, and the building sector associated with the largest value of $Z_i$, $i = 1,..4$, has the highest priority for retrofitting.
2.3 Illustration of retrofit optimization of built environment

A simplified model of Beijing City shown in Fig.2 is established to demonstrate the application of the approach, in which four building sectors are considered. Each building sector includes three building categories designed for different seismic intensity levels (SIL), i.e. SIL 6, SIL 7 or SIL 8, corresponding to PGAs of 0.06g, 0.13g and 0.25g, respectively. The number of buildings, the seismic response parameters and the basic retrofit costs are shown in Table 1.

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

The overall community functionality as a function of seismic intensity expressed by PGA, is plotted in Fig. 3. The community functionality, $F_C$, decreases with increase in the PGA intensity, reaching 0.87 (the threshold of the acceptable functionality) as the PGA reaches 0.15g.

To achieve the target community functionality of 0.87 under seismic intensity level of 8 (PGA = 0.25g), the optimum retrofit strategy is acquired using the proposed method based on cost efficiency, and shown in Table 2.

The optimum retrofit strategy mainly enhances education buildings and public service buildings, because these buildings are fewer in numbers and retrofit costs, resulting higher cost efficiencies ($Z$) than those of the residential buildings and business buildings. We can also find that many, but not necessarily all, buildings have a seismic capacity matching the considered seismic intensity following retrofit.
Table 2: Optimum retrofit strategy under seismic intensity level 8

<table>
<thead>
<tr>
<th>Building Sector</th>
<th>Building category and No. of buildings</th>
<th>Retrofit strategy</th>
<th>Cost (million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential buildings</td>
<td>R6, R7, R8 100</td>
<td>Not retrofitted</td>
<td>0.00</td>
</tr>
<tr>
<td>Business buildings</td>
<td>B6 8</td>
<td>All are retrofitted to seismic level 7</td>
<td>30.96</td>
</tr>
<tr>
<td></td>
<td>B7, B8 12</td>
<td>Not retrofitted</td>
<td>0.00</td>
</tr>
<tr>
<td>Education buildings</td>
<td>E6 2</td>
<td>All are retrofitted to seismic level 8</td>
<td>10.95</td>
</tr>
<tr>
<td></td>
<td>E7 2</td>
<td>All are retrofitted to seismic level 8</td>
<td>4.71</td>
</tr>
<tr>
<td></td>
<td>E8 1</td>
<td>retrofitted to seismic level of 9</td>
<td>3.43</td>
</tr>
<tr>
<td>Public service buildings</td>
<td>P6 10</td>
<td>5 buildings are retrofitted to level 8</td>
<td>12.44</td>
</tr>
<tr>
<td></td>
<td>P7 10</td>
<td>all are retrofitted to level 8</td>
<td>8.21</td>
</tr>
<tr>
<td></td>
<td>P8 5</td>
<td>Not retrofitted</td>
<td>0.00</td>
</tr>
</tbody>
</table>

3 Support effect of transportation system to recovery of buildings

Transportation system represents a critical component of society’s infrastructure systems, and is needed for the welfare of the public. After an earthquake, the transportation system is responsible for the transportation of search/rescue and medical team, the passing of injured to hospitals during the first few hours; and later, it is required for the delivery of repairing materials, machines and workmanship to the damaged building sites to support the recovery of built environment [4,18]. In this section, our research focuses on the role of transportation system to facilitate the repairing/restoration of buildings, and proposes a method to evaluate the supporting effect of transportation system to the recovery of damaged buildings.

3.1 Transportation network and bridge fragilities

The transporting network in Beijing city is considered in this section, and the study is limited to the 4 ring roads and 10 linking roads, as shown in Fig. 4. This network model consists of 37 nodes and 56 links, and the total number of bridges is 36. The network is defined in terms of nodes and links. A node is at the location where two or more highways intersect (usually interchanges). A link is defined by a line between two nodes with no other nodes in between.

![Fragility curves of Beijing’s bridge](image)

City transportation system comprises numerous structural components; among them, bridges are the most vulnerable components under earthquake excitations. Similar to the buildings, the
bridges of Beijing city were also designed and constructed according to 3 seismic intensity levels. In the previous study [10,17], bridge fragility information was expressed as a function of peak ground acceleration (PGA), and it was assumed that the curves be expressed in the form of two parameter lognormal distribution function. The fragility curves of bridges of Beijing city is shown in Fig. 5, in which the damage state is classified into 5 categories, i.e., none, slight, moderate, severe and collapse. Once the bridge is damaged, Table 3 shows the loss of traffic capacity depending on the degree of damage.

<table>
<thead>
<tr>
<th>Damage state</th>
<th>None</th>
<th>Slight</th>
<th>Moderate</th>
<th>Severe</th>
<th>Collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity loss</td>
<td>0</td>
<td>20%</td>
<td>50%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

### 3.2 Methodology

Damaged by the earthquake, the capacity and topology of the transportation network are changed. Thus, a network flow model specialized in managing material flow demand and road capacity is chosen to account for this change.

In the network flow model, a key issue is to solve the min-cost max-traffic problem between two nodes. The flow network is defined as a graph $G(V,E)$. $V$ is the set of all nodes and $E$ is the set of all edges. It is required that the flow network has a single source and a single sink, and suppose node $s$ is the source of transportation demand in the network, node $t$ is the sink of transportation demand [1].

The flow network holds the following properties:

1) Every edge $(u,v) \in E$ holds a non-negative capacity $c(u,v) \geq 0$.
2) Between $(u,v) \in E$, the real traffic flow $f(u,v)$ is restricted in $0 \leq f(u,v) \leq c(u,v)$
3) $\forall v \in V - \{s,t\}$, the in-flow is equal to out-flow, which means $\sum_{(u,v) \in E} f(u,v) = \sum_{(v,w) \in E} f(v,w)$.
4) $\forall (u,v) \in E$ holds a cost $b(u,v)$, and each unit flow passing by it will be punished by $b(u,v)$.

Under the constraint of maximum total traffic flow, the network flow method can minimize the total cost brought by the traffic action.

$$ Cost = \sum_{(u,v) \in E} b(u,v)f(u,v) \quad (9) $$

According to the topology of Beijing city, the graph $G(V,E)$ was first established, as seen in Fig. 4. The source node $s$ is an assumed node linked to all the nodes on the 5th ring, where receives all the resources shipped from other cities to Beijing. The sink node $t$ is an assumed node linked to all the nodes in the network. The capacity of each edge, $c(u,v)$, is controlled by the mean travel speed, number of lanes and road condition. The normalized daily capacities are shown in Fig.4. The needed resources to repair/restore the damage buildings at each node are around 200.

The damage of bridges is assumed to be statistically independent, and capacity $c(u,v)$ is determined by the damage state according to Table 3.
The received resources at each node can be simulated as the following:

1) Simulate the damage state of bridges and the damage state of buildings, and then determine the capacity matrix of the road system.
2) Establish the flow network $G(V,E)$ and add the source node $s$ and sink node $t$ into set $V$, and then calculate the cost at each node.
3) Allocate the shipped resources according to the optimal solution of network flow method, and then update the damage state of each building, update the cost at each node, and repeat step 3 for the next day analysis, so that we obtain one sample of the recovery process of the city.

3.3 Resource supply rate and analysis results

To evaluate the supporting effect of transportation system to the recovery of built environment, resource supply rate is proposed in this section. For an individual building, the resource supply rate, $r_{\text{ind}}$, is defined as:

$$r_{\text{ind}} = \frac{\Pi_s}{\Pi_n}$$

in which $\Pi_n$ denotes the demanding resources daily for the full speed recovery of the concerned building, $\Pi_s$ denotes the supplied resources daily to the building through the transportation system. As for the whole community, the resource supply rate, $r$, is defined as a weighted average of $r_{\text{ind}}$ of all buildings in the community

$$r = \frac{\sum_{j=1}^{4} \sum_{i} w_{ij} r_{\text{ind},ij}}{\sum_{j=1}^{4} \sum_{i} w_{ij}}$$

in which $r_{\text{ind},ij}$ is the resource supply rate for the $i$th building in the $j$th building sector, $w_{ij}$ is the weighting factor, which is determined by:

$$w_{ij} = \frac{\partial F_C}{\partial f_j} \frac{d f_j}{d \Pi_{ij}}$$

In which $\frac{\partial F_C}{\partial f_j}$ distinguishes the importance of different building sector to the functionality assessment of the whole community, and $\frac{d f_j}{d \Pi_{ij}}$ reflects the difference in cost efficiency of repairing different individual building in a building sector.

Suppose an earthquake occurs with a PGA of 0.25g, which causes the damage of buildings and bridges. 1000 simulations of damaged conditions of Beijing city were performed. The 1000 samples of recovery trajectory were obtained, and some of them are shown in Fig.6. In which the mean recovery trajectory shows that, on average, the community functionality is restored to an acceptable level ($F_C = 0.87$) 3 months later. But the recovery process has great uncertainty, the cases associated with 10 percentile and 90 percentile are also shown in the Figure.

The resource supply rate is also calculated using the simulated results, its probability distribution can be found in Fig. 7, labelled ‘current’, where 7(a) corresponds to the case immediately after the earthquake, 7(b) is for that one month later. It can be seen that the resource supply rate provided by transportation system has large uncertainty, and the transportation system can only ship averagely 57% of resources needed for the full speed recovery immediately after the earthquake. The resource supply rate gets larger one month later,
increases from 0.57 to 0.82 averagely, because the needed resources decrease as more damaged buildings have been repaired.

Suppose all the bridges are retrofitted to a higher seismic intensity level, their seismic fragility curves are shown in Fig. 8. Repeating the analyses above, the simulated recovery trajectories are shown in Fig. 9. It can be seen that the time for the built environment back to the acceptable level decreases to 2 months on average, and the variability of the recovery process is significantly reduced compared with Fig. 6, demonstrating the improvement in the supporting effect of transportation system to the recovery of damaged buildings after the transportation network is retrofitted.

The resource supply rate is also analyzed for the retrofitted transportation system. Its probability distributions are also shown in Fig. 7, labelled ‘retrofitted’. The mean resource supply rate increases from 0.57 to 0.70 immediately after earthquake, 0.82 to 0.92 one month after the
earthquake, when the transportation system is retrofitted. It can be seen that the resource supply rate is a meaningful indicator to evaluate the capacity of transportation system in the aspect of supporting the recovery process of damaged buildings following a hazard event.

![Fragility curves after retrofitting](image1)

![Sampled recovery trajectories after retrofitting](image2)

Figure 8: Fragility curves after retrofitting

Figure 9: Sampled recovery trajectories after retrofitting

4 Summary

This paper introduces a measurement for community functionality of built environment, and then proposes an indicator to evaluate the capacity of existing transportation system in supporting the recovery process of damaged built environment following a hazard event. Examples are provided to illustrate the applications of both the measurement for community functionality and the proposed indicator, resource supply rate of transportation network. It is demonstrated that the proposed indicator is meaningful to evaluate the supporting effect of the transportation system on the recovery process of built environment.

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