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NONLIN QUAKE: EXPERT SYSTEM FOR PERFORMANCE-BASED ANALYSIS OF STRUCTURES

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ABSTRACT

The paper presents the original developed software *Quake Nonlin* for performance-based seismic analysis of 3D structural models. Software *Nonlin Quake* consists of several independent compatible softwares that implements: create a database of two componential ground motion records (GMR), generation and processing of multicomponential GMR, creating incomplete and complete nonstationary artificial accelerograms, deterministic and probabilistic seismic hazard analysis, generation and processing of multicomponential response spectras, analysis of design parameters, processing of pushover curves and surfaces, calculation based on hybrid incremental nonlinear static-dynamic analysis, target displacement analysis, analysis and scaling of response spectras and analysis of target displacement envelope. For four considered methods for analysis of system performances: nonlinear static pushover analysis (NSPA), incremental nonlinear dynamic analysis (INDA), incremental dynamic analysis (IDA) and hybrid incremental nonlinear static-dynamic analysis (HINSDA), flow charts are shown.

KEYWORDS: *Nonlin Quake*, earthquake engineering, nonlinear analyses, performances

NONLIN QUAKE: EKSPERTSKI SISTEM ZA ANALIZU KONSTRUKCIJA PREMA PERFORMANSAMA

REZIME

U radu je prikazan originalno razvijen softver *Nonlin Quake* za seizmičku analizu 3D modela konstrukcija prema performansama. Softver *Nonlin Quake* sastoji se iz nekoliko nezavisnih kompatibilnih softvera u kojima se sprovodi: kreiranje baze zemljotresa dvokomponentalnih akceleroograma, generisanje i procesiranje multikomponentalnih akceleroograma, kreiranje nepotpunih i potpunih nestacionarnih veštačkih akceleroograma, deterministička i probablistička analiza seizmičkog hazarda, generisanje i procesiranje multikomponentalnih spektara odgovora, analiza projektnih parametara konstrukcije, procesiranje *pushover* krivih i površi, proračun hibridnom inkrementalnom nelinearnom statičkom-dinamičkom analizom, analiza ciljnog pomeranja, analize skaliranja akceleroograma i spektara odgovora i analiza anvelope ciljnog pomeranja. Za četiri razmatrane metode analize performansi sistema: nelinearnu statičku *pushover* analizu (NSPA), inkrementalnu nelinearnu dinamičku analizu (INDA), inkrementalnu dinamičku analizu (IDA) i hibridnu inkrementalnu nelinearnu statičko-dinamičku analizu (HINSDA), prikazani su tokovi proračuna.

KLJUČNE REČI: *Nonlin Quake*, zemljotresno inženjerstvo, nelinearne analize, performanse

INTRODUCTION

In the last twenty years, there was a significant development in the area of software for structural analysis leading to a number of different solutions, but most of these software are based on the *Finite Element Method* (FEM). These software applications are designed for calculating both simple and complex numerical models, where it is possible to apply a wide range of finite elements, powerful algorithms for the discretization of complex domains, and a wide array of analyses. Generally, software for structural analysis could be divided into software for everyday engineering practice and expert type software. Software designed for everyday engineering practice are intended for the general population of engineers and a large number of standard engineering problems, with the reliability and robustness of these software being constantly improved. Expert type software is designed, in most cases, to resolve complex, specific and nonstandard problems, and require experts and/or specialist with specific knowledge to be involved. Not necessarily, but they may also contain built-in modules for everyday engineering practice. A more detailed classification of software aimed at analyzing the performance of structures is based on their purpose (Ćosić, 2015):

- resolving common engineering problems, but also with integrated modules for solving nonlinear problems,
- resolving specialized nonlinear problems,
- resolving a wide array of complex nonlinear problems,
- resolving complex numerical-experimental (hybrid) simulations,
- resolving specialized nonlinear problems of the SDOF system,
- open source (nonlinear structural analysis)
- analyzing seismic hazard, risk, damage, vulnerability, reliability and loss,
- open source (analysis of seismic hazard and risk),
- selecting, formatting, converting, scaling, calculating, processing, spectral matching, filtering, generating and transforming of accelerograms and response spectra.

This paper presents the concept of the originally developed *Nonlin Quake* software system for nonlinear performance-based structural analysis, which due to its characteristics belongs to the group of software aimed at resolving specialized (nonstandard) nonlinear problems.

BASICS OF THE *NONLIN QUAKE* CONCEPT

The methodology of analysis of buildings according to their performances, as developed and implemented in the *Nonlin Quake* system, is based on the modern PBEE (*Performance-Based Earthquake Engineering*) concept. The performances of buildings are determined by applying: *Nonlinear Static Pushover Analysis* (NSPA), *Incremental Nonlinear Dynamic Analysis* (INDA), *Incremental Dynamic Analysis* (IDA), and *Hybrid Incremental Nonlinear Static-Dynamic Analysis* (HINSDA). Developed in the VB/VBA (*Visual Basic/Visual Basic for Applications*) programming language, the *Nonlin Quake* application consists of a series of modules, macros and functions. The user-software interaction unfolds through graphic user interfaces (GUI) with a large number of integrated options. The *Nonlin Quake* analysis is conducted in interaction with the *SeismoMatch*, *SeismoStruct* (or SAP 2000), SPO2IDA and MATLAB (or *Graphis*) applications, using accelerograms of natural earthquakes from the PEER GMDB earthquake database. The *Nonlin Quake* consists of the following programs (Ćosić, 2015):

- *Nonlin Quake* DB (*DataBase*),
- *Nonlin Quake* GMP (*Ground Motion Processing*),
- *Nonlin Quake* AA (*Artificial Accelerogram*),
- *Nonlin Quake* SHA (*Seismic Hazard Analysis*),
- *Nonlin Quake* RSP (*Response Spectra Processing*),
- *Nonlin Quake* PP (*Project Parameters*),
- *Nonlin Quake* PCS (*Pushover Curve-Surface*),
- *Nonlin Quake* HINSDA (*Hybrid Incremental Nonlinear Static-Dynamic Analysis*),
- *Nonlin Quake* TD (*Target Displacement*),
- *Nonlin Quake* SP (*Scaling Procedure*),
- *Nonlin Quake* TDE (*Target Displacement Envelope*).

Figure 1 shows the main user interfaces of the *Nonlin Quake* system through which all

processes are controlled, while figure 2 shows the auxiliary interfaces. In *Nonlin Quake* the system performances are considered through the time and frequency domain for the input signal (accelerogram or response spectra), and through the time and capacitive domain for the output signal (structural response).

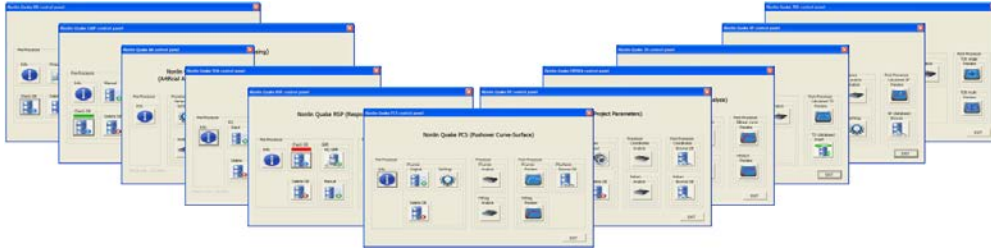


Figure 1. Main user interfaces of the *Nonlin Quake* system through which all processes are controlled (Ćosić, 2015)

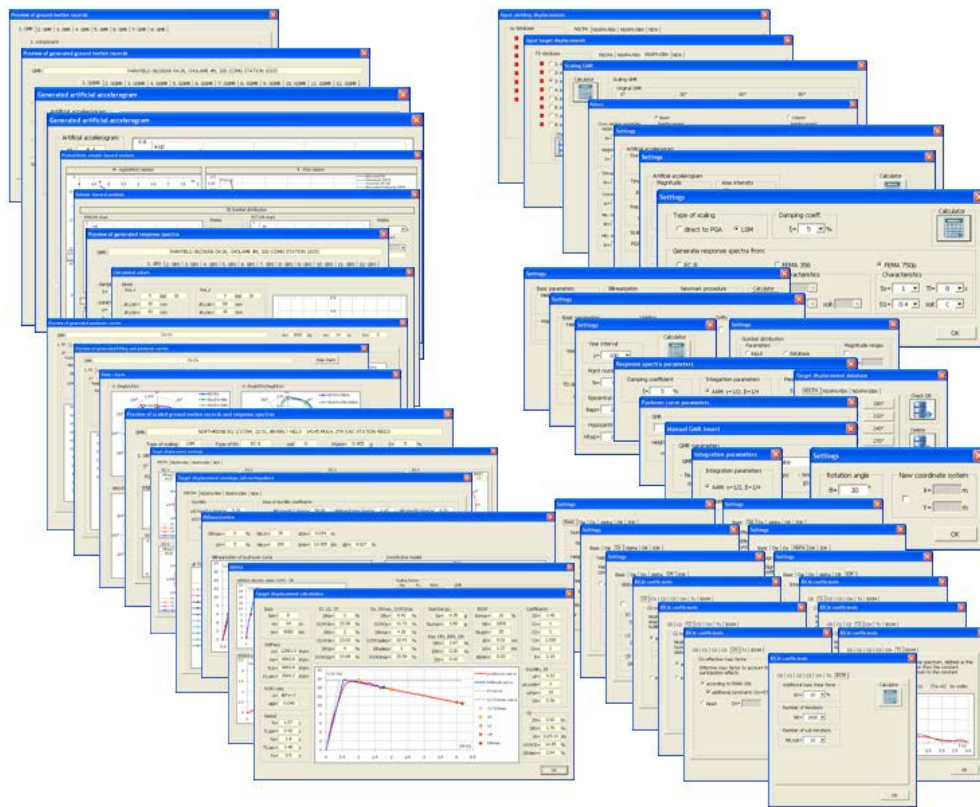


Figure 2. Auxiliary user interfaces of the *Nonlin Quake* system (Ćosić, 2015)

Depending on the type of performance analysis – NSPA, INDA (NDA), IDA or HINSDA – applied, four very different calculation flows were developed in the *Nonlin Quake* expert system. Figure 3 shows a flow chart for NSPA analysis for assessing the structural performance by using the *Nonlin Quake* expert system.

The first step consists of selecting an earthquake from the PEER GMDB database, which are then imported into the *Nonlin Quake* DB program, where the accelerograms are formatted (GMR – *ground motion record*). After that, they are imported in the *Nonlin Quake* GMP, where the GMR accelerograms are converted, calculated and processed for different angles, which is followed by the generation of the GMR surface (GMRS – *ground motion record surface*) in MATLAB (or in *Graphis*). If the *Nonlin Quake* GMP decides that the selected accelerogram is inadequate, then the selection from the PEER GMDB earthquake database is repeated or corrected.

The *Nonlin Quake* AA was developed as an alternative to using accelerograms of real earthquakes. Here, there is a possibility of generating incomplete and complete non-stationary artificial accelerograms. Artificial accelerograms in *Nonlin Quake* AA are modified by baseline correction, conducting analysis in the frequency domain, filtering and scaling the accelerogram. If incomplete non-stationary artificial accelerograms are generated, they are directly imported into the *Nonlin Quake* GMP; on the other hand, if complete non-stationary accelerograms are generated, then a previous analysis of seismic hazard and the analysis of relevant parameters are conducted in *Nonlin Quake* SHA. Then, the GMRS accelerograms from *Nonlin Quake* GMP are imported in *Nonlin Quake* RSP, where the response spectra are processed and generated in formats of spectral acceleration-vibration period (ARS – *acceleration response spectra*) and spectral displacement-vibration period (DRS – *displacement response spectra*). Here, it is also possible to carry out scaling in the time domain.

Given the fact the response spectra are generated for different angles of earthquake action, the final form provides the *acceleration response spectra surface* (ARSS) and the *displacement response spectra surface* (DRSS).

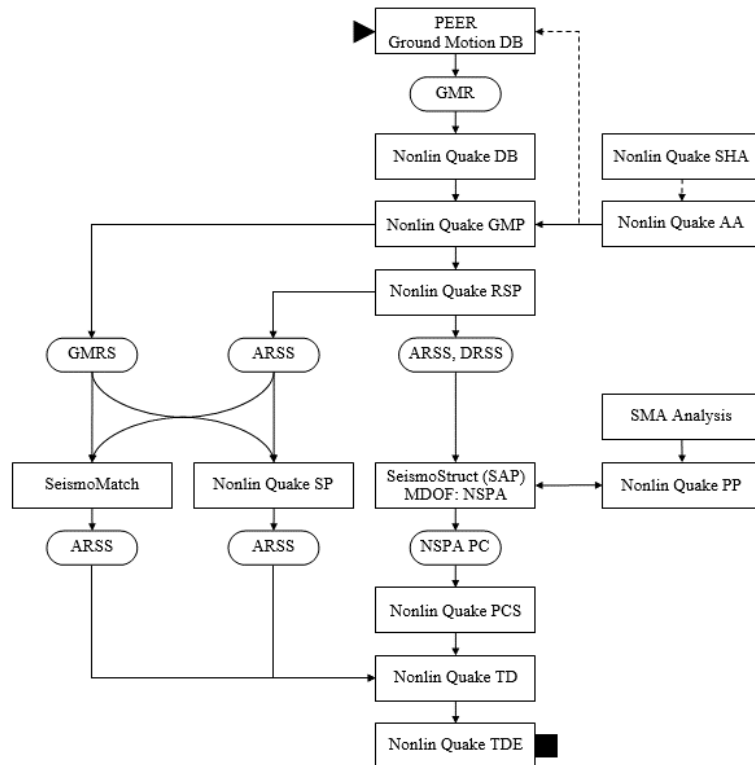


Figure 3. Flowchart of the NSPA analysis for assessing the performance of buildings using the *Nonlin Quake* expert system (Ćosić, 2015)

The ARSS and DRSS response spectra are then imported in the *SeismoStruct* (or SAP 2000) software, where the 3D MDOF model of structure is subjected to conventional and/or adaptive NSPA analysis. The structural model is previously calculated using *Spectral-Modal Analysis* (SMA) and dimensioned according to EC 2 and EC 8. The position of reinforcement bars and the corresponding reinforcement surface by cross-sections are generated in *Nonlin Quake* PP. The rotation of structure depending on the angle for which the earthquake effect is considered is also conducted in *Nonlin Quake* PP. After processing NSPA analyses in *SeismoStruct* (or SAP 2000), the NSPA pushover curves are imported in *Nonlin Quake* PCS, where additional correction, regression analyses, calculations and generation of the corresponding NSPA pushover surface are conducted. After the correction of pushover curves, they are imported into *Nonlin Quake* TD, where the level of target displacement is calculated.

On the other hand, the ARSS response spectra are imported into *Nonlin Quake* TD, where the corresponding spectral acceleration is determined based on these real response spectra. The ARSS response spectra are previously scaled according to the procedure implemented in *Nonlin Quake* SP. The other scaling alternative is to scale the GMRS accelerograms from

Nonlin Quake GMP and the ARSS response spectra from *Nonlin Quake* RSP in the *SeismoMatch* software, creating thereby new compatible response spectra based on response spectra from the regulations. These scaled or created compatible ARSS response spectra are then imported in *Nonlin Quake* TD. The procedure for determining the level of target displacement is conducted separately for each considered rotation angle, i.e. earthquake action. The calculation of levels of target displacement is followed by the calculation of the target displacement envelope in *Nonlin Quake* TDE. Here, a series of parameters were developed for assessing the structural performances.

Figure 4 shows the flowchart of INDA analysis for assessing the performance of buildings using the *Nonlin Quake* expert system. The first step consists of selecting earthquakes from the PEER GMDB database, which are then imported in the *Nonlin Quake* DB program, where the GMR formatting is conducted. After that, they are imported in the *Nonlin Quake* GMP, where the GMR accelerograms are converted, calculated and processed for different angles, which is then followed by generation of GMR surface in MATLAB (or *Graphis*). If the *Nonlin Quake* GMP processing decides that the selected accelerogram is inadequate, then the selection from the PEER GMDB earthquake database is repeated or corrected. The *Nonlin Quake* AA was developed as an alternative to using accelerograms of real earthquakes. Here, there is a possibility of generating incomplete and complete non-stationary artificial accelerograms. Artificial accelerograms in *Nonlin Quake* AA are modified by baseline correction, conducting analysis in the frequency domain, filtering and scaling the accelerogram.

If incomplete non-stationary artificial accelerograms are generated, they are directly imported in *Nonlin Quake* GMP; on the other hand, if complete non-stationary accelerograms are generated, then a previous analysis of seismic hazard and the analysis of relevant parameters are conducted in *Nonlin Quake* SHA. Then, the GMRS accelerograms from *Nonlin Quake* GMP and the artificial accelerograms from *Nonline Quake* AA are imported into *Nonlin Quake* RSP, where the ARS and DRS response spectra are processed and generated. Given the fact the response spectra are generated for different angles of earthquake action, the final form provides the ARSS and DRSS surfaces. The ARSS and DRSS response spectra are then imported in the *SeismoStruct* (or SAP 2000) software, where the 3D MDOF model of structure is subjected to NSPA analysis. The structural model is previously calculated using SMA analysis and dimensioned according to EC 2 and EC 8. The position of reinforcement bars and the corresponding reinforcement surface by cross-sections are generated in *Nonlin Quake* PP. The rotation of structure depending on the angle for which the earthquake action is considered is also conducted in *Nonlin Quake* PP. After processing the NSPA analyses in *SeismoStruct* (or SAP 2000), the pushover curves are imported in *Nonlin Quake* HINSDA, where the bilinearization, or the corresponding hybrid analysis is conducted in order to predict the scaling factor of the accelerogram and collapse level of the structure in INDA analysis.

The GMRS accelerograms from *Nonline Quake* GMP are imported into *Nonline Quake* HINSDA, where a separate scaling procedure is conducted. Results obtained from *Nonline Quake* HINSDA decide the acceleration scaling factors for INDA analysis of the 3D

MDOF model of structure in *SeismoStruct* (or SAP 2000). After being processed in *SeismoStruct* (or SAP 2000), the INDA pushover curves are imported into *Nonlin Quake* PCS, where additional correction is conducted, along with regression analysis, calculations and generation of the corresponding INDA pushover surface. On the other hand, GMRS accelerograms and the ARSS response spectra are imported into *Nonlin Quake* SP, where the accelerograms are scaled. An alternative scaling is scaling the GMRS accelerograms and the ARSS response spectra in *SeismoMatch*, creating thereby new compatible response spectra based on the response spectra from regulations. Then, the scaled or created compatible GMRS accelerograms are imported into *SeismoStruct* (or SAP 2000), where the NDA analysis of the 3D MDOF model of structure for the required level of target displacement is conducted. The procedure for determining the level of target displacement is conducted separately for each considered angle of rotation, i.e. earthquake action. The calculation of levels of target displacement is followed by calculation of the target displacement envelope in *Nonlin Quake* TDE.

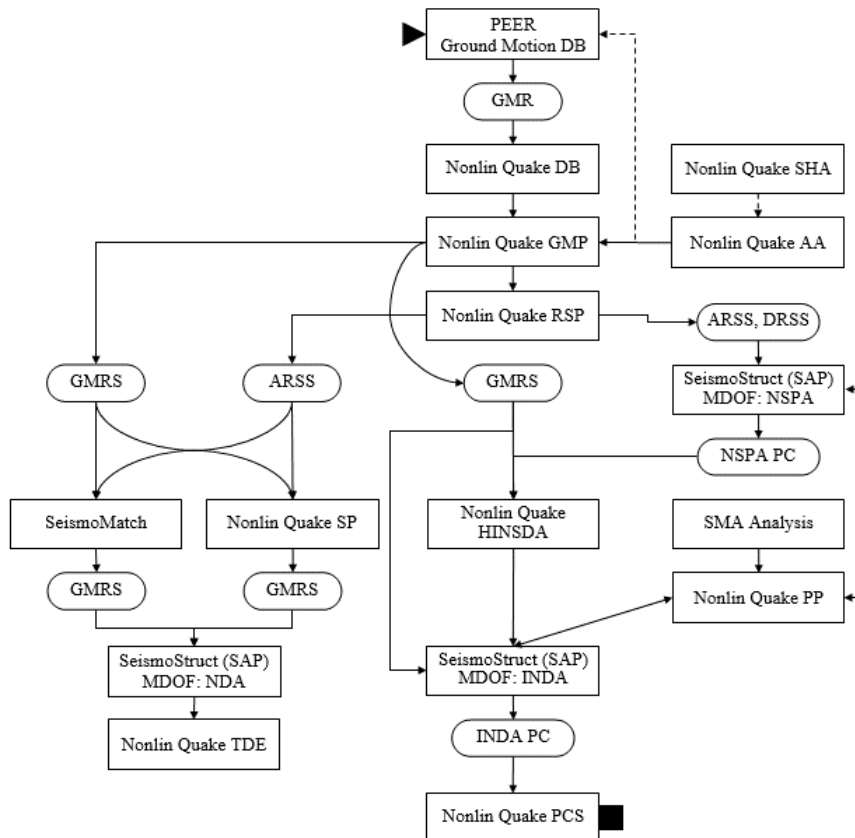


Figure 4. Flowchart of the INDA analysis for assessing the performance of buildings by using the *Nonlin Quake* expert system (Ćosić, 2015)

Figure 5 shows a flow chart of the HINSDA analysis for assessing performances of buildings using the *Nonlin Quake* expert system. The first step consists of selecting the earthquakes from the PEER GMDB database, which are then imported into the *Nonlin Quake* DB, where the GMR formatting is conducted. After formatting, the earthquakes are imported in *Nonlin Quake* GMP, where the GMR accelerograms are converted, calculated and processed for different angles, which is then followed by generating the GMRS surface in MATLAB (or *Graphis*). If the *Nonlin Quake* GMP processing decides that the selected accelerograms are inadequate, then the procedure of selecting the earthquakes from the PEER GMDB database is repeated or corrected. The *Nonlin Quake* AA was developed as an alternative to using accelerograms of real earthquakes. Here, there is a possibility of generating incomplete and complete non-stationary artificial accelerograms. Artificial accelerograms in *Nonlin Quake* AA are modified by baseline correction, conducting analysis in the frequency domain, filtering and scaling the accelerogram.

If incomplete, non-stationary artificial accelerograms are generated, they are directly imported into *Nonlin Quake* GMP; on the other hand, if complete non-stationary accelerograms are generated, then a previous analysis of seismic hazard and the analysis of relevant parameters are conducted in *Nonlin Quake* SHA. Then, the GMRS accelerograms from *Nonlin Quake* GMP and the artificial accelerograms from *Nonlin Quake* AA are imported into *Nonlin Quake* RSP, where the ARS and DRS response spectra are processed and generated. Given the fact that the response spectra are generated for different angles of earthquake action, the final form provides ARSS and DRSS surfaces. The ARSS and DRSS response spectra are then imported into the *SeismoStruct* software (or SAP 2000), where the 3D MDOF model of structure is subjected to NSPA analysis.

The structural model is previously calculated using SMA analysis and dimensioned according to EC 2 and EC 8. The position of reinforcement bars and the corresponding reinforcement surface by cross-sections are generated in *Nonlin Quake* PP. The rotation of structure depending on the angle for which the earthquake effect is considered is also conducted in *Nonlin Quake* PP. After processing the NSPA analysis in *SeismoStruct* (or SAP 2000), the pushover curves are imported into *Nonlin Quake* HINSDA, where the bilinearization, or the corresponding hybrid INDA analysis is conducted. The GMRS accelerograms from *Nonlin Quake* GMP are imported in *Nonlin Quake* HINSDA, where a separate scaling procedure is conducted. After processing the hybrid INDA analyses in *Nonlin Quake* HINSDA, the obtained pushover curves are imported into *Nonlin Quake* PCS for additional correction, regression analysis, calculations and generation of corresponding HINSDA pushover surfaces. On the other hand, GMRS accelerograms and the ARSS response spectra are imported into *Nonlin Quake* SP, where the accelerograms are scaled. Then, the scaled compatible GMRS accelerograms are imported again in *Nonlin Quake* HINSDA, where the analysis for the required level of target displacement is conducted. The procedure of determining the level of target displacement is carried out separately for each considered angle of rotation, i.e. earthquake action.

The calculation of levels of target displacement is followed by calculations of the target displacement envelope in *Nonlin Quake* TDE.

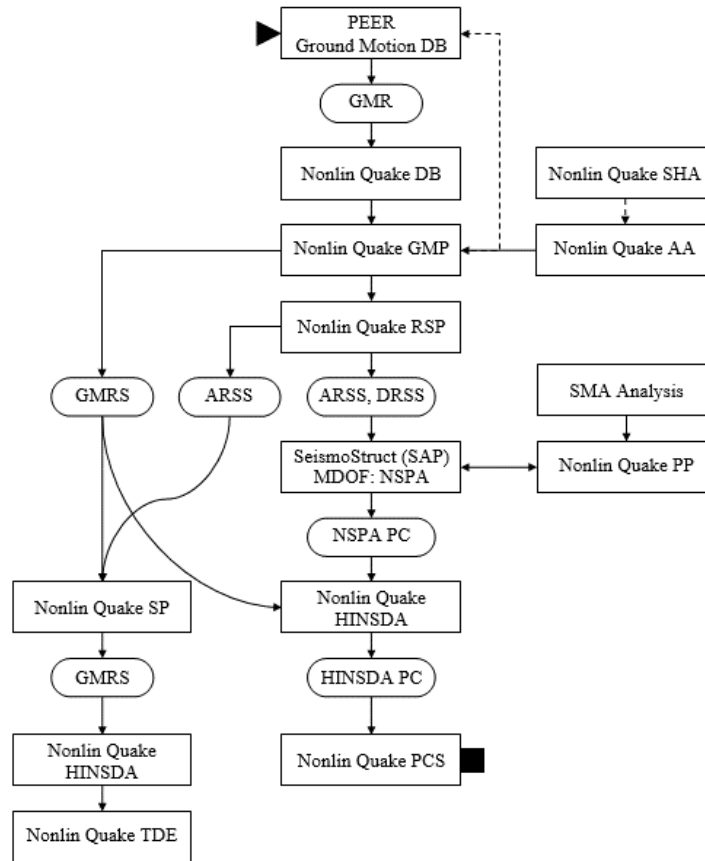


Figure 5. Flowchart of the HINSDA analysis for assessing the performance of buildings using the *Nonlin Quake* expert system (Ćosić, 2015)

Figure 6 shows the flowchart of IDA analysis for assessing the performance of buildings using the *Nonlin Quake* expert system. The process of selecting and creating the appropriate accelerograms, or ARSS and DRSS surfaces, is identical to the previous procedure. After processing the NSPA analysis in *SeismoStruct* (or *SAP 2000*), the pushover curves are imported into the *SPO2IDA* software, where the corresponding IDA analysis is conducted.

After processing the IDA analyses in *SPO2IDA*, the obtained pushover curves are imported into *Nonlin Quake PCS* for additional correction, regression analysis, calculations and generation of the corresponding IDA pushover surface.

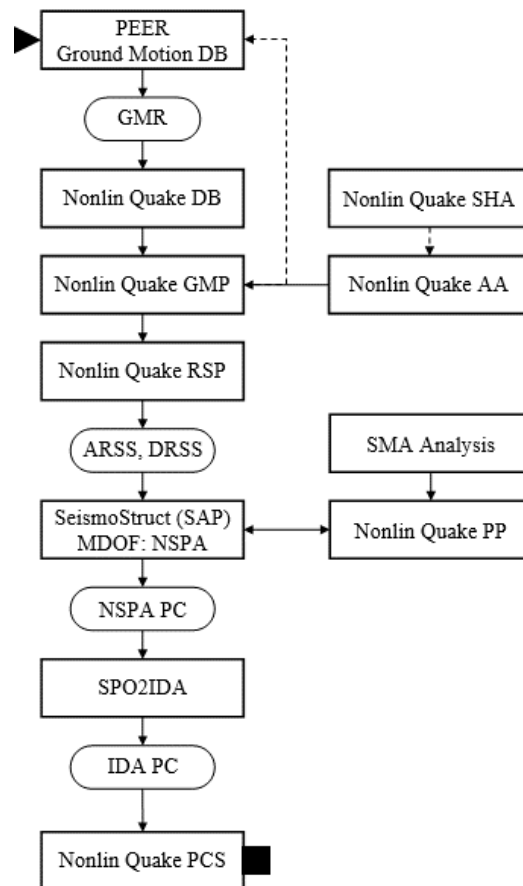


Figure 6. Flowchart of the IDA analysis for assessing the performance of buildings using the *Nonlin Quake* expert system (Ćosić, 2015)

THE ORIGINALLY DEVELOPED AND IMPLEMENTED TERMINOLOGY

In accordance with the developed PBEE methodology, an original terminology has been developed and implemented in the *Nonlin Quake* expert system. The key new terms are as follows:

- *ground motion record surface (GMRS)*,
- *response spectra surface (RSS)*,
- *intensity measure envelope (IME)*,
- *pushover surface (PS)*,
- *ductility area coefficient (DAC)*,
- *target displacement envelope (TDE)*,
- *drift surface (DRS)*,
- *interstorey drift surface (IDRS)*.

Figure 7 shows generated surfaces of the recorded ground acceleration GMRS for several earthquakes, where the process of generation starts from bi-component accelerograms. After the calculation of the accelerogram for angles θ_i the accelerogram surface is constructed by first generating the $a_{\theta}(t)$ accelograms in a planar polar coordinate system. The radial coordinate is time t_r , the angular coordinate is the angle θ . This is followed by the construction of accelograms individually in spatial cylindrical coordinate system. Here, the radial coordinate is also the time t_r , angular coordinate is the angle θ , while the vertical coordinate is acceleration $a_{\theta}(t)$. Components of the accelerogram are linearly interpolated in the radial and in tangential direction, so that a spatial rotational surface is obtained.

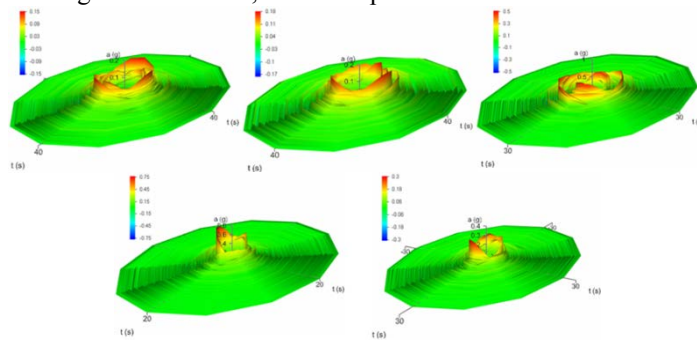


Figure 7. The generated accelerogram surfaces GMRS for earthquakes: a) *Imperial Valley* IV79, b) *Loma Prieta* LP89, c) *Northridge* NR94, d) *Palm Springs* PS86, e) *Parkfield* PA66 (Ćosić, 2015)

Figure 8 shows the generated response spectra surfaces RSS for several earthquakes, where the generation process starts from a bi-component response spectra. First, the response spectra $S_{\theta}(T)$ in a planar polar coordinate system are generated for angles θ_i . Then, to each response spectra $S_{\theta}(T)$ a vertical coordinate (S_a or S_d) has been allocated in a cylindrical coordinate system, spatial, which is then followed by the conversion in a spatial rectangular coordinate system.

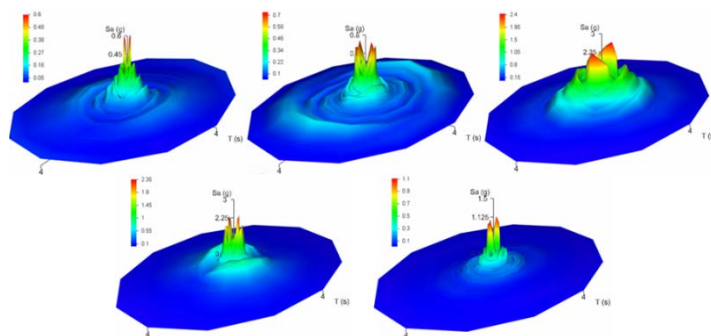


Figure 8. The generated surfaces of acceleration response spectra ARSS: a) *Imperial Valley* IV79, b) *Loma Prieta* LP89, c) *Northridge* NR94, d) *Palm Springs* PS86, e) *Parkfield* PA66 (Ćosić, 2015)

Figure 9 shows the intensity measure envelopes (IME) for several earthquakes of different intensity measures (IM): *peak ground acceleration (PGA)*, *peak ground velocity (PGV)* and *peak ground displacement (PGD)*. The intensity measure envelope is a smooth interpolated closed curve generated by connecting the discrete intensity measures of multi-component accelerograms.

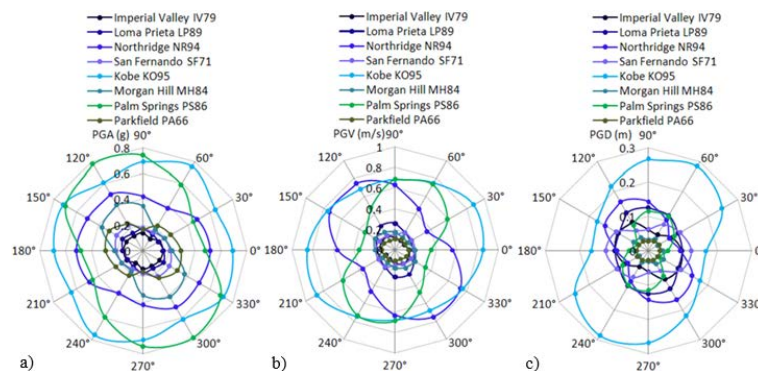


Figure 9. Intensity measure envelope: a) *PGA*, b) *PGV*, c) *PGD* (Ćosić, 2015)

Figure 10 shows the 3D wireframe model of pushover surface and rendered 3D pushover surface. The pushover surface of the 3D building model is a smooth interpolated asymmetric rotational surface generated by connecting the discrete values from incremental situations of individual pushover curves with splines in tangential direction (Ćosić and Brčić, 2013).

Figure 11 shows the 3D wireframe pushover surface and target displacement envelope, and the rendered 3D pushover surface and targeted displacement envelope. The target displacement envelope can be obtained from the cross-section of pushover curves and the demanded curves or from the cross-section of pushover curves and bilinearisation curves (Ćosić, 2015).

Figure 12 shows the constructed global drift surfaces (DRS) and interstorey drift surfaces (IDRS) for two different building models.

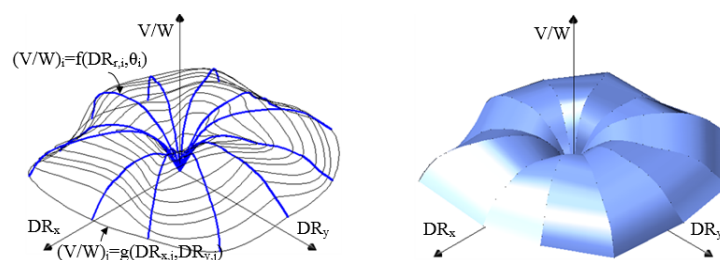


Figure 10. a) 3D wireframe pushover surface model, b) rendered 3D pushover surface (Ćosić and Brčić, 2013)

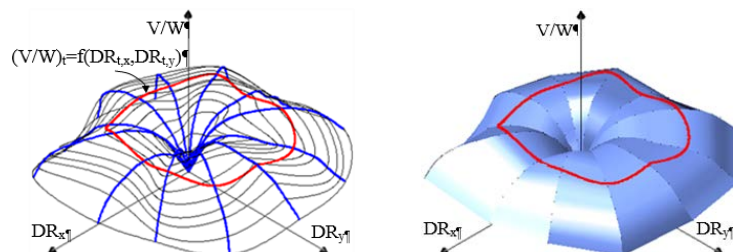


Figure 11. a) 3D wireframe pushover surface and target displacement envelope, b) rendered 3D pushover surface and target displacement envelope (Ćosić, 2015)

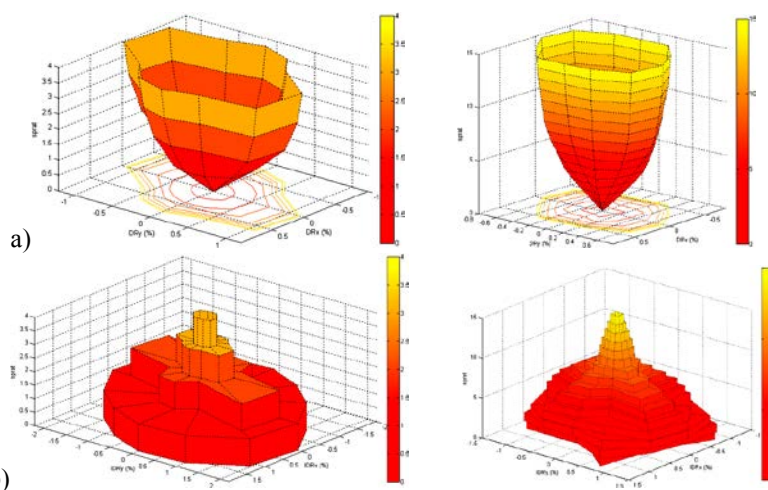


Figure 12. a) drift surface DRS, b) interstorey drift surface IDRS for two different buildings (Ćosić, 2015)

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