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Web-Based System for Evaluation and Communication of Seismic Risk

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ABSTRACT

A web-based system is designed to evaluate and communicate the seismic risk to the public. In this context, risk denotes the mean monetary and social losses. The system aims at communicating the risk to building owners with the objective of raising the public awareness of the significant seismic risk in Iran. This is the first step towards motivating the society to take appropriate risk mitigation measures. The object-oriented architecture of the system facilitates its steady growth to accommodate more advanced risk analysis techniques. The adopted risk analysis approach is tailored to the construction quality and the seismic regulations in Iran. The system receives elementary, observable characteristics of the building as input, and interprets the resulting risk in layman's terms. It is showcased by two real-world buildings at the campus of Sharif University of Technology, Tehran, Iran: one unreinforced-masonry dormitory and one steel-braced educational building. As an example result, the system predicts a significantly higher rate of fatality for the dormitory due to the poor performance of unreinforced masonry. The paper is concluded by explaining the ongoing research by the authors to further develop the system with more advanced risk communication techniques.

Keywords:
Seismic risk; Risk communication; Object-oriented programming; Web; Repair costs; Casualties

1. Introduction

This paper puts forward a functional tool for evaluation and communication of risk to building structures under the earthquake hazard. For this purpose, a web-based system is designed and implemented. The system is a practical effort to raise public awareness of the monetary and social aspects of the seismic risk. The need for such developments stems from recognition that in many earthquake-prone regions, such as Iran, there is a lack of deep concern amongst the public about the earthquake hazard. Upon the occurrence of a strong ground motion, the public becomes conscious of the importance of better adherence to seismic guidelines in design and higher quality of construction, but this consciousness diminishes over time, at least until the next severe earthquake. The academic community has a social duty here, and that is to convey the results of scientific studies in layman's terms to the public. Probabilities, costs, and death toll are metrics comprehensible to the non-technical audience. Therefore, risk in the proposed system is defined as the mean of monetary and social losses, i.e., costs and casualties, respectively. The worldwide web is selected as the medium for this communication because of its omnipresence and ease of access for the public.

The long-term vision for the proposed system is to communicate the risk to three groups of audience: Building owners, policymakers, and engineers. This paper addresses the first two groups, and ongoing research by the authors will address the third group, i.e., engineering community. In particular, the building owner inputs a set of preliminary, observable information about the building to the system, such as its location, material, number of stories, footprint area, year of construction, and load bearing system. The system will input this information into a simplified risk analysis approach, such as the one proposed by FEMA-NIBS [1]. This approach predicts the mean repair cost and the mean rate of casualties. The result is displayed and interpreted for the owner in the output of the system. For instance, the owner will know the probability of death for the building occupants as well as the average repair costs, which significantly illuminates her/his views on the risk involved.

The risk information is stored in a database. Hence, a comprehensive building inventory accompanied by risk estimates is established over time. This information is reported to policymakers to help with making decisions on risk mitigation actions. For instance, damage ratios of all buildings within a region can be shown as a bar chart that is overplayed on a map of the region. Damage ratio is the ratio of the seismic cost of repair to the replacement cost of the building. This bar chart can be used to detect the most vulnerable buildings in a region and prioritize them for retrofit.

In contrast to the simple interface for a non-technical user, it is envisioned for the future of the system to provide the engineers with a more detailed interface. It will essentially let engineers define an idealized structural model for the building. The model will then be utilized in a more detailed risk analysis methodology based on the reliability analysis and multiple interacting probabilistic models [2]. The results of this analysis include the probability distribution of social and monetary losses. Figure (1) illustrates an example in which the horizontal axis shows the continuous values of the total seismic monetary loss of a building. The vertical axis shows the exceedance probability of loss. For example, the figure shows a 10% chance that the total monetary loss exceeds $60,000. Using this system, engineers will be able to make rational, risk-based decisions on the selection of structural systems and design of the building. This is being addressed by ongoing research.

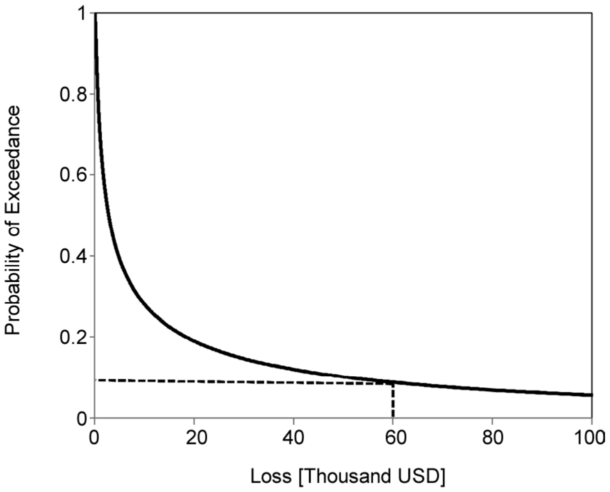


Figure 1. Probability of exceedance of the monetary loss.

Efforts to carry out probabilistic seismic hazard and risk analysis date back to late 1960's. Cornell [3] pioneered the field of probabilistic seismic hazard analysis. Peak ground acceleration versus the mean return period was an example of the results of this work. Since then, many researchers have contributed to this field. McGuire [4] presented an overview of the evolution of the probabilistic seismic hazard analysis.

The first comprehensive framework for risk analysis of buildings was proposed by the Applied Technology Council (ATC) in ATC-13 report [5]. This method used damage-probability matrices based on expert opinion to represent the conditional probability of seven qualitative damage states for a building given the discrete values of earthquake intensity in Modified Mercalli Intensity (MMI) scale.

Twenty years after ATC-13 report, the US Federal Emergency Management Agency (FEMA) and the US National Institute of Building Science (NIBS) introduced a new analytical risk analysis methodology [1, 6]. The methodology was implemented in the HAZUS® computer program. They employed fragility curves that describe the probability of exceeding different damage states given a measure of demand, e.g., peak ground acceleration, spectral acceleration, or peak drift of the structure. FEMA-NIBS also evaluated the probability of different casualty severity levels.

The present study employs the FEMA-NIBS methodology for economic and social risk assessment. However, the said methodology is adjusted in accordance with the quality of construction as well as the iterations of the seismic provisions in Iran, as described later in this paper.

In 2000s, the Pacific Earthquake Engineering Research (PEER) center put forward a new methodology for seismic risk assessment. Cornell and Krawinkler [7] originally proposed the methodology and Moehle and Deierlein [8] presented it in more detail. They employed a triple integral at its core in the context of the theorem of total probability, which is known as the PEER framing equation. The results of this approach is the probability distribution of the repair cost. A decade later, Yang et al. [9] proposed a sampling approach to evaluate the aforementioned triple integral. There are also several similar formulations proposed by other institutions, such as the Mid-America Earthquake center among others [10].

In 2010s, Mahsuli and Haukaas [2] developed an alternative methodology for risk analysis. This methodology computes risk using reliability methods in which many interacting probabilistic models evaluate the limit-state function. These models make probabilistic prediction of physical phenomena, such as the occurrence, magnitude, location, and intensity of earthquakes as well as the building response, damage, and loss. Each source of uncertainty is explicitly represented by a random variable whose distribution is obtained from observed data. These random variables are input to the aforesaid probabilistic models. This paper envisions the use of this approach to extend the proposed system with detailed risk analysis tools to be utilized by the engineering community.

Another relevant field of research includes the web-based applications for evaluation and presentation of the seismic hazard and risk. The U.S. Geological Survey (USGS) offers various such services on its website, such as an online tool to demonstrate the seismic hazard maps in the United States [11]. Another tool by USGS, dubbed Prompt Assessment of Global Earthquake for Response (PAGER) [12], predicts aftershocks and building damage states within 30 minutes of the occurrence of an earthquake. ShakeMaps [13] is another service offered by USGS, which provides near real-time maps of ground shaking intensity following significant earthquakes. In addition to USGS services, Organization of Economic Cooperation and Development (OECD) has organized an international association, named the Global Earthquake Model (GEM) [14]. The OpenQuake Engine® is an open source program under development by GEM that enables the users to conduct online seismic hazard and risk analysis.

Mahsuli and Haukaas [15] developed the Rt computer program that conducts risk analysis using the above-mentioned reliability-based approach. Rt has a growing library of probabilistic models, including models for regional seismic risk analysis of building structures. Using Rt, Mahsuli and Haukaas [16] assessed the seismic risk to the Vancouver Metropolitan region.

Risk communication is another relevant area of research, which aims at informing the public about activities that pose a threat to human health and environment. Lundgren and McMakin [17] published a com-prehensive handbook on risk communications in the field of health, safety, and environment. Lipkus and Hollands [18] showed that a visual representation of risk is a far more effective approach for risk communication than a numerical representation. The proposed risk analysis system here employs a visual risk com-munication approach to effectively convey the risk estimates and their interpretation to the public.

Indeed, reporting building responses, such as inter-story drifts and floor accelerations, are inappropriate means of the communication of seismic risk to the public. Fast and effective risk communication with the common language of losses and probabilities is the foremost novelty of the system proposed in this paper. The user-friendly interface of this system is aimed at making the results of this analysis available to a broad user group. Risk communication techniques, which are vastly employed in medicine and social sciences, are in this paper applied in earthquake engineering risk analysis. This system is also the first of its kind in Iran and paves the way for more advanced risk communication systems. Finally, the object-oriented architecture of this system makes it maintainable and extensible hence fostering its steady improvements over time.

2. Seismic Hazard Analysis

The first step in a risk analysis is to quantify the hazard intensities. The adopted FEMA-NIBS methodology, which will be described later, requires a seismic demand spectrum in terms of the spectral acceleration, S_a. The entire spectrum is constructed using S_a values at the two periods of 0.3 and 1.0 seconds, hereafter denoted by $S_{a0.3}$ and $S_{a1.0}$. These values are adopted here from the uniform hazard spectrum by Gholipour et al. [19]. Values for the two return periods of 475 and 2475 years are employed because the proposed risk analysis system is designed to compute the losses at these two hazard levels. They are respectively denoted by severe and very severe earthquake in the system.

The user inputs the location of the building to the system by clicking on Google Maps®. Subsequently, the Sa-values for the designated building at the desired return periods are determined from the uniform hazard spectrum of the nearest point for which the spectral ordinates are available. Ongoing research by the authors addresses a seismic hazard analysis of a dense grid of locations in Tehran as well as other parts of Iran [20]. Upon completion of this study, the system will benefit from a more accurate estimation of hazard in Tehran as well as expanded support for the entire country. The object-oriented architecture of the system readily facilitates the addition of hazard estimates at new locations.

3. Risk Analysis Methodology

The FEMA-NIBS approach [1] is employed as the basis for risk analysis in the proposed system. The input parameters of this approach was originally proposed based on the construction in California, United States. In this paper, the input is tailored to the construction in Iran. In particular, various editions of the Iranian seismic code are employed to determine the code-level of buildings. In addition, the lower construction quality of buildings is accounted for by modifying the damage states of the FEMA-NIBS approach. This section provides a general overview of the methodology and the modifications made in this paper.

FEMA-NIBS provides a comprehensive risk analysis approach that is used to evaluate various consequences of earthquakes that include direct physical damage and direct economic and social losses. Direct physical damage is incurred by structural components, non-structural drift-sensitive components, non-structural acceleration-sensitive components, and contents of the building. Damage in the first two ones is deemed to be governed by the displacement response and in the last two ones by the acceleration response.

Buildings are classified into 36 prototypes based on their structural system and height. For instance, there are three prototypes for low-rise, mid-rise, and high-rise reinforced concrete moment resisting frame buildings. The proposed risk analysis system determines the building prototype from three entries in the user input: 1) Material, which includes wood, steel, concrete, and masonry; 2) Load bearing system, which includes moment frame, braced frame, light frame, shear wall, unreinforced masonry infill wall, reinforced masonry infill wall, and unreinforced masonry bearing wall; 3) Number of stories from which an approximation of the building height is obtained. In the proposed system, the same building classification as that of FEMA-NIBS is employed on account of the notable similarities between the design codes of Iran and the United States. However, it is acknowledged that the building classification must be revised by future work, a development that is outside the scope of this paper.

For each building prototype, four code design levels are defined: high-code, moderate-code, low-code, and pre-code. Pre-code buildings encompass the constructions before the introduction of seismic codes in the United States, e.g., prior to 1940s. In the proposed system, the code level is identified based on the year of construction and the quality of construction, as shown in Table (1). The former determines which generation of Iranian seismic code has been employed to design the building [21]. For instance, building designed between 1971 and 2000 are regarded as low-code because they are built in accordance with non-ductile seismic provisions. The typically lower quality of construction in Iran is reflected in Table (1). According to this table, the code level is downgraded when the building suffers from an inferior construction quality. The user of the proposed risk analysis system inputs the year and the quality of construction, from which the code level is determined.

Table 1. Determination of the code level.

Year of Construction	Quality of Construction		
	Superior	**Ordinary**	**Inferior**
Before 1349 AH (1971 AD)	Pre-code	Pre-code	Pre-code
Between 1349-1378 AH (1971-2000 AD)	Low-code	Low-code	Pre-code
After 1378 AH (2000 AD)	Moderate-code	Moderate-code	Low-code

When the building prototype and code level is determined from the user input, the capacity spectrum method, originally developed by Freeman et al. [22], is employed to estimate the peak drift and peak acceleration response of the building given the spectral ordinates $S_{a0.3}$ and $S_{a1.0}$. This method computes the peak responses by intersecting a capacity spectrum with a demand spectrum. The intersection is referred to as the performance point. To construct the demand spectrum, a 5%-damped elastic S_a spectrum is first established, using $S_{a0.3}$ and $S_{a1.0}$ and the corresponding spectral displacements, S_d. Subsequently, a nonlinear demand spectrum is established by applying a reduction factor to this linear spectrum. For this purpose, the energy dissipated by the hysteretic behavior of material in the structure is represented by an equivalent viscous damping, from which reduction factors are computed for the constant-acceleration and constant-velocity spectral regions.

Next, the capacity curve of the building is established based on nonlinear static analysis. This curve is the plot of the base shear versus the displacement of the structure subject to incremental lateral loads. Two control points determine the shape of the capacity spectrum: the yield point and the ultimate capacity point. In this paper, the characteristic values of the capacity spectrum proposed by FEMA-NIBS as a function of building prototype and code level are adopted.

4. Damage and Monetary Loss

In the FEMA-NIBS [1] approach, four damage states are defined: slight damage denoted by DS_1, moderate damage denoted by DS_2, extensive damage denoted by DS_3, and complete damage denoted by DS_4. The fragility curve associated with each damage state follows a lognormal distribution given the value of the building response, e.g., the peak drift or the peak acceleration from the capacity spectrum method. The parameters of this distribution are a median response and a variability, defined as the standard deviation of the logarithm of spectral response. These parameters depend on the building prototype and the building code level. As explained before, to streamline the FEMA-NIBS assumptions for the parameters of the fragility curves to the typically lower construction quality in Iran, the code level of each building is modified. In particular, the code levels are shifted down by one level compared to those of FEMA-NIBS, as presented in Table (1). For instance, the median response that FEMA-NIBS specifies for pre-code buildings is employed to compute the damage state probabilities of low-code buildings in Iran. This practically increases the probability of higher damage states to compensate for the difference between the qualities of construction.

Given the peak spectral response evaluated in the previous step, these fragility curves provide the probability of falling in or exceeding each damage state. Thus, it is possible to compute the probability of falling only in damage state i, $P(DS_i)$, where i=1, 2, 3, 4. Figure (2) depicts an example set of fragility curves that are a function of the spectral displacement.

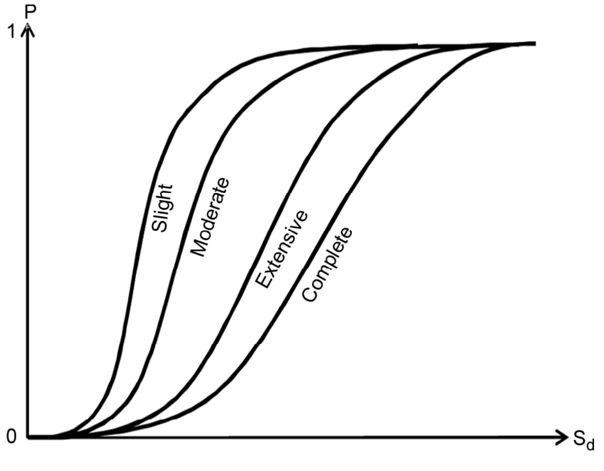


Figure 2. Damage fragility curves.

On the other hand, each damage state *i* is associated with a range of damage ratios and thus, a central damage ratio η_i as the center of the damage range. Buildings are classified into 33 occupancy classes based on their usage, such as family housing or commercial use. This is directly determined from the user input. The η_i-values depend on the building occupancy classes and are adopted here based on the recommendations of FEMA-NIBS. Having the probability of falling in each damage state and the corresponding central damage ratio, the mean damage ratio, $E[\eta]$, is evaluated as follows:

$$E[\eta] = \sum_{i=1}^{4} P(DS_i).\eta_i \quad (1)$$

This mean damage ratio is computed for each of the four damage types, i.e., structural damage $E[\eta_S]$, non-structural drift-sensitive damage $E[\eta_{ND}]$, non-structural acceleration-sensitive damage $E[\eta_{NA}]$, and content damage $E[\eta_C]$.

Provided the damage ratios, the associated monetary loss due to repair cost is computed as the product of the mean damage ratio, the building replacement cost per unit floor area, and the total building floor area. Summation over structural, non-structural, and content yields

$$l = (E[\eta_S].C_S + E[\eta_{ND}].C_{ND} + E[\eta_{NA}].C_{NA} + E[\eta_C].C_C).A \quad (2)$$

where $E[\eta_i]$ = mean damage ratios, C_i = corresponding replacement costs per unit floor area, and A = total building floor area.

5. Social Loss

This section addresses the social losses due to death and injuries. In accordance with Table (2), four severity levels of injury are defined ranging from slight injury ($k = 1$) to death ($k = 4$). For each building prototype, rates of each severity level, ψ_k, given all four aforesaid damage states, $\lambda(\psi_k | DS_i)$, are provided. As a result, the mean rate for each severity level is computed as follows:

$$E[\psi_k] = \sum_{i=1}^{4} \lambda(\psi_k | DS_i).P(DS_i) \quad (3)$$

The casualty rates for each damage state, $\lambda(\psi_k | DS_i)$, and the collapse rates are adopted from [23] and [24], respectively, for masonry structures, which form about 75 percent of the building stock in Iran [25]. Due to lack of similar studies on other building prototypes, the rates that are proposed by FEMA-NIBS are altered in the proposed system. In particular, the rate of each severity level is shifted by one damage state. For instance, the rate of the severity level *k* given damage state *i* is used as the rate of severity level *k* given damage state *i* - 1. This essentially increases the mean rate for that severity level. As a result, Damage State 4 remains without a rate. In accordance with Figure (3), this rate is computed in this paper using an extrapolation

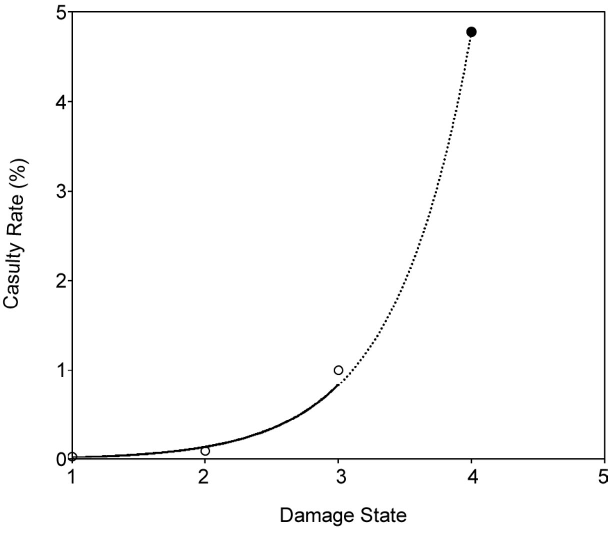


Figure 3. Curve fitting to estimate the casualty rate for Damage State 4.

Table 2. Description of injury severity levels.

Injury Severity Level	Injury Description
Severity 1	Injuries requiring basic medical aid that could be administered by paraprofessionals, such as sprain, a severe cut requiring stitches, and a minor burn
Severity 2	Injuries requiring a greater degree of medical care and surgery, but not expected to progress to a life-threatening status, such as third-degree burns and fractured bone
Severity 3	Injuries that pose an immediate life-threatening condition if not treated adequately and expeditiously, such as uncontrolled bleeding, punctured organ, and spinal column injuries
Severity 4	Instantaneously killed or mortally injured

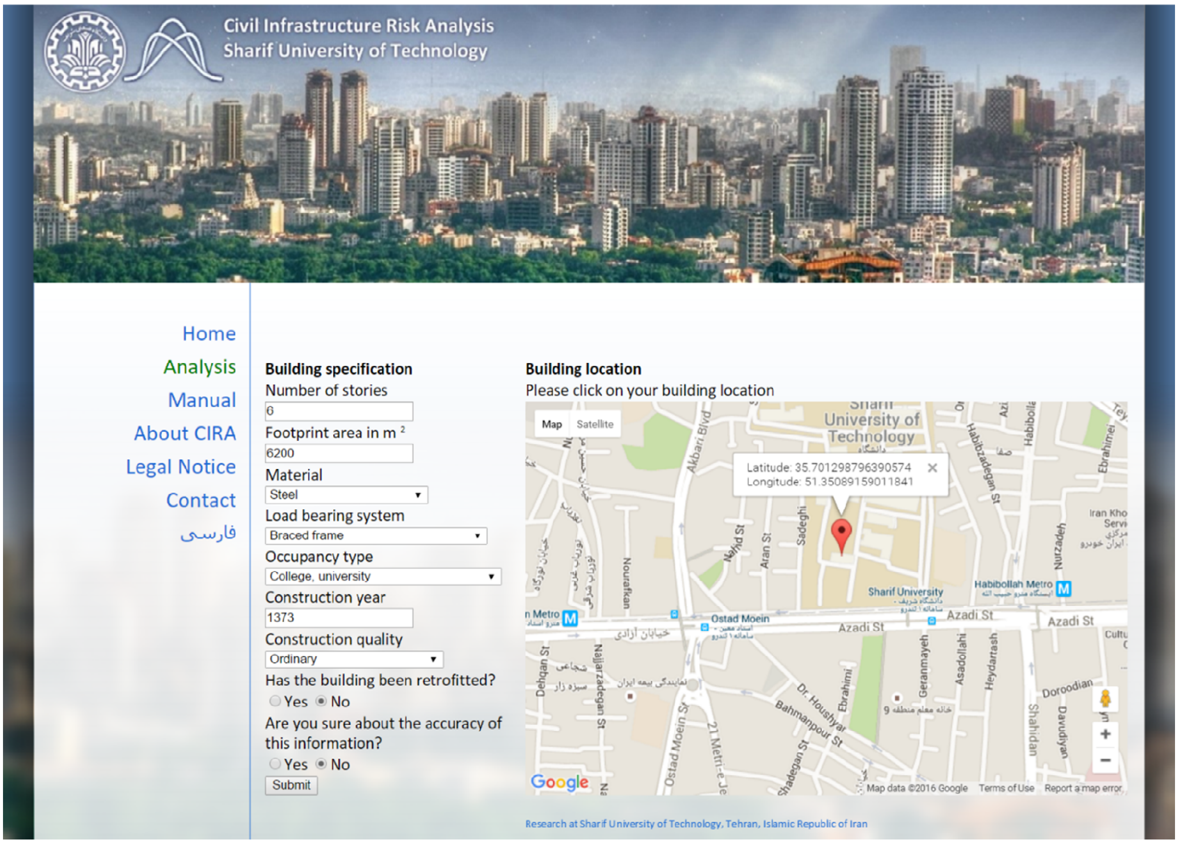
of the rates for Damage States 1 to 3, shown by hollow dots. The solid dot in Figure (3) is the predicted rate of injury for Damage State 4. This is a preliminary remedy to account for the higher rates of casualties in Iran compared to those in the United States. Future work must determine better estimates of $\lambda(\psi_k \mid DS_i)$ for all building prototypes using studies on earthquake casualties such as [26], and especially, studies on casualties in Iran and other similar regions, such as JICA and CEST [27] among others. Such updated estimates are readily incorporated in CIRA's code and databases as a result of the object-oriented architecture of the system.

6. Implementation

The described methodology is implemented as a web-based program in the PHP programming language. The service is hosted at cira.civil.sharif.edu. The word CIRA in the URL stands for Civil Infrastructure Risk Analysis. Figure (4) displays the input form of CIRA. This form takes the required properties of the building from the user, as explained before. To summarize, these properties include the building location determined by a click on Google Maps®, number of stories, footprint area, material, load bearing system, occupancy type, construction year, construction quality, and state of retrofit.

The latitude and longitude of the building is geocoded through Google Map® once the user clicks on the building location. The system identifies the nearest point in the database for which the hazard information is available to quantify $S_{a0.3}$ and $S_{a1.0}$. These values are then employed to establish the demand spectrum. Thereafter, the capacity spectrum is constructed based on the building prototype, determined by the user-given specifications. The system proceeds with finding the intersection of the demand and capacity spectra to find the peak responses, and evaluating the mean social and monetary losses from the fragility curves.

The information of the building and the results of the risk analysis are stored in a SQL database on the server. As a result, a comprehensive database of the building information and the associated monetary and social losses will be compiled over time. This information is presentable to decision-makers in order to design policies to mitigate the seismic risk.



Building specification

Number of stories: 6

Footprint area in m ^{2}: 6200

Material: Steel

Load bearing system: Braced frame

Occupancy type: College, university

Construction year: 1373

Construction quality: Ordinary

Has the building been retrofitted? ○ Yes ● No

Are you sure about the accuracy of this information? ○ Yes ● No

Submit

Building location

Please click on your building location

Latitude: 35.701298796390574
Longitude: 51.35089159011841

Research at Sharif University of Technology, Tehran, Islamic Republic of Iran

Figure 4. CIRA input form.

The output of the system presents and interprets the results of the risk analysis to the user, described next.

7. Example Analysis

To illustrate how the proposed risk analysis system presents the results to the end user, two real-world buildings at Sharif University of Technology (SUT) are subjected to risk analysis. First, the specifications of these two example buildings are presented in detail. Thereafter, the risk estimates of the two buildings, computed by the proposed system, are illustrated and compared. The Civil Engineering educational building and the Zanjan dormitory at SUT are selected for the subsequent analysis. The two buildings significantly differ in their properties, as presented shortly.

The properties of the buildings are tabulated in Table (3). The table includes all the information required to conduct a rapid risk analysis using the proposed system. It is emphasized that the simplicity of the system and its input is intended to make it available to a broad user group.

According to Table (3), the footprint area of both buildings are approximately the same. In addition, both buildings feature simple steel frames as their gravity load bearing system, i.e., frames with connections that cannot resist moment. They, however, differ markedly in their lateral force resisting system. The Civil Engineering building has concentric braced frames while the Zanjan dormitory only includes unreinforced masonry infill walls. Unreinforced masonry has exhibited one of the poorest seismic performances in the past earthquakes. Hence, it is expected that the Zanjan dormitory entails much higher levels of social and monetary losses than the Civil Engineering building. In fact, the Zanjan dormitory was erected in 1967, before the advent of seismic regulations in the Iranian building code. As a result, this building is 49 years old and therefore, it is expected to have undergone a significant deterioration over the years. In contrast, the Civil Engineering building was constructed in 1994, and designed in accordance with the second edition of the Iranian seismic code. The construction quality of both buildings at the time of construction are assumed as ordinary. The last entry in Table (3) for both buildings shows that neither have been retrofitted since the construction.

The first piece of information that the proposed system presents in the analysis output page is an estimation of the total building value, and its breakdown into structural, non-structural, and content; see Figure (5). Given the object-oriented and database-oriented nature of the system, this unit cost information can be readily updated as new data emerge.

Figure (5) shows the above-mentioned estimates for each of the two buildings in this example. The values for each category of building components,

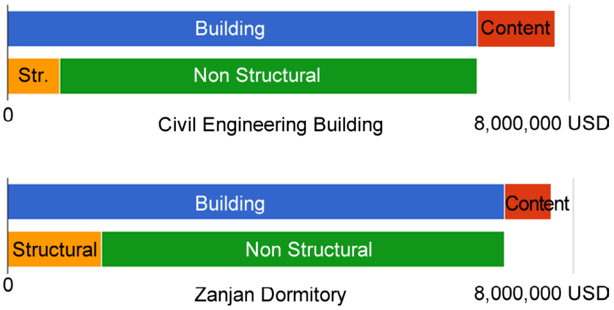


Figure 5. CIRA output showing an estimate of the building components value for Civil Engineering building (top) and Zanjan dormitory (bottom).

Table 3. CIRA output showing an estimate of the building components value for Civil Engineering building (top) and Zanjan dormitory (bottom).

	Civil Engineering Building	Zanjan Dormitory
Latitude	35.7012	35.7045
Longitude	51.3509	51.3577
Footprint Area (m^2)	6242	6500
Material	Steel	Steel
Load Bearing System	Braced Frame	Unreinforced Masonry Infill Wall
Occupancy	University/College	Dormitory
Construction Year	1994	1967
Construction Quality	Ordinary	Ordinary
History of Retrofit	No	No

e.g. structural or non-structural, pop up as the user points the cursor to the corresponding bar. These values are presented in Table (4). As seen, while both example buildings have roughly the same footprint area, the estimated value for the content of the Civil Engineering building is larger than that of Zanjan dormitory, due to the costly educational and laboratory equipment in the Civil Engineering building.

Table 4. Estimated value of the building components for the two example buildings.

	Civil Engineering Building	Zanjan Dormitory
Structural	$582,000	$1,046,000
Non-structural	$4,705,000	$4,518,000
Contents	$872,000	$523,000

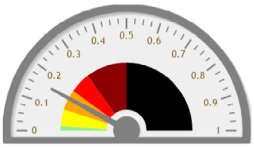
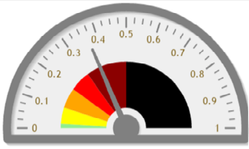
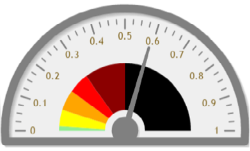
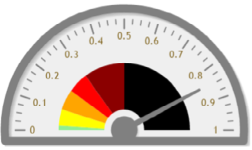
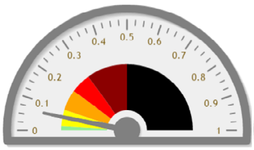
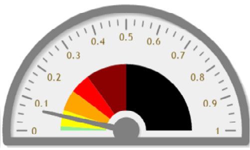
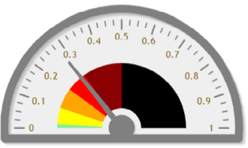
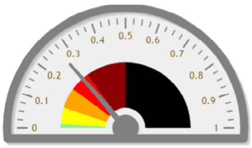
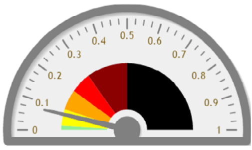
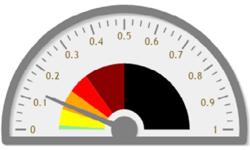
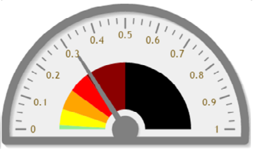
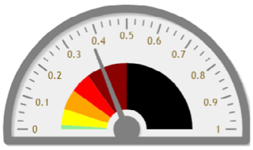
Next, CIRA illustrates the results of the risk analysis, starting with damage and monetary losses. A summary of the results for the two example buildings is provided in Table (5). The gauges in this table show the damage ratios of the structural and non-structural components, as well as the total damage ratio for each building under severe and very severe earthquakes. Recall that these two intensity levels correspond to return periods of 475 and 2475 years, respectively. Each gauge points to a number between 0 and 1 as the corresponding damage ratio.

Mean structural damage ratio is the first risk estimate of CIRA. As illustrated in the first row of Table (5), after a severe earthquake, the structural components of the Civil Engineering building will incur a monetary loss equal to 15.8% of the estimated value of structural components. This damage ratio for Zanjan dormitory rises to 36.9%, more than twice the ratio of the Civil Engineering building. In very severe earthquakes, the structural damage ratios are 59.1% and 84.6%, respectively. The latter denotes a near total destruction for the Zanjan dormitory. In accordance with [28], a structural damage ratio beyond 50% warrants demolishing and reconstructing the building. To emphasize this, the range of 50% to 100% of the damage ratio gauge in CIRA's output is shown in black.

The inferior performance of the Zanjan dormitory is not surprising. As explained earlier, the lateral force resisting system of this buildings consists of mere unreinforced masonry infill walls. These walls are virtually non-ductile structural elements with brittle failure modes, and incur significant damage in the aftermath of even moderate earthquakes. The situation is worsened for this building on account of the fact that it is categorized as pre-code whereas the Civil Engineering building is categorized as low-code.

The difference between the non-structural damage ratios for the two buildings is also noticeable. As the second row of Table (5) shows, the non-structural components of the Civil Engineering building incur a damage ratio of 6.5% and those of

Table 5. CIRA output showing the damage ratios for the two example buildings.

	Severe Earthquake (475 Years)		Very Severe Earthquake (2475 Years)	
	Civil Engineering Building	Zanjan Dormitory	Civil Engineering Building	Zanjan Dormitory
Structural				
Non-structural				
Total				

the Zanjan dormitory a damage ratio of 7.1% under severe earthquakes. These damage ratios under very severe earthquakes are estimated at 28.3% and 27.1%, respectively. The variation of nonstructural damage ratios between the two buildings is considerably less than the variation of structural damage ratios. This is consistent with FEMA-NIBS [1] fragility functions in which the median spectral accelerations are identical for pre-code and low-code buildings.

CIRA also presents a total damage ratio for each building, computed as the weighted average of structural and non-structural damage ratios. This information appears in the last row of Table (5) for the two example buildings subject to both severe and very severe earthquakes. As seen, the total damage ratio for the Civil Engineering building is 7.3% and for Zanjan dormitory building is 12.7% under severe earthquake, and 31.7% and 37.9% under very severe earthquakes, respectively. The total damage ratios are closer for the two buildings than the structural damage ratios because nearly 70% of the building's worth belongs to non-structural components, and these components incur damage ratios that are more-or-less similar in value.

The final section in the risk analysis results of the proposed system displays the rate for each of the four injury severity levels, i.e., slight injury to fatal injury. This rate denotes the expected number of the injured per 100 occupants of the building. Such results are depicted in Figure (6) for the example buildings subject to severe and very severe earthquakes. For instance, it is expected that roughly 5% of the nearly 800 occupants of the Zanjan dormitory building, i.e., approximately 40 persons, suffer from light injury after a very severe earthquake. The number for fatal injuries diminishes to 0.4% or roughly three persons. It is stressed that the jargon and the analysis results are interpreted for the end user in lay language. For instance, clicking on the term "non-structural components" brings up the meaning behind this expression in simple terms. It is also clarified for the user what each of the losses under various earthquake intensity levels entail.

8. Concluding Remarks

This paper targets the area of risk communication. A web-based program is designed and implemented for rapid risk analysis of building structures. To this end, a simplified risk analysis approach is implemented that computes the mean monetary and social losses of the building, i.e., the mean repair cost and mean rate of casualties. The adopted approach is streamlined in accordance with the Iranian seismic code and the lower construction quality in Iran. A novel object-oriented architecture is designed for the system to facilitate its maintainability and extensibility with more advanced risk analysis techniques and further consequences. The system is aimed at raising the public awareness of the huge seismic risk in Iran, and motivating building owners to invest in safety. The output of the system

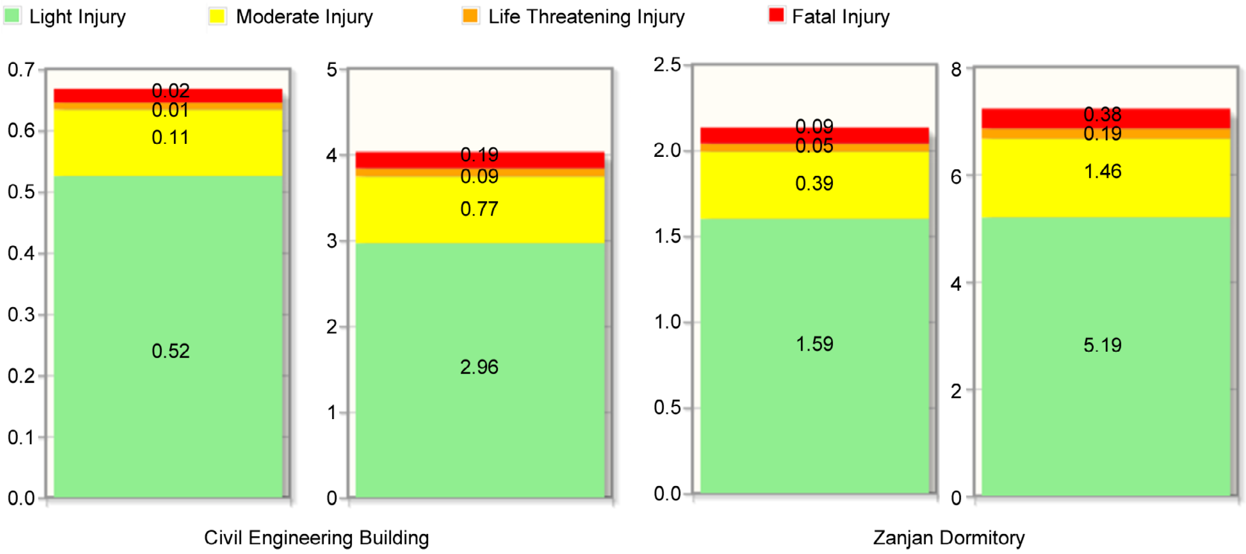


Figure 6. CIRA output showing the injury rates under severe and very severe earthquakes. The numbers represent the injured per 100 building occupants.

is presented and interpreted for the end user in lay language. Ongoing research by the authors will augment this system with advanced risk analysis techniques, such as reliability-based risk analysis methods. It is hence envisioned for the system to compute the probability distribution of various consequences, including repair costs, casualties, downtime, and socioeconomic losses. This will promote risk-based design and decision-making in the construction industry, and eventually leads to an added-value in engineering practice.

In an illustrative example, two real-world buildings on the campus of Sharif University of Technology are subjected to risk analysis with the proposed system: a dormitory building with unreinforced masonry structural system and an educational building with steel braced frame system. Subject to a 2475-year earthquake, dubbed very severe earthquake in the system, the results indicate a 7.2% rate of injury and fatality for the dormitory, almost twice the 4.0% rate for the educational building. This is owing to the inferior seismic performance of unreinforced masonry construction. In addition, the system predicts a damage ratio of 86% for the dormitory, i.e., a near total destruction, while the damage ratio for the educational building is notably lower at 59%. However, the results reveal a 28.3% non-structural damage ratio for the educational building, which is slightly higher than the ratio of 27.1% for the dormitory, owing to the presence of costly laboratory equipment in the educational building.

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