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INSPECT-PBEE: A performance-based earthquake engineering GUI for IDARC-2D



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ABSTRACT

Designs that are performance and functionality driven typically mandate the nonlinear analysis. Up To date, nonlinear analysis remains a sophisticated tool that may not appeal to majority of structural/earthquake practicing engineers due to the required effort, time and its iterative nature. There are several available commercial and research-oriented packages that perform nonlinear analyses. IDARC-2D is one of the powerful and freely available tools for nonlinear analyses. This paper presents INSPECT-PBEE which is a software pre/post processor package developed to facilitate the use of IDARC-2D program and automates the seismic performance evaluation of structures. It operates in two modes; a pre-processor and a post-processor, developed using C# programming language and .Net libraries. The pre-processor package simplifies the nonlinear modeling process on IDARC-2D using its useful Graphical User Interface (GUI). The post-processor component provides a powerful tool that automates the seismic performance assessment of structures using inelastic dynamic analyses. Furthermore, it has two options for evaluating the seismic performance, either user-specified criteria or following the well-established procedure described in the FEMA P695 document.

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Code metadata

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Legal Code License	BSD3-ClauseLicense
Code versioning system used	git
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If available Link to developer documentation/manual	N/A
Support email for questions	malhamaydeh@aus.edu

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Computing platforms/Operating Systems	Windows OS.
Installation requirements & dependencies	.Net Framework v4.5.1
If available, link to user manual – if formally published include a reference to the publication in the reference list	N/A
Support email for questions	malhamaydeh@aus.edu

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1. Motivation and significance

The seismic performance of structures can be estimated using several performance assessment techniques. In general, these techniques are based on analyses that account for both geometric

and materials nonlinearities such as pseudo-static pushover analysis, response history analysis and Incremental Dynamic Analysis (IDA). Seismic performance evaluation provides a profound insight into the behavior of structures during earthquake excitations. It is a very powerful method in highlighting the possible structural design deficiencies and the expected failure mechanisms due to seismic loads. Assessing the seismic performance of existing structures helps in establishing the required rehabilitation techniques to enhance the performance and meet the preset design objectives. On the other hand, investigating the seismic performance of new proposed designs will allow implementing the proper measures to satisfy the performance objectives at early stages of a performance-driven design. Seismic performance evaluation of new and existing structures is an essential part of Performance-Based Earthquake Engineering (PBEE). PBEE aims at designing structures that are capable of demonstrating anticipated desirable performance objectives, in contrast to the conventional approach of designing structures to strictly satisfy the codes' requirements. The process of PBEE relies on accurate prediction of seismic capacities and demands. It utilizes the pre-defined performance objectives which combines the damage or performance limit states with the seismic hazard level. Incorporating PBEE, it is possible to make decisions concerning the choice of structural systems and detailing levels based on life-cycle performance and cost analysis [1–7].

The seismic capacity of structures is usually estimated using either nonlinear static procedures (e.g. pushover analysis) or nonlinear dynamic procedures (e.g. IDA). In pushover analysis, the structure's capacity is established by applying lateral displacements or forces with a vertical distribution pattern on the structure. This capacity backbone relationship is generally independent of any seismic demand and can be used to assess the structure's performance against the set performance objectives [8]. In the dynamic procedures, the seismic capacity is commonly estimated using IDA. IDA is a very powerful dynamic analysis method which gives a better estimate of the structure capacity when subjected to earthquake ground motions. Furthermore, it traces the behavior of the structure under seismic loading starting from the elastic range to the formation of plastic hinges and finally to the collapse of the structure as the ground motion intensity is increased [9]. IDA is performed by applying a suite of multiply-scaled ground motion records on the structure until collapse occurs. The increase in intensity measure of ground motions is achieved using multiple scale factors with small increments. IDA is considered similar to dynamic pushover which provides enhanced details about the structural behavior compared to the conventional static pushover. In addition, it shows the sensitivity of expected structural response to changes in ground motions intensity and allows for evaluation of the seismic performance using the fragility curves [3,9,10].

Investigating the seismic performance of structures using IDA might be considered unreasonable and costly to many practicing engineers and some researchers. This is generally due to the time and computational effort required in the entire process, starting from selecting representative earthquake ground motions, scaling the ground motion records, performing significant number of dynamic analyses and processing the results. Finally, these results are used to establish IDA and fragility curves that will aid in assessing the seismic performance. Adding to the complexity, if the performance is found unsatisfactory the entire process will have to be repeated after making the necessary adjustments to the design and/or modeling.

Inelastic Seismic Performance Evaluation Computational Tool for Performance Based Earthquake Engineering (INSPECT-PBEE) is a program intended to generally facilitate the use of IDARC-2D [11]. INSPECT-PBEE is a major upgrade to INSPECT [12], which aims at facilitating and automating the PBEE evaluation of structures from the creation of the nonlinear analysis model to generation of all

plots needed to investigate the performance. INSPECT-PBEE is designed to simplify the entire process of seismic performance evaluation. It operates in three modes: Pre-Processor, Post-Processor or Open Plot File. First mode facilitates the creation of nonlinear analysis models on IDARC-2D [11] using the user-friendly pre-processor Graphical-User Interface (GUI). Furthermore, it allows using individual runs (e.g. pushover analysis or single inelastic dynamic analysis) to perform seismic performance investigations. The second mode allows the users who have existing IDARC-2D models to perform nonlinear analysis and assess the seismic performance of structures. The post-processor mode in INSPECT-PBEE automates the analysis and processing of results that would otherwise have to be performed manually by the user. The third mode allows re-opening of previously run projects. INSPECT-PBEE would be found useful and appealing to structural/earthquake engineering students, researchers and practitioners alike. Unlike similar existing software packages (e.g. Opensees [13], SeismoStruct [14], etc.) INSPECT-PBEE second (Post-Processor) mode provides a comprehensive tool for assessment and quantification of the seismic performance of structures based on FEMA P695 [15] methodology. The Post-Processor mode does not only perform IDA, but also has the option, within a few clicks, to perform a complete seismic performance assessment following the detailed procedure of FEMA P695 [15]. The reader is referred to the previous version of INSPECT-PBEE (i.e. INSPECT) [12], for more details. Below, is a brief summary of the major INSPECT-PBEE features which allow it to stand out from the crowd, with respect to its predecessor (INSPECT) and other software packages:

- (1) Streamlines and automates the, otherwise extremely cumbersome and labor-intensive, PBEE iterative design process.
- (2) Allows users to strictly implement the FEMA P695 seismic performance assessment procedure, for new structural systems (undefined in building codes).
- (3) Offers superior computational performance enhancements through automatic multiple core parallelization of simultaneous IDARC-2D instances.
- (4) Achieves substantial speed-up by automatically allocating computation resources and suppressing all popping IDARC-2D instances' black windows.
- (5) Provides full user access to monitoring and controlling of the analysis process through the "Execution Monitor", which allows the user to:
 - (a) Monitor the analysis progress in real-time for all individual processes.
 - (b) Notifies the user if the requested number of runs exceeds the computational resources (RAM, etc.) of the computer running the IDA.
 - (c) Allows pausing, resuming and stopping the analysis at any point for inspection of individual IDARC-2D instances' input/output files.
 - (d) Supports making real-time changes to input files and re-run any particular instance of IDARC-2D, if needed.
- (6) Supports importing multiple formats of ground motion records.
- (7) Offers normalization and scaling of ground motion records to any seismic hazard level.
- (8) Utilizes the state-of-the-art "maximum likelihood" approach in developing the fragility curves.
- (9) Automatically performs two-dimensional interpolation for FEMA P695 uncertainty parameters' tables.
- (10) Supports convenient multi-session operation through "save" and "load" capabilities throughout the model creation steps.

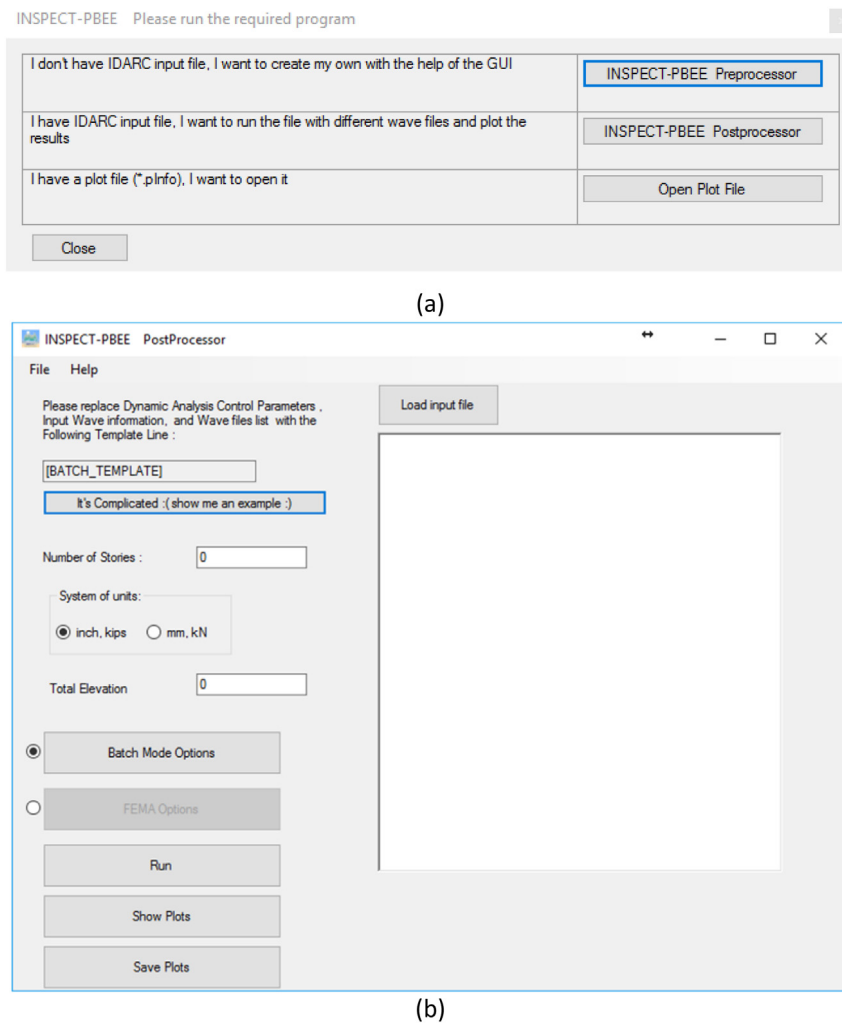


Fig. 1. (a) INSPECT-PBEE start options; (b) INSPECT-PBEE post-processor GUI.

- (11) Saves tremendous and cumbersome debugging by automatically performing critical compatibility checks on input parameters and analysis parameters.
- (12) Exports all results in multiple formats (tabulated numerical values as well as images of plotted responses).
- (13) Includes the option to “save” and “load” the final fragility results for future reference without the need for re-running any analyses.
- (14) Reports the fitted fragility curves for use any other scientific computing environment (e.g. MATLAB, EXCEL, etc.).
- (15) Exports the entire project folder (with sub-folders) for archiving purposes.
- (16) Clears the entire project folder (with sub-folders) for starting new projects' folders.

2. Software description

As previously mentioned, INSPECT-PBEE can operate in one of three modes: (1) Pre-Processor mode, (2) Post-Processor mode, (3) Open a Plot File for a previously run project. The Pre-Processor mode is similar to the original INSPECT software [12], and it provides a user-friendly GUI. It simplifies the creation of nonlinear analysis numerical models for IDARC-2D. This mode is useful for users who do not have pre-created IDARC-2D models and prefer to deal with a GUI. On the other hand, the Post-Processor mode is essentially for users who have existing IDARC-2D models and

would like to automate the IDA and seismic performance evaluation processes. It is worth mentioning that, starting from the pre-processor mode the users can continue and use the created model to perform seismic assessment of the structure (i.e. seamlessly transition from the pre-processor into the post-processor). The following subsections present the features provided by INSPECT-PBEE pre- and post-processor modes. Fig. 1(a) shows INSPECT-PBEE start up window. It can be seen that user is given the following three options: (1) to start the pre-processor, (2) to start the post-processor or (3) to open a plot file from a previously completed session.

2.1. Pre-processor features

Inelastic Damage Analysis of Reinforced Concrete (IDARC-2D) [11], is a software developed to analyze and evaluate the performance of reinforced concrete buildings and frames. Modeling in IDARC-2D requires generating a text file with the building information, material properties, structural elements types and analysis options. Detailed explanation of the input text file creation is provided in the user's manual of the program. This method of data input has a few advantages such as the small size of the file, ease of portability, and ease of access and modification. The disadvantages of this method, however, dwarf the advantages. The first major disadvantage is the inability to run multiple cases simultaneously, and the second is the difficulty to detect and correct inadvertent input

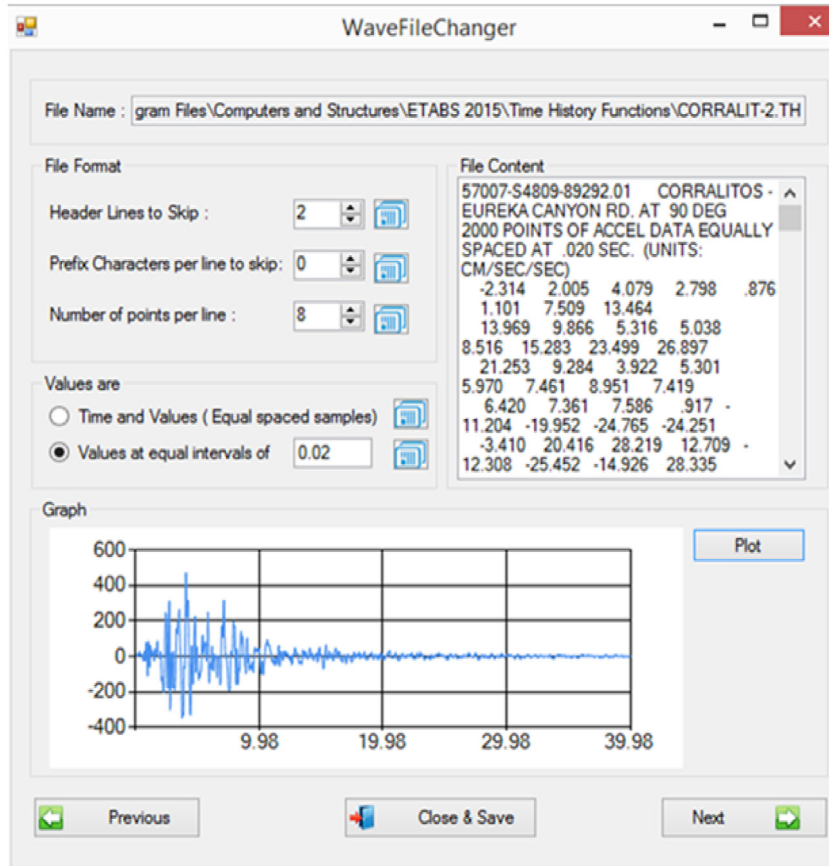


Fig. 2. “WaveFileChanger” interface.

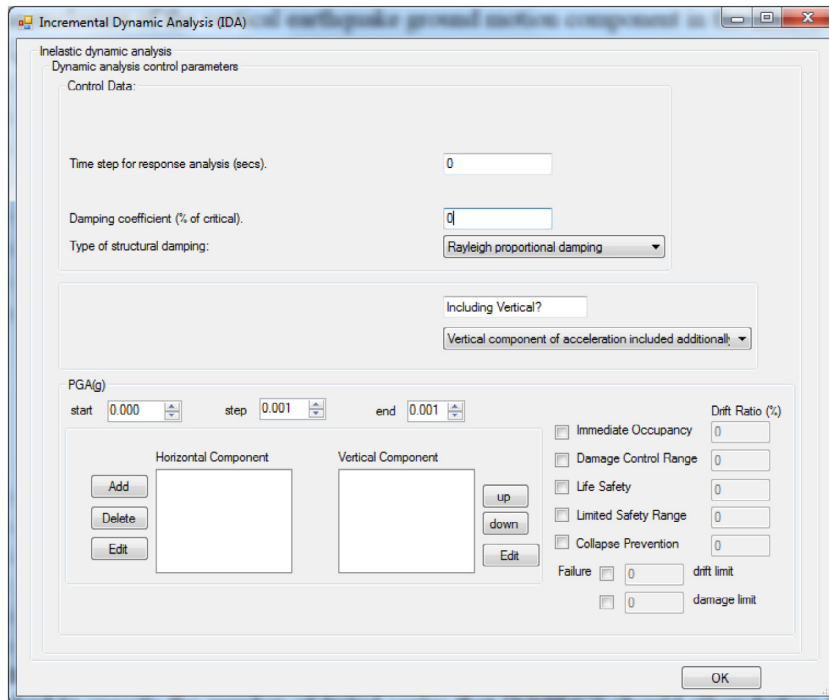


Fig. 3. Batch mode options dynamic analysis control parameters.

mistakes. Inadvertent input mistakes could prevent the program from running, or worse, give erroneous results. These inadvertent mistakes include whitespaces, and invalid or insufficient parameters, etc. Whitespaces are basically blank lines left with or without notice from the user. Invalid parameters could be those outside the limits necessary for the program's function. In other cases, invalid parameters could be using numbers other than integers for column types or number of floors, etc. If a user were to define the number of stories and mistakenly input more or less floor elevations or nodal weights than predetermined, the program would fail to run, and the user would have no idea why. Having a GUI capable of detecting these kinds of errors would prove to be very helpful for new and experienced users alike. More details about the features of the pre-processor mode and its GUI can be found in the previous version (INSPECT) [12].

2.2. Post-processor features

The post-processor mode can be used with existing IDARC-2D models or can build on the files generated using the pre-processor GUI. It is an attractive tool that can be utilized to perform IDA and evaluate the seismic performance of structures. INSPECT-PBEE post-processor mode is developed to ease the IDA process using IDARC-2D and simplify the post processing of results. Fig. 1(b) shows INSPECT-PBEE post-processor GUI.

INSPECT-PBEE post-processor gives flexibility in choosing the seismic performance evaluation criteria. As shown in Fig. 1(b), the criteria can either be user-specified criteria (batch mode options) or it can adopt the FEMA P695 collapse evaluation methodology (FEMA options) [15]. FEMA P695 is a well-established and well-known methodology that is extensively used in seismic performance investigation and quantification (e.g. [3,16,17]).

2.2.1. Generic/user-defined performance criteria (batch mode options)

The batch mode options are developed to provide the user with flexibility in investigating the seismic performance of structures using any specific criteria. It allows the user to perform IDA using any pre-existing earthquake ground motions or a generic white noise earthquake record that can be generated by IDARC-2D. Additionally, the user can choose to scale the time history records using any preferred procedures. The pre-existing record could be specified through a “wave” text file. The used earthquake record can be in single or multi columns of ground accelerations to be run in IDARC-2D. However, many earthquake ground motion records are in free formats since they could be obtained from different earthquake databases. The most common formats are:

(a) Coupled values {time (typically in seconds), ground acceleration (typically in g's)}.

(b) Ground accelerations reported at a fixed time step {ground acceleration (typically in g's)}.

Both of these formats could contain single or multi column(s) of ground accelerations. Additionally, the earthquake record file may contain some commentary header line(s) for description, etc. Thus, INSPECT-PBEE developers, programmed a user-friendly interface “WaveFileChanger”, to convert the commonly found formats into the necessary format required by IDARC-2D to run, i.e. ground acceleration data points in single/multiple column(s). The user can define the number of header lines (if any) to skip from the original record file, the number of prefix characters (if any) to skip per line and the number of data points to be read per line. Furthermore, the time-history of the earthquake record could also be plotted from within INSPECT-PBEE for quick and easy user inspection, as illustrated in Fig. 2.

Furthermore, INSPECT-PBEE batch mode options allow the user to have full control over the dynamic analysis parameters needed

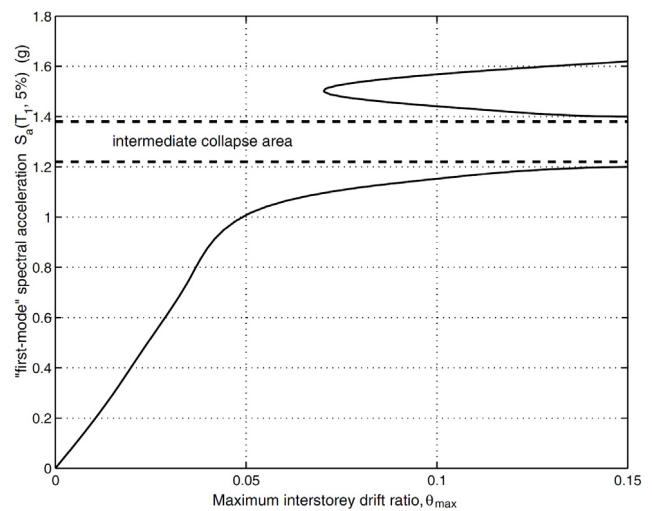


Fig. 4. Structural resurrection on the IDA curve, adapted from [9].

in the IDARC-2D model. Fig. 3 highlights the several input parameters needed to perform IDA using the batch mode. As shown in Fig. 3, the user has the option to specify the analysis time step, damping coefficient and type of structural damping. It is generally recommended to use an analysis time step small enough to ensure the accuracy and stability of the numerical simulation. It also allows for the inclusion of the vertical earthquake ground motion component in the IDA. The user can simply include the vertical component of ground motions and read their time-history files using the “WaveFileChanger” features described earlier. The records intensity measure in INSPECT-PBEE is Peak Ground Acceleration (PGA). This is chosen as it is compatible with IDARC-2D requirements and will leave the user with increased flexibility. The user can specify the start, increments and end of PGAs to be used in the IDA.

Finally, the drift ratio (%) limit can be specified at all the damage/performance limit states according to the criteria adapted by the user, such as ASCE41-13 [18]. Once all dynamic analysis control parameters are input, the analysis process can be initiated using the “RUN” button. Before starting the analysis, the user will be asked to specify the number of failed scale factors that shall be permitted before force-terminating the analysis of that particular ground motion record. This option gives the user a great opportunity to save a lot of time that would be unnecessarily spent in trying to run the analysis for records at higher scale factors. This feature can be utilized in two scenarios. First, if the user is aware of the boundaries of the problem in hand, a small figure could be specified for the number of failed scale factors before force-terminating the earthquake record. This way, the program will force-terminate any higher scales for the failing record and hence saves a lot of time for the user.

Second, if boundaries are not well-known, it might be useful to specify a very large number for the allowed failed scale factors. This is necessary to capture any band sensitivity and/or weaving and structural resurrection response in the IDA as shown in Fig. 4.

Once the IDA increments are specified, INSPECT-PBEE will quickly check the number of specified runs to complete the analysis. If the number of requested runs is very large that windows cannot allocate memory to create a sufficient window to control all those runs, the process will not be initiated. Instead of crashing during the analysis and wasting the time and effort, the software will show a warning message indicating that the execution monitor cannot be created and total number of runs should be decreased. The warning message can be seen in Fig. 5. This is an

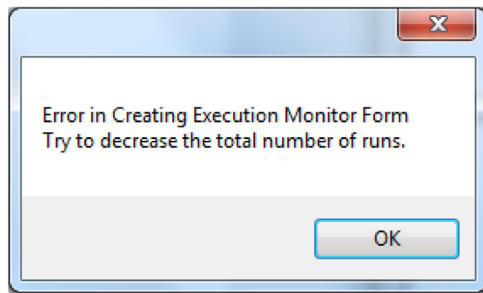


Fig. 5. Large number of runs warning message.

extremely useful tool that adapts to the individual specifications of the machine used to run the simulations.

If the number of requested runs can be handled by windows, the analysis will start in the single control window which is the “Execution Monitor” of INSPECT-PBEE. The “Execution Monitor”, shown in Fig. 6, provides the user with several features that are very useful when performing IDA.

It has a color-coded graphical interface, gray for pending runs, pink for running, green for successful completion, red for failed runs and dark red for force-failed runs. Right-clicking on any of the run boxes, allows the user to open the working folder for that run. The user may reduce the time step for the analysis and reinitiate the simulation run. Once the analysis is complete, the “Execution Monitor” can be closed and all performance plots and results summary will be shown. All input and output files used and resulting from the analysis can be exported and saved in any directory specified by the user. The user may choose to clear all the run files from INSPECT-PBEE working directory to avoid any accidental use of results from previous analyses. However, the software will automatically clear all the files in its directory when asked to make a new run with different IDA parameters. In the plots window, the user can export all summary of results, save plots as images and export plots data. As illustrated in Fig. 7, INSPECT-PBEE provides a summary of the most important response output parameters needed in the seismic performance evaluation (i.e. maximum story shear, maximum drift ratio, maximum story drift and total damage index). It also provides summary of probabilities of collapse or exceeding the specified damage states.

Sample peak response plots produced by INSPECT-PBEE are shown in Fig. 8. Additionally, INSPECT-PBEE provides profile plots (i.e. any response output parameter versus building stories) for all ground motion records at all analysis increments such as those presented in Fig. 9. In addition to the peak response plots and profile plots, INSPECT-PBEE provides the user with both observed (analytical) and fitted collapse fragility curves. It gives the user several options to specify failure/collapse criteria. Those options are: exceeding a certain drift ratio, exceeding a specified damage index or when IDARC-2D analysis is terminated due to numerical convergence issues. If the user did not specify any of these limits, the INSPECT-PBEE software assumes a default values of 10% for the drift ratio and 3 for the damage index.

INSPECT-PBEE adopts the maximum likelihood method for estimating the collapse fragility function parameters and fitting the collapse fragility curves [19]. It provides fragility curves for all the damage states required and as specified by the user. Additionally, it shows the fitted curves with the observed points on the same plot. Fig. 10 shows sample observed and fitted fragility curves generated by INSPECT-PBEE using the maximum likelihood method.

2.2.2. FEMA P695 performance criteria

FEMA P695 methodology standardizes the process of seismic performance evaluation of structures, since it has clear and well-documented guidelines. In INSPECT-PBEE, the second option for

seismic performance evaluation fully adopts and automates FEMA P695 methodology for seismic collapse evaluation of structures. The first step in the performance evaluation methodology is choosing the analysis software and the creation of nonlinear analysis models. All nonlinear models can be produced using INSPECT-PBEE pre-processor GUI. Once the models are created, the next step would be the selection and scaling of the ground motions that will be used in performing the IDA. FEMA P695 utilizes two sets of ground motion records taken from PEER NGA database [20]. The two record sets implemented in FEMA P695 methodology are classified according to their epicenter distance to far-field and near-field sets. The reason for this classification is to investigate the collapse fragility sensitivity to directionality and pulse effects. After selecting the ground motion records set, the records must be scaled up since most available records are not strong enough to cause failure in modern structures. The scaling process consists of two steps; normalization and scaling. First, all records are normalized using their Peak Ground Velocity (PGV) which is the geometric mean of the two horizontal components PGVs. Then, all normalized records are scaled up using a single scaling factor to ensure that 50% of the scaled records cause the structure to collapse. The scaling method implemented in FEMA P695 is equivalent to the scaling procedure of ASCE7-10 [21]. FEMA P695 scales the records such that the median spectral acceleration of the records match the MCE-level spectral acceleration at the fundamental period of the structure. While the ASCE7-10 scaling method matches the spectral accelerations of the records to the MCE demand over a range of time periods.

The IDA is then performed using the scaled records. The intensity of each ground motion is incrementally increased until the structure reaches collapse, as per the user specified criteria. The maximum story drift at each increment is extracted and the IDA (maximum story drift ratio versus intensity measure) curves are plotted. Using the IDA results, the median collapse intensity (\hat{S}_{CT}) is estimated as the spectral acceleration at which half of the records used (i.e. 22 records for Far-Field set and 28 records for Near-Field set) causes the structure to collapse. Then the corresponding MCE spectral acceleration, 5% damped, at the structure’s fundamental period is calculated (S_{MT}). Subsequently, the Collapse Margin Ratio (CMR) is determined as the ratio between \hat{S}_{CT} and S_{MT} . The CMR is then adjusted to account for the frequency content (spectral shape) of the records and the elongation of the structure’s fundamental period due to damage before collapse. This is incorporated indirectly using Spectral Shape Factors (SSF) rather than choosing the analysis ground motion records based on the fundamental period of each structure. Furthermore, the IDA results shall account for the different sources of uncertainties which are: record-to-record uncertainty, design requirements related uncertainty, test data uncertainty and nonlinear modeling uncertainty.

Once IDA results are modified to consider the total uncertainty, the calculated CMR is then adjusted to account for the spectral shape of the records used in the analysis. The Adjusted Collapse Margin Ratio (ACMR) is obtained by multiplying the CMR by SSF (i.e. $ACMR = SSF * CMR$). ACMR is an essential factor in evaluating the collapse safety and expected seismic performance of structures. FEMA P695 provides values in Table 7–3 for acceptable ACMRs. The values depend on the total system collapse uncertainty (β_{TOT}) and the allowed probability of collapse at MCE level. Higher total system uncertainty and lower collapse probability increases allowable ACMRs. For any structural system to have an acceptable performance, the calculated ACMR should be higher than acceptable ACMR for 20% collapse probability. This means that the system should have a probability of collapse at the MCE spectral accelerations level that is less than 20%.

In INSPECT-PBEE this entire detailed and extensive process of collapse safety and seismic performance evaluation using FEMA

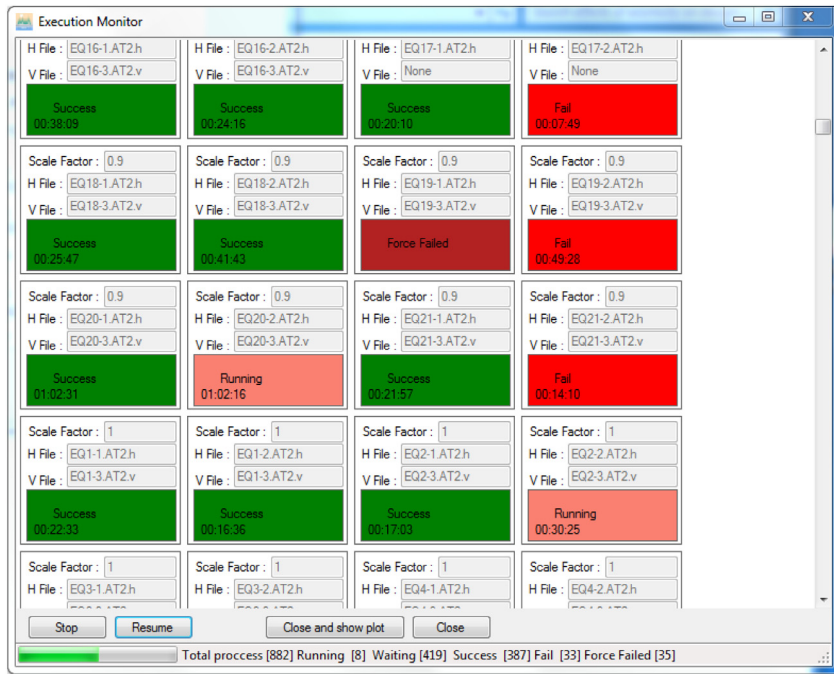


Fig. 6. “Execution Monitor” in INSPECT-PBEE . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

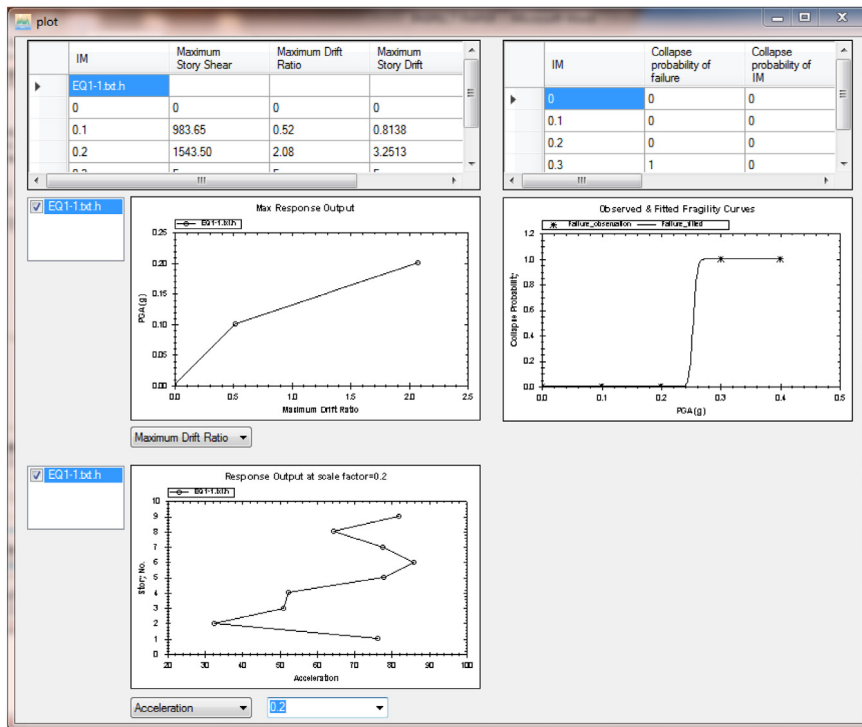


Fig. 7. Batch mode options output and results summary.

P695 methodology is automated. To start with, the software database includes both sets of records (i.e. Far-Field and Near-Field) and allows the user to easily choose one complete set of records, any single record or include both sets in the analysis. Once the FEMA option is selected from INSPECT-PBEE post-processor main window, the user is taken to several windows to specify the problem parameters and specifics. First, the dynamic analysis parameters should be specified as presented in Fig. 11(a). In this window, the user can control the analysis time step which should

be as recommended previously in Section 2.2.1. Additionally, the damping ratio (% of critical), type of structural damping, vertical component and intensity measure increments are specified in this window.

The next window, shown in Fig. 11(b), will allow the user to specify the uncertainty parameters corresponding to quality rating of design requirements, quality rating of test data and quality rating of the index archetype models. The uncertainty parameters are used to calculate the total system collapse uncertainty which

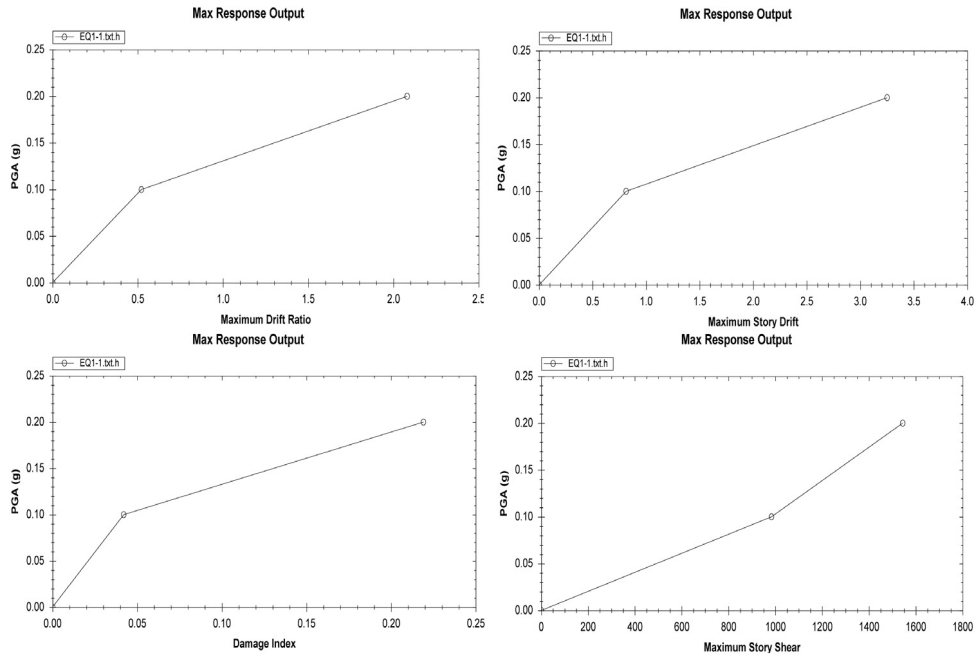


Fig. 8. Sample peak response plots.

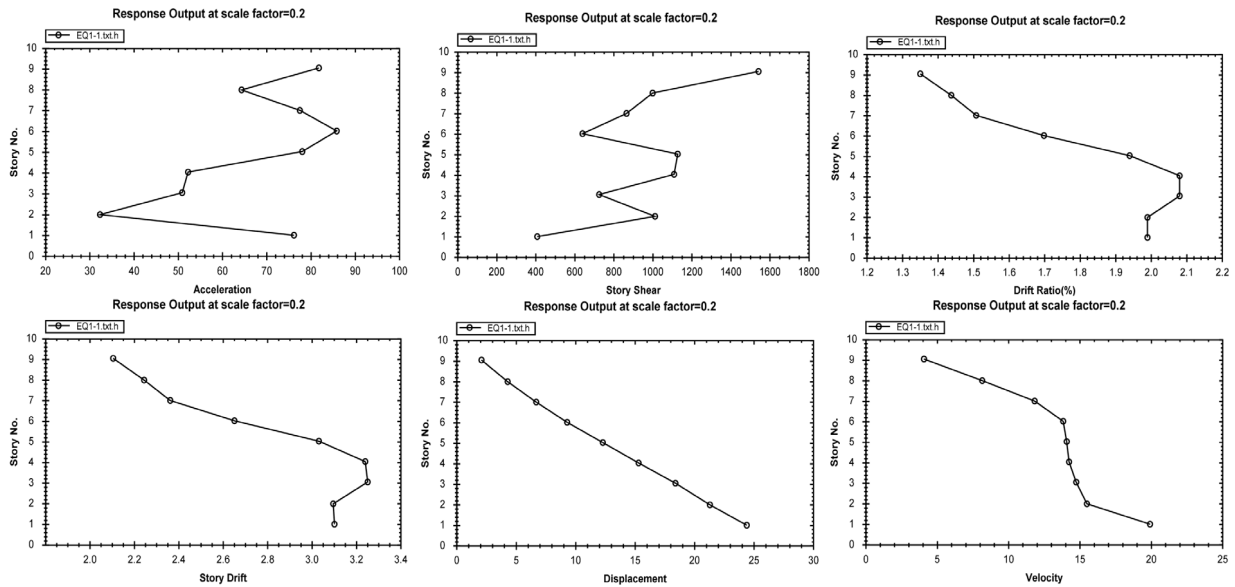


Fig. 9. Sample profile plots.

is used in scaling the records, adjusting collapse fragility curves and estimating the acceptable ACMR for the structural system. Furthermore, it also permits the user to specify the drift ratios for the different damage states to be considered in the collapse fragility analysis. It should be noted that INSPECT-PBEE FEMA options allow the user to specify the failure/collapse limits similar to the batch mode options described in Section 2.2.1. Additionally, in Fig. 11(b) the user chooses the Seismic Design Category (SDC) as per FEMA ranges. The SDC is necessary for scaling the records and calculating the fundamental time period of the structure. Furthermore, the system ductility should be specified by the user and will be used in evaluating the SSF to account for the records frequency content. Hints for calculating the period-based ductility according to FEMA P695 is given when the user clicks on the question mark next to the entry box, as shown in Fig. 11(c).

After inputting all parameters, the next step, illustrated in Fig. 12, is to select the values to be used in calculating the approximate period of the structure and then choose the records set for the IDA. Once the records set is chosen, the user is allowed to decide which records to be included in the analysis. At this stage, all parameters required for the FEMA P695 methodology have been input by the user. With a single click on the run button, the seismic performance of the structure will be investigated in accordance with FEMA P695 collapse safety evaluation procedures. As explained, the procedure is systematic and well-documented. However, INSPECT-PBEE gives the users a great opportunity for complete automation of the process which makes it approachable and attractive for most users. It will internally execute the process from scaling of earthquake ground motions to summarizing all

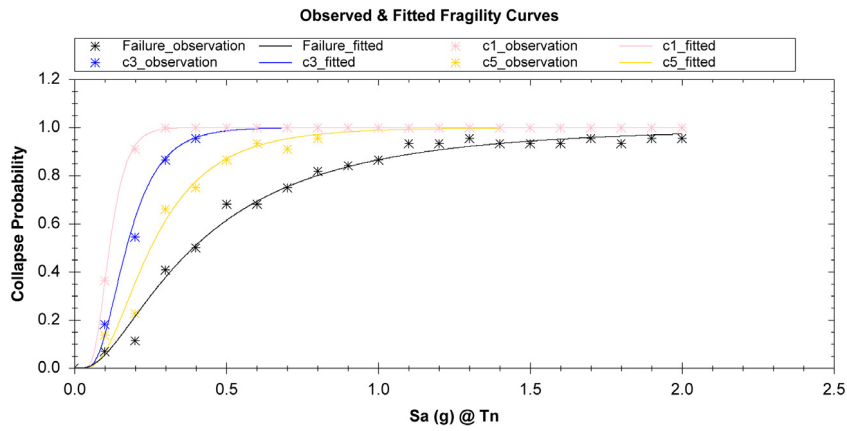


Fig. 10. Observed and fitted fragility curves.

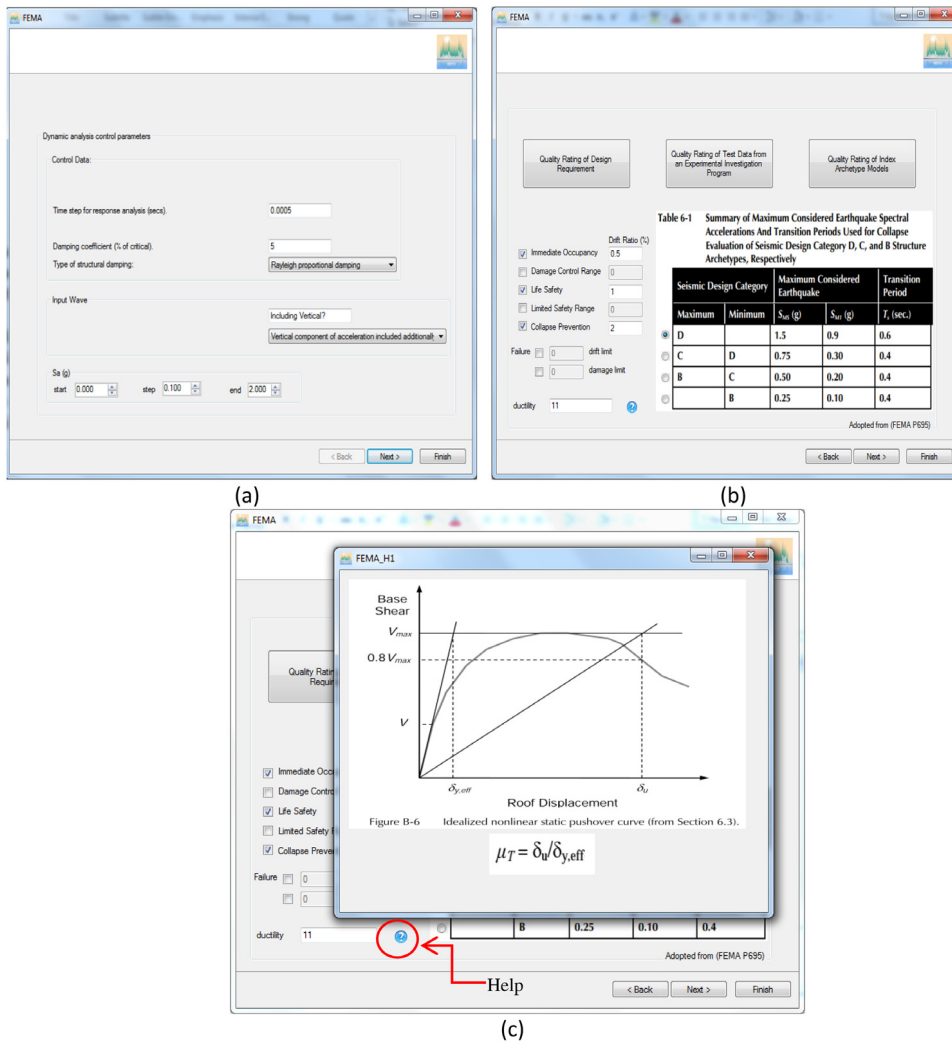


Fig. 11. FEMA options: (a) Dynamic analysis parameters; (b) Uncertainty and fragility input parameters; (c) Hints for period-based ductility calculations.

the results, fragility analysis and evaluating the seismic performance. Usually, the scaling step in seismic performance investigation of structures is very crucial. It often requires the structural/earthquake engineers to seek assistance from geotechnical engineers to filter and scale earthquake ground motions to match a target response spectrum.

Using INSPECT-PBEE, the scaling is done internally using a well-established standard (i.e. FEMA P695). The IDA is performed using IDARC-2D and peak response parameters are extracted and summarized in tables and plots, as explained earlier in the batch mode options (Section 2.2.1). Furthermore, all FEMA parameters which require interpolation, such as acceptable ACMR and SSF, are found using bilinear interpolations. Bilinear interpolation is

advancement to the conventional linear interpolation used when interpolating for parameters or functions that depends on two variables. It interpolates linearly in one direction and repeats the same in the other direction to result in quadratic interpolation [22]. The INSPECT-PBEE software developers incorporated this powerful interpolation technique to increase the accuracy in finding any parameter from FEMA P695 tables.

In addition to the maximum response and profile plots, FEMA options in INSPECT-PBEE provide adjusted fragility curves for different damage states similar to those shown earlier in Fig. 10. The adjustment accounts for the different sources of uncertainty and the spectral shape of the ground motion records used in the IDA. The fitted and adjusted fragility functions parameters' (i.e. mean and dispersion) are reported, making it possible for the user to re-create the fragility curves using Excel or Matlab. Programming FEMA P695 methodology for collapse safety and performance investigation significantly reduces the time and effort required otherwise to perform the analysis manually using IDARC-2D. This allows practicing engineers and researchers to effectively invest their time and effort in investigating the design and modeling related issues. Thus, this facilitates performance-based seismic design for new structures and seismic performance evaluation for existing ones. It effectively increases the feasibility and applicability of PBEE.

3. Illustrative example

A detailed verification example on application of the pre-processor mode can be found in the previous version of INSPECT-PBEE [12]. The post-processor mode has many significant features and a single illustrative example cannot be sufficient. However, most of its features have been emphasized in the previous section. This example is provided to highlight the most powerful feature in the post-processor mode, which is the automation of FEMA P695 options for seismic performance evaluation. In this regard, fragility analysis and seismic performance investigation is performed for a contemporary 6-story reinforced concrete office building. The building lateral force resisting system comprises of specially detailed reinforced concrete shear walls. The gravity load resisting system is made up of flat plates and columns. For more details about the studied building's characteristics and design details, the readers are referred to [4,23–25]. For the seismic performance evaluation, the Far-Field ground motions set of FEMA P695 is selected in this example. A pre-existing IDARC-2D nonlinear model of the building is used to directly utilize the post-processor GUI. IDA is performed for the selected building for a range of spectral accelerations from 0.2g to 1.2g with increments of 0.2g. Then, fragility curves are plotted for three performance levels from ASCE41-13 [18], which are; Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). In order to do the same analysis manually using IDARC-2D, the far-field ground motion records must be downloaded from PEER NGA database. Then, the records are processed to be compatible with IDARC-2D, normalized and finally scaled. Manual creation of 6 analysis models for each ground motion record is needed, a total of $6 \text{ (no. of scale factors)} \times 22 \text{ (no. of ground motion records)} \times 2 \text{ (two horizontal components for each record)} = 264$ models are required. The IDA results are extracted from each output file and then adjusted in accordance with FEMA P695 approach to incorporate the uncertainties and ground motions' spectral shape. The adjusted results are finally used to establish fragility curves based on maximum likelihood method. This very brief description of the performance investigation process using FEMA P695 highlights the significance of INSPECT-PBEE post-processor in reducing the needed time and effort. The results obtained using the manual approach and INSPECT-PBEE post-processor are shown in Fig. 13. It can be seen that the

adjusted fragility curves, with reasonable accuracy, are matching at the three performance levels. The slight differences are due to the solver used in excel and the one utilized in INSPECT-PBEE.

This illustrative example also presents a brief, but representative verification of the post-processor mode FEMA options by comparing the final software output (i.e. adjusted fragility curves). It should also be noted that there is a 100% match between the manually calculated ACMR for this building, which is 1.43, and the value calculated by INSPECT-PBEE.

4. Impact

Although IDA can be manually performed using IDARC-2D, it is a very time consuming process especially the extraction and processing of results. The time constraints force most users to make a trade-off and reduce the analysis time increments and IDA scaling increments to reasonably control the time frame and associated cost with the process. The choice of the analysis time step is very crucial when using IDARC-2D. The response analysis time step should be always kept smaller than the input wave time step and the ratio between wave time step and analysis time step must be an integer number. IDARC-2D nonlinear analysis and P-delta calculations are very sensitive to the analysis time step, and a value of 0.005 is generally suggested for archetypical structures by IDARC-2D user's manual (Appendix A in the report) [11]. However, it is recommended to use a smaller value for structures with low redundancy of elements or structures expected to experience significant changes in stiffness during analysis. Choosing a large time step for the analysis will cause numerical instabilities due to large unbalanced forces and will either pre-maturely terminate the analysis due to convergence issues or provide unreasonable results (e.g., very large drift ratios and/or damage indices). The use of a small time step to ensure smooth changes in elements' stiffness will, by default, increase each IDA running time. However, the use of INSPECT-PBEE allows for automation of the run process and extraction of results which gives the user a better chance to use a smaller time step without worrying about the impact on the analysis run time. In fact, INSPECT-PBEE features automatic multiple core parallelization. It will automatically scan the operating system and determine the number of available cores. Based on the number of cores it will process equal number of simultaneous runs. This will effectively allow for maximum utilization of the system capacity by running the maximum possible number of analyses in parallel. The software developers performed a testing for the speed up feature of INSPECT-PBEE. A benchmark problem is selected and solved using the software to highlight the significance of the execution monitor in reducing the run time. The testing is performed using a machine with total of 8 cores and 20 GB RAM. Fig. 14(a) illustrates the CPU utilization as the "ExecutionMonitor" uses more cores to complete the same analysis project and speed-up the process. It is worth mentioning that the utilization does not reach 100% due to windows scheduler control processes which results in saturation at about 93%. It can be observed that there is almost a linear relation between speed and no. of cores. It is not completely linear as there are some tasks that are usually completed in sequence. After utilizing 8 cores, the speed-up will not improve since the machine has only 8 CPU cores. Running more threads will not increase the performance as the extra threads will compete with the running threads for the same CPU cores. This may also decrease the performance of the parallelization process, since it may need extra processing resources for synchronization and context switching. Fig. 14(b) shows the impact of utilizing more cores on the relative running time required to complete the same analysis project. The relative running time has an inverse exponential relation with the number of CPU cores used. It is noted that the relative running time does not improve beyond 8 cores, again since the machine has only 8 cores.

TABLE 12.8-2 VALUES OF APPROXIMATE PERIOD PARAMETERS C_T AND α

Structure Type	C_T	α
Moment-resisting frame systems in which the frames resist 100% of the required seismic force and are not enclosed or adjoined by components that are more rigid and will prevent the frames from deflecting where subjected to seismic forces:		
<input type="radio"/> Steel moment-resisting frames	0.028 (0.0724) ^a	0.8
<input type="radio"/> Concrete moment-resisting frames	0.016 (0.0466) ^a	0.9
<input type="radio"/> Eccentrically braced steel frames	0.03 (0.0731) ^a	0.75
<input checked="" type="radio"/> All other structural systems	0.02 (0.0488) ^a	0.75

^aMetric equivalents are shown in parentheses.

Adopted from (ASCE7-5)

ground motions record set type

Near

Far

< Back Next > Finish

Fig. 12. Fundamental period calculation and records set selection.

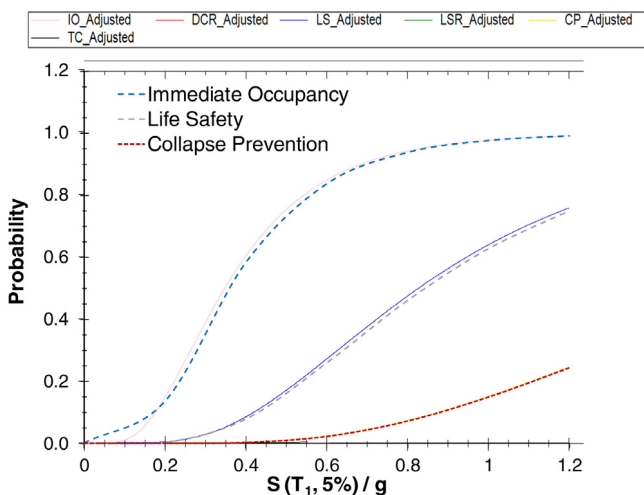


Fig. 13. Adjusted fragility curves: Manually calculated and INSPECT-PBEE generated.

Furthermore, using smaller increments for the IDA provides a clear picture of the structure's behavior and captures all potential nonlinear mechanisms. Using IDARC-2D alone, running it at a small intensity measure increments will force the user to create more files/models, perform a large number of runs and deal with many processing "DOS black windows". On the other hand, using INSPECT-PBEE, the user will not have to deal with any "DOS black windows" from IDARC-2D. The INSPECT-PBEE software was developed in such a way to suppress all the "DOS black windows" regardless of the number of runs being processed. The user will have to deal with a single window, the "Execution Monitor", controlling all the runs. The "Execution Monitor" allows the user to pause, resume or re-run the entire analysis process at any time. This is very useful especially that the program will occupy all available

cores to maximize the efficiency and may cripple the system if the user tries to use the computer during the analysis. Not many nonlinear analysis packages will allow this feature; even IDARC-2D does not have the option of pausing the analysis of a single file.

Moreover, there is a summary bar provided at the bottom of the "Execution Monitor" which provides the user with the total number of runs, successfully completed runs, pending runs, failed runs and force-failed runs without the need for scrolling through the Execution Monitor. Additionally, in the "Execution Monitor" the user has the option of stopping any single run either successfully completed, failed, force-failed or running. The user has the option of opening the model of that run, refining the time increment or any input and re-run the analysis. This is very useful in adjusting any failing run/collapse that is happening due to time step sensitivity. It allows for including these runs in the overall results processing.

Furthermore, INSPECT-PBEE permits the user to have multiple sessions. It allows saving all the work done in the post-processor file and reloading that file later to do changes or run the analysis with different parameters or performance criteria.

Using IDARC-2D and manually processing the IDA results to investigate the seismic performance of structures is another concern to many earthquake engineering researchers and practitioners. This lengthy process is not only time consuming, but might also increase the possibility of errors during the creation of several needed analysis models and extraction of results from output files. INSPECT-PBEE post-processor offers a major advantage of automating the seismic performance evaluation of structures using IDA. It automates the process from the replication of analysis models using the different records' scaling factors to processing and plotting the results. This saves a lot of time and reduces unnecessary effort lost in doing repetitive work and hence minimizes chances of having errors throughout. The software produces all needed plots to investigate the seismic performance of structures. Therefore, it gives a better opportunity to effectively allocate time in evaluating the performance, assessing design and resolving modeling related issues.

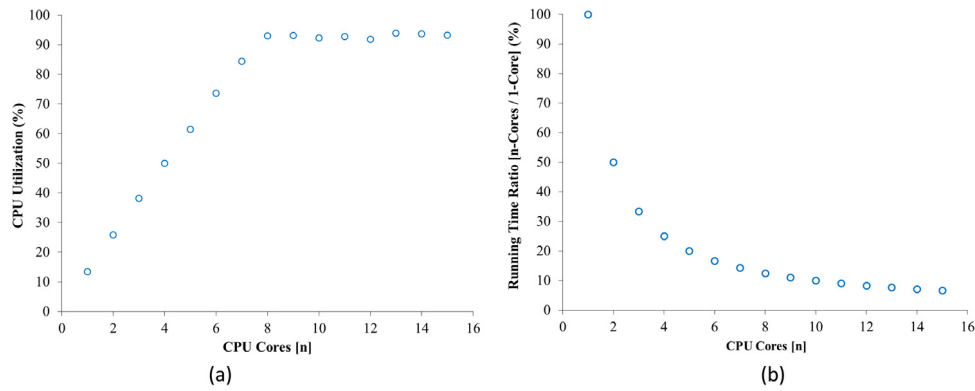


Fig. 14. Speed-up testing results.

5. Conclusion

INSPECT-PBEE offers a GUI solution for the well-established software for nonlinear and dynamic analysis, IDARC-2D. It consists of three modes; pre-processor, post-processor and open plot file. INSPECT-PBEE pre-processor [12] provides a friendly GUI for creating nonlinear analysis models for IDARC-2D. The GUI grants the users many advantages over the classic text input of IDARC-2D. With the GUI, the software becomes much simpler to use, more efficient, and has a less steep learning curve for new users. The post-processor mode includes a range of functions for automating the analysis and post processing of results from IDARC-2D. It allows the user to carry out automated IDA, and collapse evaluation following either user specified criteria or FEMA P695 procedure. Using INSPECT-PBEE post-processor batch mode options, the user is not only able to load different earthquake records for IDA, but also has control over the range of intensity measures to scale the used earthquake records. All the user should do is specify the range of peak ground accelerations for the input records. Furthermore, the user gets a summary of all the IDA runs along with summary of peak response output, maximum response plots, profile plots and fragility curves. The FEMA P695 options in INSPECT-PBEE post-processor provides the user with a fully automated seismic performance investigation of structures following a very credible and well-established procedure. It includes normalization and scaling of ground motions, creation of nonlinear analysis models for the different scale factors, performing the analysis and processing of results. The user will only have to define the range of spectral accelerations for the IDA. Moreover, all FEMA P695 parameters and tables are incorporated in INSPECT-PBEE post-processor database to perform the auto-collapse evaluation. The 20% acceptable Adjusted Collapse Margin Ratio (ACMR_{20%}) from FEMA P695 is then compared with the ACMR from IDA in order to evaluate the building seismic performance and the adequacy of its design. Multiple plots such as fragility curves are also plotted for the different performance levels. The post-processor features grant the user a very powerful set of tools to effectively perform seismic performance investigation of structures with significant reduction in effort, time and errors. This makes the process more appealing to practicing engineers and researchers. It allows them to allocate more of their time for the interpretation of results, verification of modeling and design flaws.

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