BIM-BASED SEISMIC RISK ASSESSMENT FRAMEWORK FOR INFRASTRUCTURE SYSTEMS

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Abstract

Building information modeling (BIM) methodology has been widely adopted for engineering projects, such as buildings, bridges, pipelines, and roads. However, BIM has yet to be fully utilized for risk assessment of critical facilities with multiple infrastructure systems. In this study, a BIM-based seismic risk assessment framework is proposed. The digital BIM model contains component-level information on the building's structural and non-structural elements, and this digital data allows the execution of component-based analysis of seismic risk. The seismic vulnerability of the components can be evaluated according to fragility curves, where each model element is attributed its corresponding fragility parameters. Each model element is assigned the median and standard deviation capacity for each damage state. Subsequently, various seismic scenarios can be simulated. The results of the simulations allow quick assessment of the seismic performance of the infrastructure and identifying the most vulnerable components. The proposed framework provides a valuable tool for engineers and decision-makers in assessing the seismic risk of infrastructures and implementing necessary measures to increase their resilience. Our preliminary work shows that BIM can provide valuable information and visualization tools for seismic risk assessment and can help improve the efficiency of the assessment process.

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1. Introduction

Over the past few decades, modern societies have become increasingly dependent on critical infrastructures (CIs) to function properly continuously, particularly during extreme and hazardous events [1], [2]. Extreme events can cause significant damage to these infrastructures, resulting in severe economic and human impacts. The impacts of seismic events on structures and infrastructure systems can be significant and widespread, affecting not only the physical structures themselves but also the surrounding environment and communities [1].

Common examples of CIs are listed in Table 1. These CIs regularly consist of several structural and non-structural components that include utilities, HVAC systems (Heating, ventilation, and air conditioning), generators, fire alarm systems, and more. Each component responds differently to a given
risk scenario, rendering overall CI risk assessment a complex task. Therefore, developing efficient frameworks for CI risk assessment can be extremely valuable, as it allows better quantification of overall risk at the component-level. Visualization has been proved to of utmost importance when engineers must convey their conclusions and recommendations to decision makers in an accessible and easily understood format [3]. Powerful and advanced tools could be used to provide visualization tools to aid the decision-making process by presenting complex information. In turn, this can lead to better preparedness, thus policies and measures aimed at increasing the resiliency of communities in face of life-threatening scenarios [4], [5].

Table 1: Examples of CIs

<table>
<thead>
<tr>
<th>Type of CI</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Power plants, oil refineries, electrical grids</td>
</tr>
<tr>
<td>Transportation</td>
<td>Airports, highways, railways, bridges, tunnels</td>
</tr>
<tr>
<td>Water and sanitation</td>
<td>Water treatment plants, sewage systems</td>
</tr>
<tr>
<td>Communications and information</td>
<td>Internet networks, data centers, telecommunication</td>
</tr>
<tr>
<td>Emergency services</td>
<td>Hospitals, police stations, fire stations</td>
</tr>
<tr>
<td>Financial services</td>
<td>Banks, stock exchanges, payment systems</td>
</tr>
<tr>
<td>Government</td>
<td>Government buildings, military installations</td>
</tr>
<tr>
<td>Food and agriculture</td>
<td>Farms, food processing plants, distribution networks</td>
</tr>
</tbody>
</table>

Building information models (BIM) are digital representations of the physical and functional characteristics of structures that allow for the storage of information in a modular and easily maintainable way. While BIM has been initially developed for buildings, BIM has been extended to manage various types of infrastructures [6]. The architectural and engineering industry is rapidly integrating BIM for enhancing the collaboration between various engineers and stakeholders and improving the building design and construction process [7]. Numerous researchers have demonstrated how BIM can be utilized to deliver powerful visualization tools. Nevertheless, the potential of BIM is far from being realized, particularly in the context of risk assessment.

Component-level information refers to detailed data on the individual parts or components that make up a building or infrastructure system. In the context of BIM, component-level information includes characteristics such as the geometry, size, shape, materials, costs and physical properties of each component. This information is stored in a digital format, allowing for different types of analyses. This potential has been realized by different researchers. For example, [8] use a case study of a reinforced concrete (RC) frame building to demonstrate the use of BIM to select between three decision-making scenarios with different seismic retrofit strategies and alternatives. Vitiello et al. (2019) demonstrated how BIM can be employed for handling large amounts of information for the objective of cost estimation of repairs following seismic events [9]. Xu et al. (2019) developed an algorithm for damage prediction at the component-level. There, they coupled the BIM components with performance groups based on FEMA P-58. Accordingly, the costs of repairs following a seismic event can be computed and visualized [10].

In this paper, we propose a methodology for utilizing BIM so that the risk to a CI can be evaluated at the component level. We focus on the example of seismic hazard. The seismic risk assessment process involves extracting information from the properties of the BIM model components. The seismic vulnerability of the system's components is represented by fragility curves that are matched to each component's properties. Subsequently, the seismic vulnerability of each component is calculated based on the hazard curve. Finally, the vulnerability of each component is visually represented in a 3D model. We explain the key terms related to seismic risk assessment and discuss the challenges and limitations of the proposed methodology.
2. Methodology

The proposed BIM-based seismic risk assessment framework consists of five steps, as illustrated in Figure 1. These steps are hereby outlined in the Sections 2.1-2.5.

Figure 1 - Methodology framework

2.1. Structure or infrastructure system BIM model

The first step in the methodology is the creation of a digital BIM-model containing detailed information on the structural and non-structural elements of the infrastructure system. This model should include component-level geometry, material properties, and connection details. For the example in the current paper, the model is created and managed in Autodesk Revit software. This model serves as the foundation for subsequent steps in the seismic risk assessment process. It is crucial to define the necessary level of information within the model to ensure accurate and reliable assessments.

2.2. Attribution of fragility curves to each model element.

The second step involves attributing fragility curves to each component in the BIM model. A fragility curve is a graphical method to express the probability of a component or system exceeding a certain damage state (DS) as a result of an earthquake's intensity measure (IM) parameter. As shown in Figure 2, fragility curves for a structure, system, or components are represented as a lognormal cumulative distribution function (CDF), which requires two parameters to be fully defined: the median capacity of the component to resist damage state \( (\theta_{ds}) \) and the standard deviation of the capacity \( (\beta_{ds}) \). In the case of multiple and sequential damage states, the damage states are ordered by damage severity (from least severe to the most severe damage), and the fragility function defines the probability of being in a specified damage state (Eq. 1).
\begin{align}
P(\text{DS} = d_s|\text{IM}) &= \left\{ \begin{array}{ll}
1 - P(\text{DS} \geq d_s|\text{IM}) & i = 0 \\
(1 - P(\text{DS} \geq d_s|\text{IM}) - P(\text{DS} \geq d_{s+1}|\text{IM})) & 1 \leq i \leq n - 1 \\
1 - P(\text{DS} \geq d_s|\text{IM}) & i = n
\end{array} \right.
\end{align}

\textbf{DS} \quad \text{Uncertain damage state of a particular component \{0,1,…N\}} \\
\textbf{d}_s \quad \text{A particular value of DS} \\
\textbf{N}_\text{DS} \quad \text{Number of possible damage states} \\
\textbf{IM} \quad \text{Uncertain excitation, the ground motion intensity measure (i.e., PGA, PGD, or PGV)} \\
\textbf{x} \quad \text{A particular value of IM} \\
\Phi \quad \text{Standard cumulative normal distribution function.} \\
\theta_{d_s} \quad \text{The median capacity of the component to resist a damage state } d_s \text{ measured in terms of } \text{IM} \\
\beta_{d_s} \quad \text{The logarithmic standard deviation of the uncertain capacity of the component to resist a damage state } d_s

The fragility curves are generated based on empirical data, analytical studies, or expert judgment [11]. The data of fragility parameters for structure and system infrastructure, and for individual components can be found in the literature [12]–[15]. In this research, we use this data to assign fragility parameters to the BIM-model components. Each component in the BIM model is attributed with fragility parameters: the median and standard deviation capacity for each damage state. This step may require integration with external databases or tools for the generation and assignment of fragility curves.

![Figure 2 - Example of fragility curves for different types of possible infrastructure components](image)

\section*{2.3. Derivation of a seismic hazard curve}

The seismic hazard curve is derived for the infrastructure system’s location, taking into account the seismicity of the region, local soil conditions, and other relevant factors. The hazard curve represents the relationship between the probability of exceedance of a given ground motion level and the corresponding return period. This curve is essential for determining the seismic demand on the
infrastructure system and is typically obtained from regional seismic hazard studies or through probabilistic seismic hazard analysis (PSHA).

2.4. Calculation of the seismic vulnerability

In this step, the seismic vulnerability of each component is calculated by combining the fragility curves and the seismic hazard curve. For each component, the probability of exceeding each damage state is evaluated under various seismic scenarios. This involves calculating the conditional probability of exceeding a specific damage state given a certain ground motion level and then integrating over the range of possible ground motion levels. The result is a vulnerability index for each component, which quantifies the likelihood of the component experiencing different levels of damage under seismic loading.

2.5. 3D visualization of the seismic vulnerability

The final step in the proposed methodology is the 3D visualization of the infrastructure system’s seismic vulnerability. The BIM environment allows for an interactive exploration of the vulnerable components and damage states. This visualization enables engineers and decision-makers to quickly identify the most vulnerable components and assess the overall seismic performance of the infrastructure system. Furthermore, the visualization can be used for communication with stakeholders and to support decision-making processes related to seismic retrofitting, maintenance planning, and emergency response.

By integrating the detailed component-level information available in BIM models with the seismic risk assessment process, the proposed framework offers a comprehensive and efficient approach for evaluating the seismic vulnerability of infrastructure systems. This approach can support the development of targeted strategies for enhancing the resilience of these systems in the face of seismic hazards.

3. Case Study: Seismic Risk Assessment of a Sewage Pumping Station

To demonstrate the effectiveness and feasibility of the proposed BIM-based seismic risk assessment framework, a conceptual case of a sewage pumping station is discussed. The pumping station is a critical component of a wastewater management system. Its primary function is transporting sewage or wastewater from lower-elevation areas to higher-elevation areas, enabling the wastewater to continue to a treatment facility through gravity-fed sewer systems or pressurized pipes. In order to ensure continuous operation of the system during and after a seismic event, it is crucial to assess the pumping station’s seismic vulnerability and implement necessary measures.

The sewage pumping station considered in this case study is a reinforced concrete structure located in a seismically active region. The pumping station has two pumps, electrical systems, pipes and valves, and other non-structural components necessary for its operation. A BIM model of the pumping station was created using Autodesk Revit, including general information on the structural and non-structural elements.

The analysis follows the five steps of the proposed BIM-based seismic risk assessment framework:

- Creation of a BIM model: A detailed digital BIM model of the sewage pumping station was created, including information on the structural and non-structural elements.
- Attribution of fragility curves to each model element: Fragility curves were attributed to each component in the BIM model based on the median and standard deviation capacity for each damage state obtained from the literature.
- Derivation of a seismic hazard curve: A seismic hazard curve was derived for the location of the pumping station. The hazard curve considers regional seismicity, local soil conditions, and other relevant factors.
• Calculation of the seismic vulnerability of each element: The seismic vulnerability of each component was calculated by combining the fragility curves for each damage state and the seismic hazard curve.

• 3D visualization of the element's seismic vulnerability: The seismic vulnerability of the pumping station and its components was visualized in a 3D model. The visualization presents the vulnerability based on the classification of each color.

The results of the case study highlight the effectiveness of the proposed BIM-based seismic risk assessment framework in identifying the most vulnerable components of the sewage pumping station. The 3D visualization will enable to quickly assess the overall seismic performance of the infrastructure system and prioritize potential retrofitting and maintenance efforts.

4. Discussion and Conclusion

The BIM-based seismic risk assessment framework presented in this paper represents a step forward in the application of BIM for infrastructure seismic risk assessment. By leveraging the detailed component-level information available in BIM models and attribution with fragility curves and hazard analysis, the proposed framework provides a comprehensive and efficient approach for evaluating the seismic vulnerability of infrastructure systems at component level. This approach can support the development of strategies for enhancing the resilience of these systems in the face of seismic hazards.

The use of BIM for seismic risk assessment offers several advantages. First, the component-level information available in BIM models can improve the accuracy the risk assessment process. By attributing fragility parameters to individual components, it is possible to account for variations of different components properties that may impact the seismic performance of the infrastructure system. This concept can be especially valuable for identifying vulnerable components and prioritizing retrofitting and maintenance efforts. Second, by incorporating seismic risk assessment into the BIM environment, it becomes possible to track and manage the vulnerability of the infrastructure system over time and to update the risk assessment as new information becomes available. Finally, the 3D visualization capabilities of the BIM environment offer powerful tools for communicating the results of the seismic risk assessment to stakeholders and decision-makers. It becomes easier to convey complex information and support decision-making processes related to seismic retrofitting, maintenance planning, and emergency response.

In conclusion, this paper has presented a framework for BIM-based seismic risk assessment for infrastructure systems. The proposed framework combines the component-level digital information available in BIM models with fragility curves and hazard analysis to provide a comprehensive and efficient approach for evaluating the seismic vulnerability of infrastructure systems. The study has demonstrated the potential of BIM to improve the accuracy and efficiency of the seismic risk assessment process and to support the development of targeted strategies for enhancing the resilience of infrastructure systems in the face of seismic hazards.

As the adoption of BIM in the engineering and construction industry continues to grow, there are significant opportunities to further refine and expand the application of BIM for infrastructure risk assessment. Currently, work is underway to refine the code and to allow to explore the integration of other types of hazards and risk assessment methodologies into the BIM environment, as well as the development of advanced tools for visualizing and managing risk information throughout the infrastructure lifecycle.

5. Limitations and further research

The proposed methodology still requires additional work that includes coding and verification of results. Furthermore, the work is limited to simple single-story facilities, as more complex solutions are required to cope with structures with multiple floors. In such cases, it would be required to perform a structural analysis to identify the intensity on each floor and only then calculate the risk. A further constraint is that
the methodology requires prior knowledge of the fragility parameters for each structural component. If there is no prior knowledge of the fragility parameters, they need to be assessed.

While we have focused on seismic hazard, it is possible to use the proposed methodology to assess other types of risks. However, this requires modifying the methodology according to the unique characteristics of each risk.

References