RAPID WEB-BASED SEISMIC RISK ANALYSIS OF BUILDINGS

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ABSTRACT

A web-based system is designed and implemented at *cira.civil.sharif.ir* to evaluate and communicate the seismic risk to the public. Risk, in this context, denotes the probability distribution of monetary and social losses, i.e., repair cost and injuries, respectively. The system envisions three groups of target audience: 1) Building owners with the objective of raising the public awareness about the significant seismic risk in Iran; 2) Engineers with the objective of promoting risk-based design in engineering practice; 3) Policy-makers with the objective of providing a comprehensive database of building information and risk estimates for mitigation decisions. This paper addresses the communication of risk to the first group, and the object-oriented architecture of the system facilitates its steady growth to address the other two groups. The paper presents the implemented risk analysis approach and the modifications made to tailor this approach to the construction quality and the seismic provisions in Iran. The paper also illustrates the input interface of the system for data collection and its output interface for presenting and interpreting the risk analysis results to building owners. The paper is concluded by explaining the ongoing research to further develop the system in order to address all three groups of audience enumerated above.

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 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 erodes over time, at least until the next severe earthquake event. 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 probability of exceedance for 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 fundamental vision for the proposed system is to communicate the risk to three groups of audience: Building owners, engineers, and policy-makers. A building owner inputs to the system a set of preliminary, observable information about the building, such as location, material, number of stories, footprint area, year of construction, and load bearing system. The system will input this information into a simlified risk analysis approach, i.e., FEMA-NIBS (2012). This approach predicts the mean repair cost and the mean number of casualties. The result is displayed and interpreted for the owner in the output of the system. For instance, the owner will know the odds of death for the building occupants as well as the average repair costs, which significantly illuminates her/his views of the risk involved. This is addressed in this paper.

In contrast to the simple interface for a non-technical user, it is envisioned for the system to provide the engineers with a more detailed interface. It essentially lets the engineer define an idealized structural model for the building. The model is then utilized in a more detailed risk analysis methodology based on reliability analysis and multiple interacting probabilistic models Mahsuli and Haukaas (2013). The result of this analysis includes the complete 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 the building in million Rials. The vertical axis shows the exceedance probability of loss. For example, the figure shows a 10 percent chance that the total monetary loss be exceeds 60 million Rials.

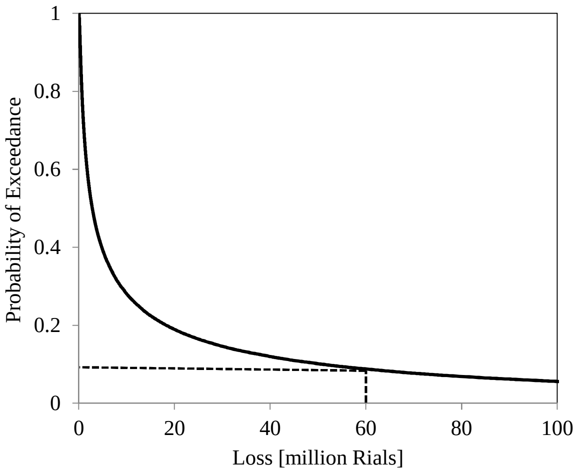


Figure 1: Complete curve of monetary loss probability of exceedance

The simple and intuitive interface of the system is aimed to foster the use of probabilities in engineering practice. Using this system, engineers will be able make rational, risk-based decisions on the selection of structural systems and design of the building under consideration. This will result in an added value in engineering practice.

Finally, 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 policy-makers to help with making decisions on risk mitigation actions. Figure 2 illustrates a schematic example of such results. The bars at the location of each building are a measure of its monetary loss for that building, e.g., damage ratio. Damage ratio is the ratio of the seismic cost of repair to the cost of replacing it with the same construction. This bar chart can be used to detect the most vulnerable buildings in a region and prioritize them for retrofit.

Figure 2: Schematic image of risk analysis results for buildings in an urban region

The scope of the system is currently limited to building structures. To quantify the uncertainty in the earthquake intensity, the system adopts the probabilistic seismic hazard analysis results from the literature. Such results are limited for cities other than Tehran. Hence, pending in-house hazard analysis, the system only provides services to the residents of Tehran. In passing, it is noted that hazard means the probability of exceeding a measure of intensity.

The first comprehensive framework fir risk analysis of buildings was proposed by the Applied Technology Council (ATC) in ATC-13 report ATC (1985). This method used damage-probability matrices based on expert opinion to represent the conditional probability of different qualitative damage states of a building given the discrete values of earthquake intensity in Modified Mercalli Intensity (MMI) scale. ATC-13 defined seven qualitative levels for building damage caused by earthquake and applied this method to evaluate California damage data.

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 FEMA-NIBS (2012). They employed fragility curves that describe the probability of exceeding different damage states given a measure of demand, e.g., the peak ground acceleration, or the spectral acceleration, or the peak drift of the structure. FEMA-NIBS also evaluated the probability of different casualty severity levels. The present study employs the FEMA-NIBS (2012) methodology for monetary and social risk assessment. However, the said methodology is adjusted to the seismic provisions and quality of construction in Iran.

As mentioned earlier, the vision behind this paper is to provide the complete probability distribution of losses using advanced risk analysis methodologies. One such methodology was proposed by the Pacific Earthquake Engineering Research (PEER), Cornell and Krawinkler (2000). The PEER approach is based on a total probability integration, known as the PEER framing equation, and implicitly accounts for uncertainties through conditional probability models.

In contrast, Mahsuli and Haukaas (2013) developed a methodology for risk analysis in that explicitly account for uncertainty. This methodology computes risk by 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. Reliability methods are suited for risk analysis because they efficiently in compute the small probability of rare events. These events are particularly important in risk analysis application because they have dramatic consequences. This paper envisions the use of approach to provide detailed risk estimates for engineers and decision makers. To this end, probabilistic models should be developed for the typical construction of buildings in Iran.

Another relevant field of research is the web-based applications for evaluation and presentation of the seismic. The US Geological Survey present various such services online on its website, such as the seismic hazard maps USGS (2015). FEMA-NIBS (2012) developed a computer application named HAZUS-MH® for risk analysis with their proposed methodology. Finally, Mahsuli and Hakaas (2012) developed the Rt program to carry out the aforementioned multi-model reliability analysis.

Indeed, building responses, such as inter-story drifts are a poor vehicle for the communication of the seismic risk to 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. This system is also the first of its kind in Iran and paves the way for more advanced approaches for risk communication. Finally, the object-oriented architecture of this system makes it maintainable and extensible hence fostering its steady improvements over time.

SEISMIC HAZARD ANALYSIS

The first step in a risk analysis is to quantify the hazard intensities. In the adopted FEMA-NIBS (2012) methodology, described shortly, requires the seismic demand spectrum in terms of the spectral acceleration, *Sa*. The entire spectrum is constructed using *Sa* values at the two periods of 0.3 and 1 seconds, hereafter denoted by $Sa_{0.3}$ and $Sa_{1.0}$. These values are adopted from the uniform hazard spectrum by Gholipour et al.

(2008) for the City of Tehran. The system is to provide the mean loss estimates for severe and very severe earthquake levels defined by the return periods of 475 and 2475 years, respectively.

Currently, the *Sa*-values are available for merely three points in Tehran. The *Sa*-values for a designated building at each return period are determined from the uniform hazard spectrum of the nearest point amongst these three. Ongoing research by the authors addresses a seismic hazard analysis a dense grid of locations in Tehran as well as other parts of Iran. 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 code of the system readily facilitates addition of the hazard estimates at new locations.

RISK ANALYSIS

The FEMA-NIBS (2012) methodology is employed as the basis for risk analysis of the proposed system. The inputs to this methodology is proposed the construction in California, US. In this paper some of the inputs are tailored to the Iranian seismic provisions as well as the lower construction quality of buildings in Iran. This section provides a general overview of the methodology and the modifications made in this paper.

FEMA-NIBS (2012) provides a complete risk analysis approach that can be used to evaluate different earthquake damage and losses, e.g. direct physical damage, induced physical damage, direct economic/social losses and indirect economic losses. The scope of this paper is limited to direct physical damage and social loss.

Direct physical damage is caused by the damage of four different sources, i.e. structural components, non-structural drift sensitive components, non-structural acceleration sensitive components, and contents of the building. Structural components include beams, columns, shear walls, etc. Non-structural drift sensitive components are mainly architectural components, such as nonbearing walls and partitions. Non-structural acceleration sensitive components comprise mechanical and electrical components. Finally, the building contents include the house furniture and equipment. The former two are deemed to be governed by the displacement response of the building while the latter two by the acceleration response. Hence, the capacity spectrum method, developed by Freeman, and Nicoletti (1975) is employed to predict the peak drift and acceleration response of the building. This method will be described in detail.

Buildings are classified into 36 building prototypes based on their structural system and height. For instance, there are three prototypes for low, moderate, and high-rise reinforced concrete frame buildings. Moreover, buildings are classified in 33 occupancy classes based on their usage, such as family housing or commercial use. Finally, for each building prototype, four code design levels are defined: high, moderate, low, and pre-code. Pre-code buildings encompass the constructions before the introduction of seismic codes, e.g., prior to 1940's. The code level is identified based on the year of construction and the quality of construction, as shown in Table 1. The former determines the generation of the seismic code that was employed to design the building. For instance, buildings designed prior to 1975 are regarded as low-code because they are built in accordance with non-ductile seismic provisions. In the proposed system, the evolution of the Iranian seismic code is the basis for determining the code level, as illustrated in Table 1.

Table 1: Modification of the FEMA-NIBS (2012) approach for the determination of the code level

Year of construction	Quality of construction		
	Superior	Ordinary	Inferior
before 1349	Pre-code	Pre-code	Pre-code
1349 to 1378	Low-code	Low-code	Pre-code
after 1378	Moderate-code	Moderate-code	Low-code

CAPACITY SPECTRUM METHOD

This method computes the peak responses of the building 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 *Sa* spectrum is first established. This curve is built using the $Sa_{0.3}$ and $Sa_{1.0}$ values, as described in the preceding section. Subsequently, a nonlinear demand spectrum is built from this linear spectrum. For this purpose, the energy dissipated by the hysteretic behavior of the material in the structure is represented by an equivalent viscous damping referred to as hysteretic damping. The 5%-damped elastic spectrum is then reduced by reduction factors R_A and R_V in the constant acceleration and constant velocity regions, respectively. The factors R_A and R_V are functions of the effective damping, ${}_{eff}$, which is the sum of the elastic damping, ${}_{E}$, and the hysteretic damping, ${}_{H}$:

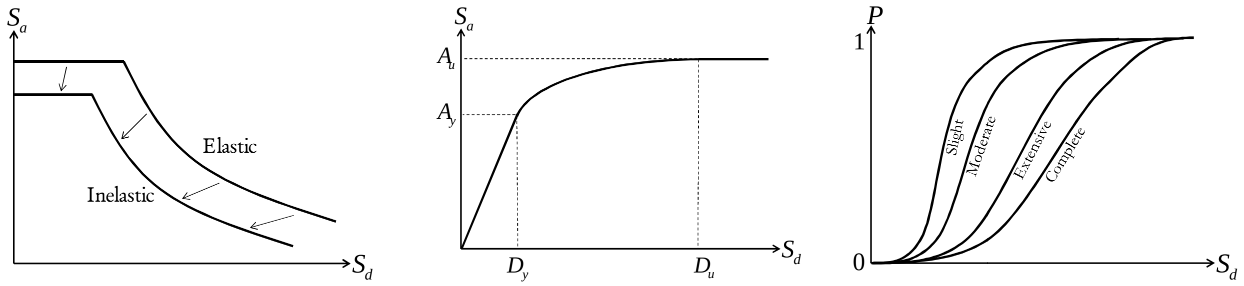
$$R_A = \frac{2.12}{3.21 - 0.68\ln({}_{eff})} \quad , \quad R_V = \frac{1.65}{2.31 - 0.41\ln({}_{eff})} \tag{1}$$

$${}_{eff} = {}_{E} + {}_{H} \tag{2}$$

The value of the elastic damping ${}_{E}$ is determined from the material damping right before the yield point of the material. The value of the hysteretic damping is determined from the area enclosed by the hysteresis loops of the structure, as follows:

$${}_{E} = © \cdot \left(\frac{E}{2® \cdot D \cdot A} \right) \tag{3}$$

where D = peak displacement response, A = acceleration at the peak displacement response, E = energy represented by the area of the hysteresis loop, which is defined as a symmetrical push-pull of the building capacity curve up to the peak positive and negative displacements $\pm D$, and © = degradation factor representing the fraction of the equivalent viscous damping that is considered as hysteretic damping. For the degradation factor ©, the values proposed by FEMA-NIBS as a function of the building prototype and the earthquake duration represented by the earthquake magnitude are adopted. Figure 3a depicts an example of elastic and inelastic demand spectra.



(a) (b) (c)

Figure 3: (a) Demand spectrum, (b) capacity spectrum, and (c) damage fragility curve

Capacity curves of buildings are established based on nonlinear static-equivalent analyses, also known as pushover analyses. These curves are the plot of the base shear versus roof displacement of the structure subject to incremental lateral loads. In order to make these curves comparable with a demand spectrum, the abscissa of these curves is transformed to spectral displacement, S_d, and the ordinate to spectral acceleration, Sa, using the modal properties of the structure. Two control points determine the shape of the capacity spectrum: the yield point and the ultimate capacity point. The spectral ordinates of these points are characterized by spectral displacements of D_y and D_u and spectral accelerations of A_y and A_u, respectively. Figure 3b illustrates an example capacity spectrum. In this study, the characteristic values of the capacity spectrum proposed by FEMA-NIBS as a function of building prototype and code design level are adopted.

MONETARY LOSS

In the FEMA-NIBS (2012) approach, four damage states are defined as follows: 1) Slight, 2) moderate, 3) extensive, and 4) complete. The fragility curve associated with each damage state has 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 code design level. Given the peak spectral response evaluated in previous steps, 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 3c depicts an example set of fragility curves.

On the other hand, each damage state i is associated with a damage factor range and thus, a central damage factor η_i as the center of the damage range. 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 central damage factor, the mean damage ratio, E[η], is evaluated as follows:

$$\mathrm{E}[\eta] = \sum_{i=1}^{4} P(DS_i) \cdot \eta_i \tag{4}$$

This mean damage ratio is computed for each of the four damage type, i.e., structural damage, E[η_S], non-structural drift-sensitive damage, E[η_{ND}], non-structural acceleration-sensitive damage, E[η_{NA}], and content damage, E[η_C].

Provided the damage ratios, the associated monetary loss due to repair cost is computed by multiplying it with the building replacement cost per unit floor area and the building floor area. Summation over structural, non-structural, and content yields:

$$l = \left(\mathrm{E}[\eta_S] \cdot C_S + \mathrm{E}[\eta_{ND}] \cdot C_{ND} + \mathrm{E}[\eta_{NA}] \cdot C_{NA} + \mathrm{E}[\eta_C] \cdot C_C\right) \tag{5}$$

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

SOCIAL LOSS

This section addresses the social losses due to death and injuries. FEMA-NIBS (2012) defines four severity levels of injury ranging from slight injury (k=1) to death (k=4). Rates of each severity level, ψ_k, given all four aforesaid damage states, $\lambda(\psi_k|DS_i)$, are given for each building prototype. As a result, the mean rate of each severity level is computed as follows:

$$\mathrm{E}[\psi_k] = \sum_{i=1}^{4} \lambda(\psi_k \mid DS_i) \cdot P(DS_i) \tag{6}$$

To tailor the FEMA-NIBS (2012) data to the lower quality of construction in Iran, the severity level rates are 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. This rate is computed in this paper using an extrapolation of the rates for Damage States 1 to 3, shown by hollow dots. The solid dot is the predicted rate for Damage State 4.

Table 2: Description of FEMA-NIBS (2012) 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

LIFETIME RISK

The mean monetary and social losses that are presented in the previous sections are given the occurrence of an earthquake. To account for the uncertainty in the earthquake occurrence in the lifetime of the building, the mean losses are multiplied by the rate of earthquake occurrence and the time period under consideration. For instance, if severe earthquakes with a return period of 475 years are considered in a 50-year time period, considered as the typical lifetime of a building, the mean loss is multiplied by 50/475.

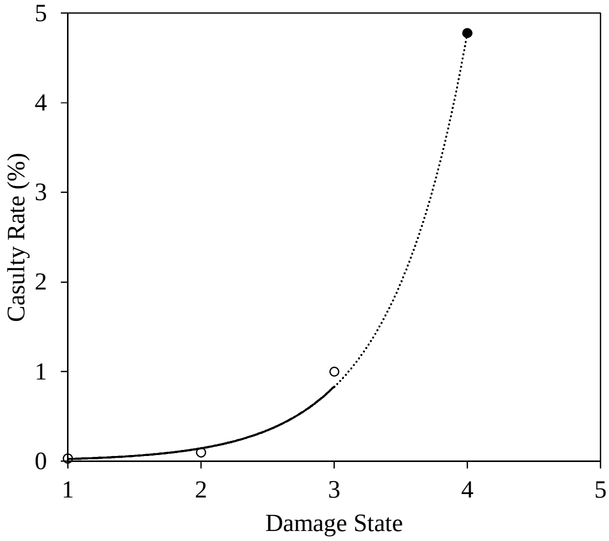


Figure 4: Curve fitting to estimate casualty rate for complete damage state.

IMPLEMENTATION

The described methodology is implemented as a web-based program in the PHP programming language. The service is hosted at *http://cira.civil.sharif.ir*. The word CIRA in the URL stands for Civil Infrastructure Risk Analysis. Figure 5 displays the input form of CIRA. This form takes the required properties of the building from the user, the building location, number of stories, footprint area, material and load bearing system. The latitude and longitude of the building is geocoded through Google Map® once the user click on the building location. The system identifies the nearest point in the database for which the hazard information is available to quantify the Sa-values for the building. These values are then employed to establish the demand spectrum while the capacity spectrum is constructed based on the building specifications given by the user. The system proceeds with finding the intersection of the spectra to find the peak responses, and evaluating the mean social and monetary losses from the fragility curves given those responses.

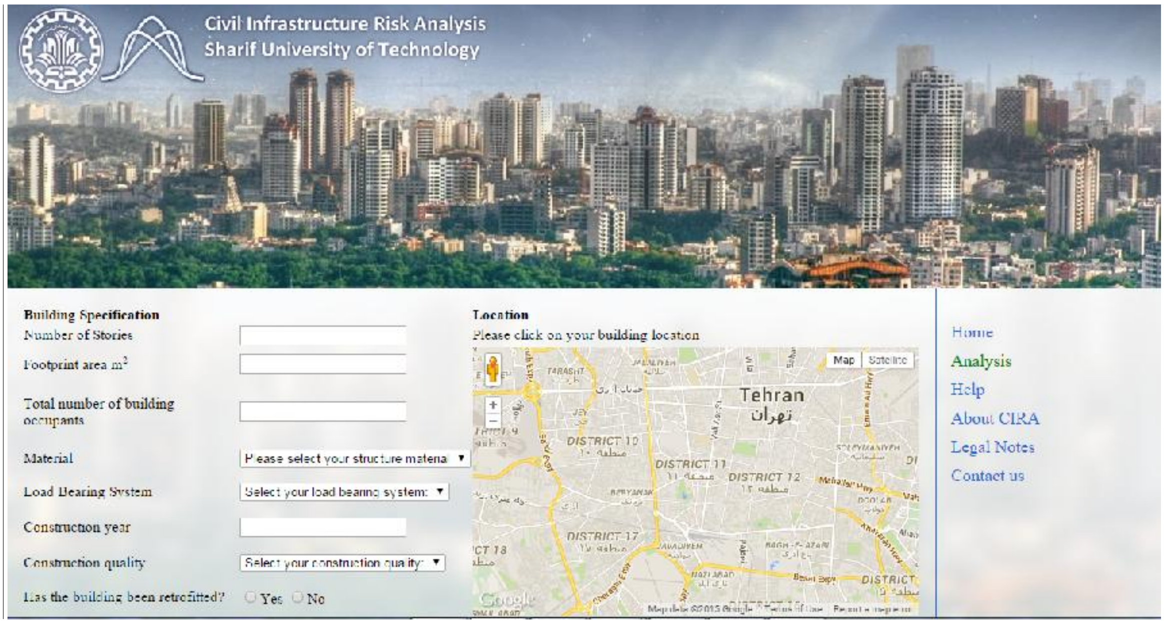


Figure 5: CIRA input form

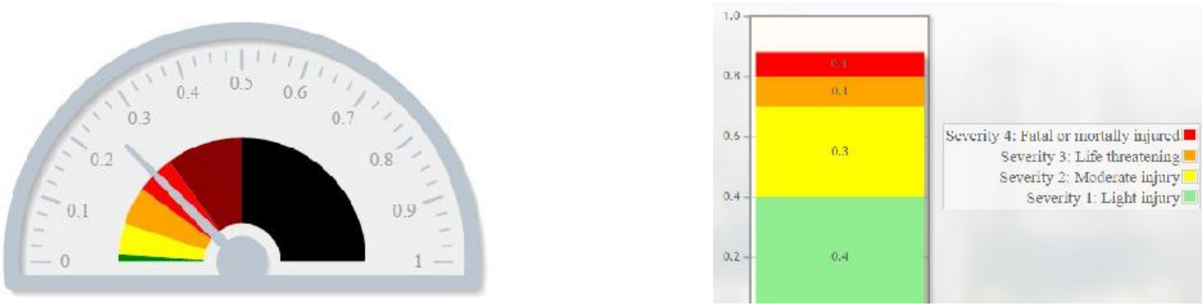


Figure 6: CIRA output for monetary loss (left) and social loss (right)

At this point, the system navigates to the output page to illustrate and interpret the results to the user. Figure 6 shows example output diagrams of the system. The left diagram indicates the mean overall damage ratio given the occurrence of an earthquake with a return period of, say, 475 years. The right diagram shows the mean rates for the four severity levels of injury given an earthquake occurrence. The mean total repair cost and its disaggregation into structural and non-structural losses are also presented to the user along with an explanation of the jargon in lay language.

CONCLUSIONS

This paper targets the area of risk communication. An object-oriented web-based program is designed and implemented for risk analysis of building structures. In this phase of the project, a simplified risk analysis approach is implemented that computes the mean monetary and social losses of the building, e.g., the mean repair cost and mean rate of casualties. This is aimed at raising the public awareness of the huge seismic risk in Iran, and motivating building owners to invest on safety. The next phases of the project will employ more advanced risk analysis approaches, such as "multi-model reliability analysis." This will entail a web interface to a high-performance computing center to carry out costly probabilistic analyses. The results of such analyses include the complete probability distribution of various consequences, such as the repair costs, number of injuries, and downtime. This will allow the engineering community to make risk-based design decisions and eventually leads to an added value in engineering practice.

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