COMPDYN 2011
III ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis, V. Plevris (eds.)
Corfu, Greece, 25–28 May 2011

INTEGRATED SYSTEM FOR EARTHQUAKE IMPACT ASSESSMENT

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Keywords: NISRAF, Earthquake Impact Assessment, Hybrid Simulation, Hazard Characterization, Model Calibration, Hybrid Fragility Analysis, Uncertainty Quantification.

Abstract. *NEES Integrated Seismic Risk Assessment Framework (NISRAF) integrates several components in order to obtain the most reliable earthquake impact assessment results: hybrid simulation with free-field and structural sensor measurements, hazard characterization, system identification-based model updating technology, hybrid fragility analysis, and impact assessment tool. Software has been built and verified, concurrently, via applications to an actual test bed in California. Regional impact assessment results of the Los Angeles area under the 1994 Northridge earthquake, using the generated hazard map and fragility curves, showed reasonable accurate, although conservative. Also, the implemented uncertainty quantification analysis aids decision-makers to judge the estimated losses easily and quickly, which will contribute to the development of more suitable and more confident recovery plans and emergency responses.*

The novelty of the proposed system derives primarily from the integration of components of earthquake impact assessment—most of which have not been deployed in such an application before. To achieve seamless integration and to arrive at an operational system, several components were used innovatively, tailored to perform the role required by NISRAF. The integrated system brings the advanced tools of earthquake hazard and structural reliability analyses into the context of societal requirement for accurate evaluation of the impact of earthquakes on the built environment.

1 INTRODUCTION

The 2008 Sichuan, China, earthquake caused thousands of deaths and over $150 billion economic losses [1]. In 2010 an earthquake in Port-au-Prince, Haiti, killed more than a quarter of million people, and resulted in losses over $14 billion [2]. These catastrophes show the severe damage earthquakes can inflict. Since 1960s, practitioners and researchers—through field investigations after devastating earthquakes, along with theoretical and experimental studies—have significantly improved our understanding of earthquakes and strategies to mitigate the impact. Examples of disciplinary developments are strong-motion measurements, system identification, model updating, structural performance evaluation through experimental and analytical simulations, fragility derivation, and the development of consequence estimation software.

The above component-specific studies allow researchers to focus on a particular problem at a fundamental level. Even though these specific studies have progressed considerably and produced mature research results, uncertainties remain in their outcomes not only because of their inherent characteristics, but also because of the interactions between them. For example, the derivation of fragility curves requires that a large amount of simulations be performed. It is essential to have an accurate structural model which closely represents the response of the real structure. In most fragility simulations, however, either a very simplified structural model is used or a complicated numerical model is used without being calibrated to measured response. Such methods, therefore, introduce significant and by-and-large unquantifiable uncertainties in the derived fragility curves. Moreover, the fragility curves heavily depend on input ground motions, particularly when the fragility curves are defined in terms of peak ground acceleration (PGA) [3]. The ground motion is in turn influenced by source, path, and site characterization, each of which is a formidable challenge in its own right. The realism of both model and input is therefore essential to the accuracy and applicability of the ensuing fragility relationships.

Earthquake impact assessment is the basis for emergency planning, mitigation, response, and recovery. The realism of the outcome, such as the effect on civil infrastructure systems, economy, and societal activities, is the essential ingredients to developing plans that adequately protect vulnerable communities. As mentioned above, significant progress has been made in earthquake impact assessment, including consequence estimation methodology as well as developing software that provides decision-makers with a tool to assess the impact [4]. Generally, the impact assessment software is composed of three main components: namely, (i) Hazard, (ii) Fragility, and (iii) Inventory. Among these, the inventory can be improved through the development and application of survey methods and technologies. This renders the accuracy of the assessment dependent on the reliability of the fragility curves and hazard characterization. Unquantifiable uncertainty and inaccuracies in the latter two components of hazard and fragility lead to earthquake impact assessments—that are unreliable and that do not form a viable basis for societal readiness.

2 METHODOLOGY

To reduce the above-mentioned uncertainties and unreliability in impact assessment, an integrated framework is proposed, developed, and demonstrated via application to an actual test bed. Figure 1 illustrates the proposed framework and how its components are combined to achieve the main goal of this research. As can be seen, the proposed framework, referred to as NEES Integrated Seismic Risk Assessment Framework (NISRAF), integrates hybrid simulation with free-field and structure sensor measurements, hazard characterization analysis, system identification-based model updating technology, hybrid fragility analysis, and earthquake impact assessment tools. The procedure is specifically proposed and programmed for ease of use.

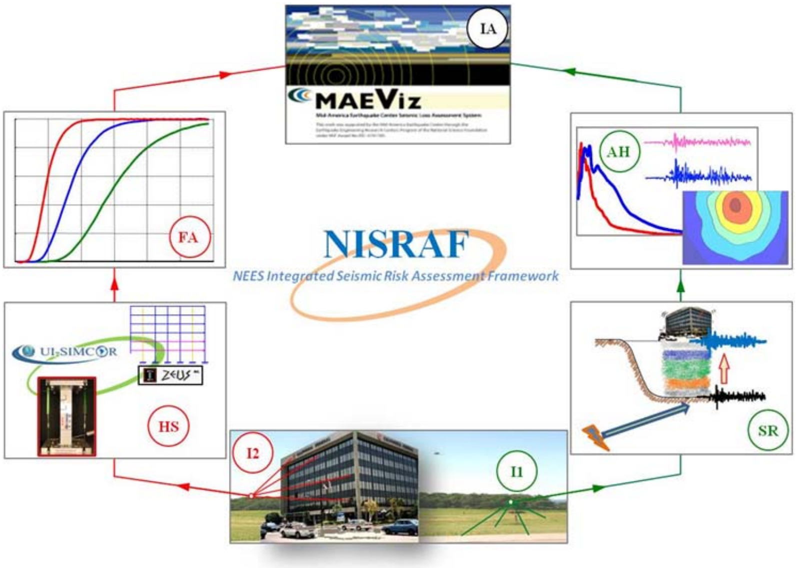

Figure 1: Schematic of the proposed integrated framework

In the schematic representation of the integrated framework given in Figure 1, free-field measurements (**I1**) along with nonlinear site response analysis (**SR**) are used to generate the advanced hazard map and ground motion records (**AH**). The measured and synthetic records are then used as seismic inputs in hybrid simulation and fragility analysis. Meanwhile, the structural model is calibrated with the measured structural response (**I2**). Next, hybrid simulations (**HS**) are performed with the most critical component of the structural system tested in the laboratory and the remainder of the structure simulated analytically. These simulations are conducted to derive the mean seismic intensity value (PGA, for example) of the corresponding performance limit state. The fragility curves (**FA**) of the structure are then generated using the hybrid simulation data and the dispersions from the literature. Finally, the derived fragility curves and the calibrated hazard map are fed into the impact assessment tools, such as MAEviz [5] (**IA**) to evaluate the seismic losses.

The integrated system provides an opportunity to bring together all the sub-disciplines, capitalizing on the respective advances of each sub-discipline. This method of integration is not only intended to provide a tool, but it is also intended to stimulate the sub-communities of researchers to investigate the problems at the interfaces between them. Through this systematic and transparent framework, uncertainties from each sub-discipline can be managed more effectively and the use of the instrumentation will increase. For example, the reliability of probabilistic seismic hazard can be significantly improved through the use of free-field strong-motion measurements. Analytical and hybrid (analytical-experimental) simulations can be more realistic due to calibration with system identification results from sensor measurements. The uncertainties resulting from deriving fragility relationships can be greatly reduced through the use of more reliable representation of hazard and more accurate structural models. Confidently, with seismic hazard from field measurements and fragility curves from more accurate models, NISRAF can significantly improve upon earthquake impact assessment results with higher reliability. In the subsequent sections, the methodologies and techniques utilized in each component will be discussed and then followed by the development and implementation of this integrated framework.

3 ADVANCED COMPONENTS UTILIZTED IN NISRAF

To achieve a seamless integration and to arrive at an operational and verified system, several components were used innovatively, tailored to perform the role required by NISRAF. The integrated system brings the advanced tools of earthquake hazard and structural reliability analyses into the context of societal requirement for accurate evaluation of the impact of earthquakes on the built environment.

3.1 Advanced hazard analysis

Owing to uncertainties from seismo-tectonic, earthquake energy attenuation and site conditions, it is difficult to estimate accurately the ground motion parameters. Many methods for seismic hazard analysis have been developed over the past decades, such as the Deterministic Seismic Hazard Analysis (DSHA) and Probabilistic Seismic Hazard Analysis (PSHA). Due to the probabilistic nature and the simple assumption for the local site effect, i.e. site coefficients F_a, F_v [6], uncertainties remain in the procedure and outcome. To reduce these uncertainties, an hazard characterization analysis component, including site response analysis is proposed.

As shown in Figure 3, this approach is composed of (i) seismic hazard analysis, (ii) synthetic ground motion generation, (iii) site response analysis, and (iv) hazard map generation. First of all, the natural records are directly investigated to evaluate the hazard characterization. Synthetic records of different hazard levels are then generated to evaluate the hazard as well as to provide various ground motions for further use in hybrid simulation and fragility curves derivation. Step-by-step procedure to generate synthetic ground motion with the advanced method is given below:

Step 1: At the beginning of the analysis, the user is prompted to define the seismic parameters (magnitude, distance, fault mechanism and site condition).

Step 2: User specified response spectra or spectra based on strong motion attenuation relationships (the Next Generation Attenuation (NGA) models [7], for example) and the predicted duration [8] are produced.

Step 3: Finally, synthetic ground motions for different hazard levels are generated through SIMQKE [9] based on the information defined previously.

Subsequently, both the natural and synthetic records are ready to be modified to reflect the local site effect. DEEPSOIL [10]—a 1-D site response analysis program—is implemented in NISRAF to conduct the site response analysis.

In addition to the hazard analysis, synthetic ground motion generation and site response analysis, the advanced hazard characterization method also provides a function to generate hazard map, which is the exposure of the impact assessment. To generate the hazard map, users are prompted to define the scenario events, the site conditions and the region of interest. The hazard map is then generated and shown on NISRAF.

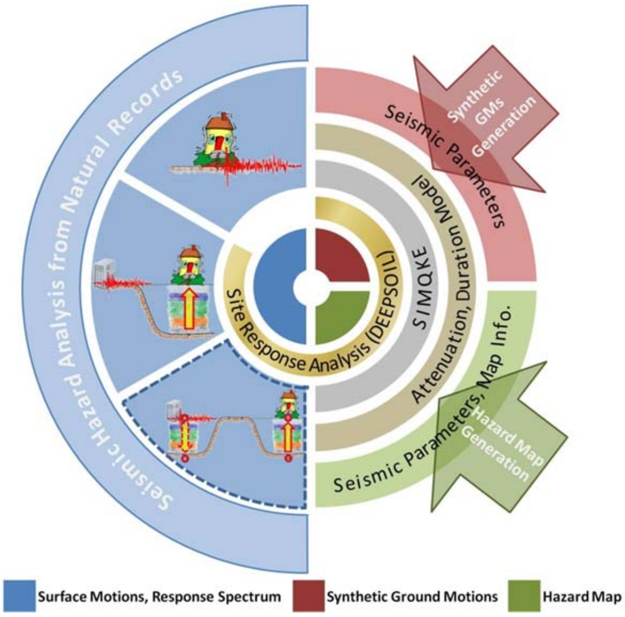

Figure 2: Methodology and procedures of the advanced hazard characterization analysis method

3.2 Efficient model calibration

Finite element model simulation provides a powerful way to understand the response of structures. Unfortunately, even well-constructed models may produce significant differences in some dynamic response predictions, in particular when the structure behaves nonlinearly. The difference is from the uncertainties of the material, boundary conditions and the contribution of the non-structural elements in the real structures. In order to overcome this drawback, a model calibration component based on the experimental or real response—which is composed of system identification and model updating techniques—is proposed. The following sections give an overview of these techniques.

System Identification

Among the many state-space based system identification methods, the Eigensystem Realization Algorithm (ERA) [11] is implemented in NISRAF due to its wide application and good performance in multi-input multi-output (MIMO) problems. The basic idea of ERA is to find a minimum realization of the system (a state-space representation with minimum dimensions) using the Singular Value Decomposition (SVD) on the Hankel matrix built by the Markov parameters (impulse response functions), so that the modal properties can be extracted from the realized minimum state-space representation.

A two-step strategy is applied to filter out computational and noise modes. Since more singular values are retained, more potentially genuine modes can be identified. In NISRAF, the dimension of the realized system N is increased until an adequate number of modes are included. For each particular order of a system, three commonly used mode accuracy indicators, namely Modal Amplitude Coherence (MAC) [11], Extended Modal Amplitude Coherence (EMAC), and Modal Phase Colinearity (MPC) [12] are used to filter out the computational or noise modes. The retained modes are then deemed trustable and a stabilization diagram is plotted for further confirmation. All modes—which are based on the idea that a genuine mode should always be identified with a different order of realized system, as long as the system order is adequate for that mode—are gathered in this diagram. Among the same order of modes identified and plotted in the stabilization diagram, the one with highest EMAC value is then selected as the confirmed mode.

Model Updating

Model updating aims to minimize the discrepancies between the numerical and real model by adjusting the stiffness and mass matrices. The objective function is formed as a linear combination of the natural frequency residuals and mode shape residuals, with different weighting factors for each residual.

$$F(x) = w_f \sum_{k=1}^{N_f} \left(\frac{f_{ak} - f_{ek}}{f_{ek}} \right)^2 + w_m \sum_{k=1}^{N_m} \frac{cos^{-1}(\sqrt{MAC_k})}{(\pi/2)} \tag{1}$$

f_{ak} and f_{ek} denote the analytical and experimental natural frequencies; w_f and w_m are weighting factors applied to the frequency residuals and mode shape residuals, respectively. *MAC* (Modal Assurance Criteria) is a measurement of mode shape discrepancy and is defined as [13].

$$MAC_i = \frac{(\emptyset_{ai}^T \emptyset_{ei})^2}{(\emptyset_{ai}^T \emptyset_{ai})(\emptyset_{ei}^T \emptyset_{ei})} \tag{2}$$

$\emptyset_{ai}$ and $\emptyset_{ei}$ are analytical and experimental mode shapes. *MAC* = 1 means $\emptyset_{ai}$ and $\emptyset_{ei}$ are perfectly matched; *MAC* = 0 means they are orthogonal. It is known that *MAC* is rather insensitive to the change of mode shape. It is also noted that the *MAC* is actually the square of the inner product between the two mode shape vectors. Therefore, the objective function for the mode shape residual is formed as the normalized angle between the two mode shape vectors, which are much more sensitive to the changes in the mode shape.

3.3 Advanced hybrid fragility analysis

Fragility, or vulnerability, presents the probability of reaching or exceeding a specific performance level under a specific seismic hazard. Fragility curves relate the effects of seismic hazard to the damage of the structures. Through the application of fragility curves, loss from earthquake hazard is estimated.

Generally, fragility curves are sub-divided into four categories based on data sources, namely empirical, judgmental, analytical, and hybrid fragility curves [14]. Empirical fragility curves are developed through field investigations after earthquakes—are the most realistic. However, this observation data is scarce and clustered in the low damaged range. Judgmental fragility curves are based on expert opinion, and are therefore subjective. Unlike the empirical and judgmental fragility curves, analytical fragility curves are more general, curves are allowed to be generated for different limit states and different structural types, although at a higher computation cost. Due to this limitation, most analytical fragility curves are generated either by simple models or by complicated models without calibration to the real structural response, which can result in uncertainties in these curves.

To reduce the uncertainties, a hybrid fragility analysis method is proposed. In this approach, hybrid simulation with critical element tested in the laboratory and the rest simulated in the calibrated finite element model is performed to evaluate the structural response. By scaling ground motions, several hybrid tests are conducted to reach the target structural response. The PGA of the scaled ground motion is then assumed as the mean PGA for the current limit state. Here, the target structural response is defined for different limit states, such as interstory drift angle of 0.7% for immediate occupancy limit state for steel moment frame building. With the mean PGA values and the dispersions from similar structures found in the literature, the fragility curves are generated based on the lognormal distribution assumption. Figure 3 illustrates the methodology and procedures of the proposed advanced hybrid fragility analysis method.

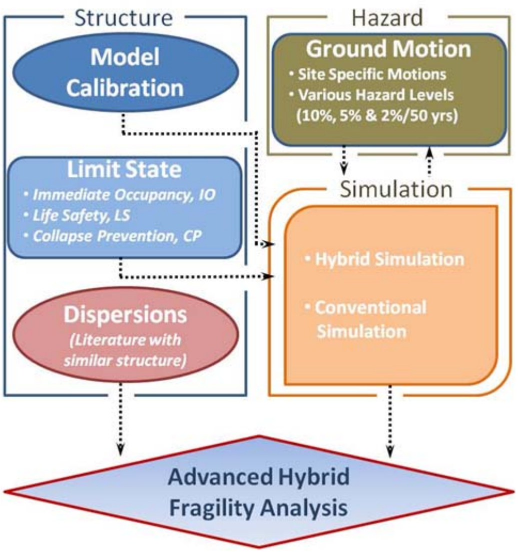

Figure 3: Methodology and procedures for the advanced hybrid fragility analysis

4 NEES INTEGRATED SEISMIC RISK ASSESSMENT FRAMEWORK

NISRAF, a software package with a graphical user interface (GUI) under the MATLAB environment has been developed for the purpose of making impact assessment more efficient and more reliable. Several components—instrumentation, advanced hazard characterization, system identification, model updating, hybrid simulation, advanced hybrid fragility analysis and impact assessment tools—have been implemented and tailored with novel methods to build the seamless, transparent and extensible framework. Figure 4 shows several components with GUI implemented in NISRAF.

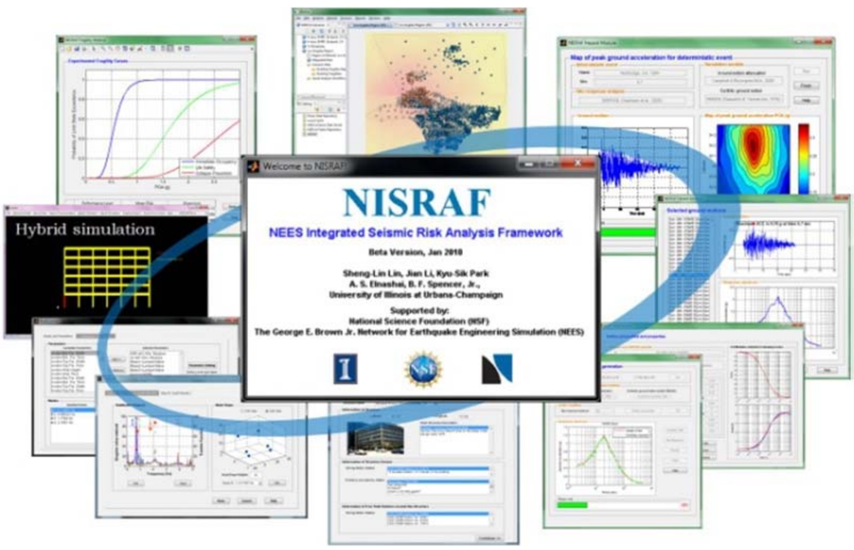

Figure 4: Components with GUI in NISRAF

Several advanced features contained in this integrated framework are given below:

1. *Open source software with friendly GUI:* In NISRAF, each component (module) is developed separately before being incorporated into the framework. Consequently, it is easy to understand and maintain. This software, as well as the source code, will be open to the public. The open source feature will allow NISRAF to be utilized efficiently, as well as improve its integrity and robustness.
2. *Extensible and accessible:* As mentioned previously, each component is developed and verified separately. Hence, it is extensible and accessible to any of the latest research findings and program techniques.
3. *Efficient and reliable impact assessment:* This is the first time that all the components for impact assessment are integrated and work seamlessly in just one software platform. Concurrently, the integrated feature brings the most advanced tools of earthquake hazard and structural reliability analyses into the context for accurate evaluation of impact assessment. Surely, with these seamlessly integrated advanced techniques, which provide a more accurate hazard and structural model and hence generate superb fragility curves, the assessment of earthquake impact will be more efficient and more reliable

As mentioned previously, this is the first time to integrate all components of earthquake impact assessment in one analysis platform. Through NISRAF, uncertainties from hazard and fragility can be reduced or managed efficiently; therefore the results from impact assessment can be more realistic and reliable. Meanwhile, NISRAF provides a chance for seismologists, geotechnical and structural earthquake engineers, structural control and impact assessment experts to ameliorate algorithms in order to bring out more confident assessment results. Through its extensible and accessible feature, the new or improved algorithm can be easily incorporated into NISRAF.

5 CASE STUDY

NISRAF has been successfully developed and demonstrated via a heavy-instrumented building in Burbank, California [15]. Earthquake impact assessment on a single building provides the possible damage and loss under scenario or historical earthquake events for this specific building. It indeed provides valuable information to reduce and mitigate losses in particular for the essential buildings, such as hospitals and schools. However, regional impact assessment—seismic losses for a region, especially urban area—is more valuable for decision-makers to develop emergency response and recovery planning. In this section, earthquake impact assessment in the Los Angeles area was carried out; comparison and uncertainty were also presented and discussed, respectively.

5.1 Introduction

Los Angeles, California—a high seismic urban region—was selected to demonstrate the regional impact assessment. Near one million inventory data exported from HAZUS-MH was used as the inventory input. The hazard map of PGA for the 1994 Northridge earthquake in the Los Angeles area and fragility relationships for all building types and code levels were fed into MAEviz to perform earthquake impact assessment. Reference was made to Lin [15] for more detailed information about the generation of the hazard map. Below, fragility relationships utilized in this application will be illustrated, followed by the discussion on the impact assessment result and uncertainty analysis in NISRAF.

5.2 Parameterized fragility method

A database contained fragility relationships for all building types is an essential ingredient of regional impact assessment. The proposed advanced hybrid fragility analysis provides an alternative method to derive more reliable fragility relationships. Definitely, this hybrid approach can be applied to any other building types to generate the related fragility curves. However, considerable time and effort are required. For the mid-rise steel moment resisting frame building in Los Angeles area, its fragility relationships have been generated in order to demonstrate fully the hybrid fragility analysis implemented in NISRAF [15]. Extension of the database for fragility relationships to other building types is underway. Currently, an alternative method to derive fragility relationships for other building types is the Parameterized Fragility Method, PFM [16]. In the following paragraphs, PFM will be reviewed first, followed by the derivation of fragility relationships for other building types using PFM.

Parameterized Fragility Method, an analytical fragility analysis approach, derives fragility curves through dynamic time history analysis on a single-degree-of-freedom (SDOF) model. It is, therefore, parameters corresponded with structure types and ground motions representative of site hazard characterization are essential for this methodology's use in regional impact assessment.

In HAZUS-MH, 36 building types (from W1: wood, light frame to MH: mobile homes) are defined [17]. Meanwhile, structural parameters (i.e. period, yield and ultimate strength) for 36 building types under 4 code levels (i.e. pre-code, low-code, moderate-code, and high-code) are tabulated. However, the majority of these parameters are based on engineers' opinions and experts' judgment. To be more realistic and reasonable, the latest research findings on structural capacity were incorporated. For example, parameters for wood frame and unreinforced masonry buildings were replaced according to the more comprehensive investigations [18, 19]. In addition, sets of ground motions specific for Los Angeles area were used as earthquake demand when performing dynamic time history analysis in PFM.

Consequently, fragility relationships for 36 building types under 4 code levels particularly for the Los Angeles area were generated based on structural parameters and specific ground motions.

5.3 Assessment results and comparison

The MAEviz interface depicted in Figure 5 presents the distribution of the direct economic building loss for the Los Angeles area in the 1994 Northridge earthquake, using the hazard map and fragility curves generated by NISRAF. The mean total loss was 20.7 billion dollars. Table 1 provides a comparison of the direct economic building loss of the study area between NISRAF and observed data. In this table, Lower_B. and Upper_B. stand for Lower Bound and Upper Bound, respectively. In general, results of Lower_B. and Mean NISRAF loss provide bounding values of the observed loss. Therefore, NISRAF predicted reasonable accurate and modestly conservative assessment results for the Los Angeles area in the 1994 Northridge earthquake.

Table 1: Direct economic building loss (Los Angeles county under the 1994 Northridge earthquake)

	Observed*	NISRAF		
		Lower_B.	Mean	Upper_B.
Dollar in Millions	18,500	17,938	20,706	23,474
Difference (%)	0.00	-3.13	10.65	26.89

**[20]*

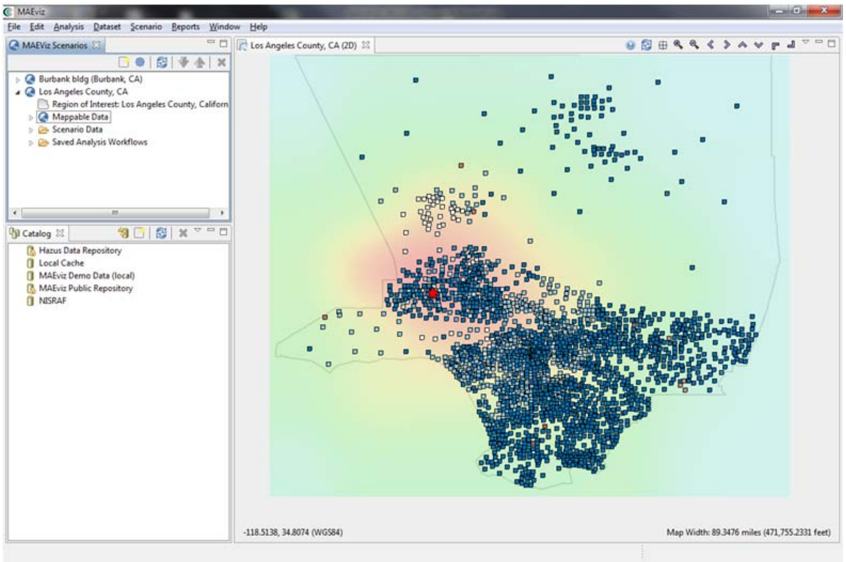

Figure 5: Earthquake impact assessment in Los Angeles area

5.4 Uncertainty analysis

Earthquake impact assessment is essential for disaster planning as well as developing risk reduction policies and emergency responses. As mentioned previously, an impact assessment package is composed of seismic hazard, fragility function, and inventory data. Mathematically, the loss estimation can be described by the following equation [21]:

$$P[Loss] = \sum_{s}\sum_{LS}\sum_{d} P[Loss|D = d] \cdot P[D = d|LS] \cdot P[LS|IM = s] \cdot P[IM = s] \qquad (3)$$

where $P[\blacksquare]$ is the probability of loss (direct or indirect loss from the earthquake events), IM is the intensity measure of the seismic hazard (PGA or S_a), and s is the realization of the intensity measure. $P[LS|IM = s]$ is the conditional probability of reaching or exceeding structural limit states, and $P[D = d|LS]$ is the conditional probability of reaching damage. Here the term $P[LS|IM = s]$ refers to fragility or vulnerability discussed in previous section.

Due to the random nature and limited knowledge in earthquake engineering, numerous assumptions are made and many approximated methods are applied when performing impact assessment. Therefore, various types (aleatory and epistemic) of uncertainties exist in earthquake impact assessment, for example, the prediction of seismic intensity, the generation of fragility functions, the assumption of distribution of damage ratio, the inventory uncertainties and others. With additional investigation and knowledge, it is definitely possible to reduce the epistemic uncertainties, such as by providing more realistic seismic hazard characterization, more reliable fragility relationships generated through NISRAF, and more accurate inventory data. Nevertheless, uncertainties are unavoidable, particularly in the case of aleatory uncertainties (randomness).

One advanced feature of MAEviz that distinguishes it from HAZUS-MH is its uncertainty quantification analysis, which not only provides users with the mean value of the predicted losses, but also the uncertainty information (the standard deviation values). With this contribution of uncertainty analysis in MAEviz, NISRAF—to be consistent with its user-friendly feature—presents the uncertainties through an intuitive and friendly interface [15], as shown in Figure 6. Through this intuitive interface, a pie-chart of different losses (i.e. structural, non-structural, and contents) is presented. Also, losses with upper-bound and lower-bound vary with the different confidence level which was selected by the users.

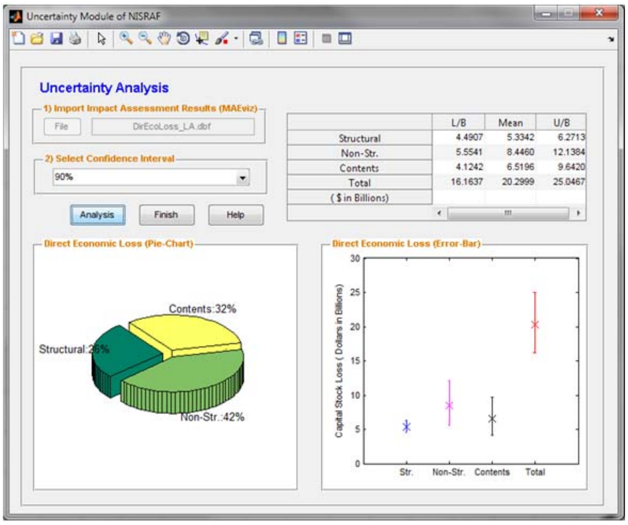

Figure 6: Uncertainty qualification analysis in NISRAF

The actual test bed in California, the regional impact assessment in the Los Angeles area, was carried out to demonstrate the integrated framework as well as its components. This example demonstrated not only the seamlessly-integrated, extensible, and transparent framework, but also that all the elements required for impact assessment can be performed under just one software platform. Consequently, the reasonable accurate, although conservative impact assessment results confirmed one of the advanced features of NISRAF, which is more efficient and more reliable impact assessment. Meanwhile, the implemented approximate uncertainty quantification analysis can assist decision-makers to judge the losses easily and quickly, which will contribute to the development of more suitable and more confident recovery plans and emergency responses.

6 CONCLUSIONS

NISRAF is intended to serve as a user-friendly software platform through which impact assessment can be efficiently and reliably performed by combining hazard (exposure) and fragility (sensitivity), to provide assessment of impact on the built environment at the regional scale. Concurrently, it is intended to extend the state-of-the-art hybrid simulation approach to fragility analysis, and propose refined methods for hazard characterization and model calibration. The successful completion of the development of the framework and verification of its components demonstrates that these objectives have been achieved. In addition, the application of NISRAF will be a stimulus for cooperation between not only for geotechnical and structural earthquake engineers, and impact assessment experts, but also for seismologists and structural control researchers improving their algorithms in order to pursue the ultimate goal of accurate and reliable earthquake impact assessment.

ACKNOWLEDGEMENTS

This research was supported by National Science Foundation, Grant Number 0724172 (NEES Simulation Development), Dr. Joy M. Pauschke, Program Director.

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