COMPUTER AIDED DESIGN AND ANALYSIS OF RC FRAME BUILDINGS SUBJECTED TO EARTHQUAKES

O. El Kafrawy[1], M. Yousuf[1] and A. Bagchi[2]

ABSTRACT

Computer use in structural analysis and design dates back a number of decades. As computer processors become more powerful, the scope of computer aided design and engineering expands. However, many specialized analysis tools in structural engineering lack the flexibility in user interface and analysis process automation that is usually assumed in computer aided design and engineering. This paper focuses on the earthquake resistant design of reinforced concrete building frames and IDARC2D, a computer program that facilitates seismic response analysis of RC frame buildings. The paper presents a user interface design and a scheme for automating the analysis process for large scale simulation for evaluating the seismic performance of RC building frames subjected to earthquake ground motion. Such large scale simulation produces a huge amount of data that needs to be post processed in order to extract meaningful information about the behaviour of a building under earthquakes. The paper also discusses the development of such post processor. As a case study, a six story RC frame building designed based on the NBCC 2005 seismic provisions is analyzed using the software tools discussed here. The building is assumed to be located in Vancouver in western Canada. The seismic provisions of NBCC 2005 are different from those in the earlier edition of the code. NBCC 2005 presents an objective-based format where the design is achieved through the attainment of acceptable solution, rather than just satisfying the minimum requirements. For earthquake resistant design, evaluation of the seismic performance of buildings is essential to determine if an acceptable solution in terms of performance is achieved. The seismic performance of the buildings has been evaluated using nonlinear static and dynamic analysis. A set of eight simulated ground motion records which are compatible with the seismic hazard spectrum of Vancouver has been used in the dynamic analysis. The advantages of the tools developed herein are demonstrated along with a summary of the results for the selected building.

KEY WORDS

computer assistance, structural analysis, building frames, earthquake resistant design, seismic performance.

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[1] Graduate Student, Department of Building, Civil & Environmental Engineering, Concordia University, Montreal, QC, Canada.

[2] Assistant Professor, Department of Building, Civil & Environmental Engineering, Concordia University, 1455 de Maisonneuve Blvd. W., EV 6.111, Montreal, QC, Canada, H3G 1M8,
Phone: (514) 848-2424 (ext. 3213), Fax: (514) 848-7965, Email: abagchi@bcee.concordia.ca.

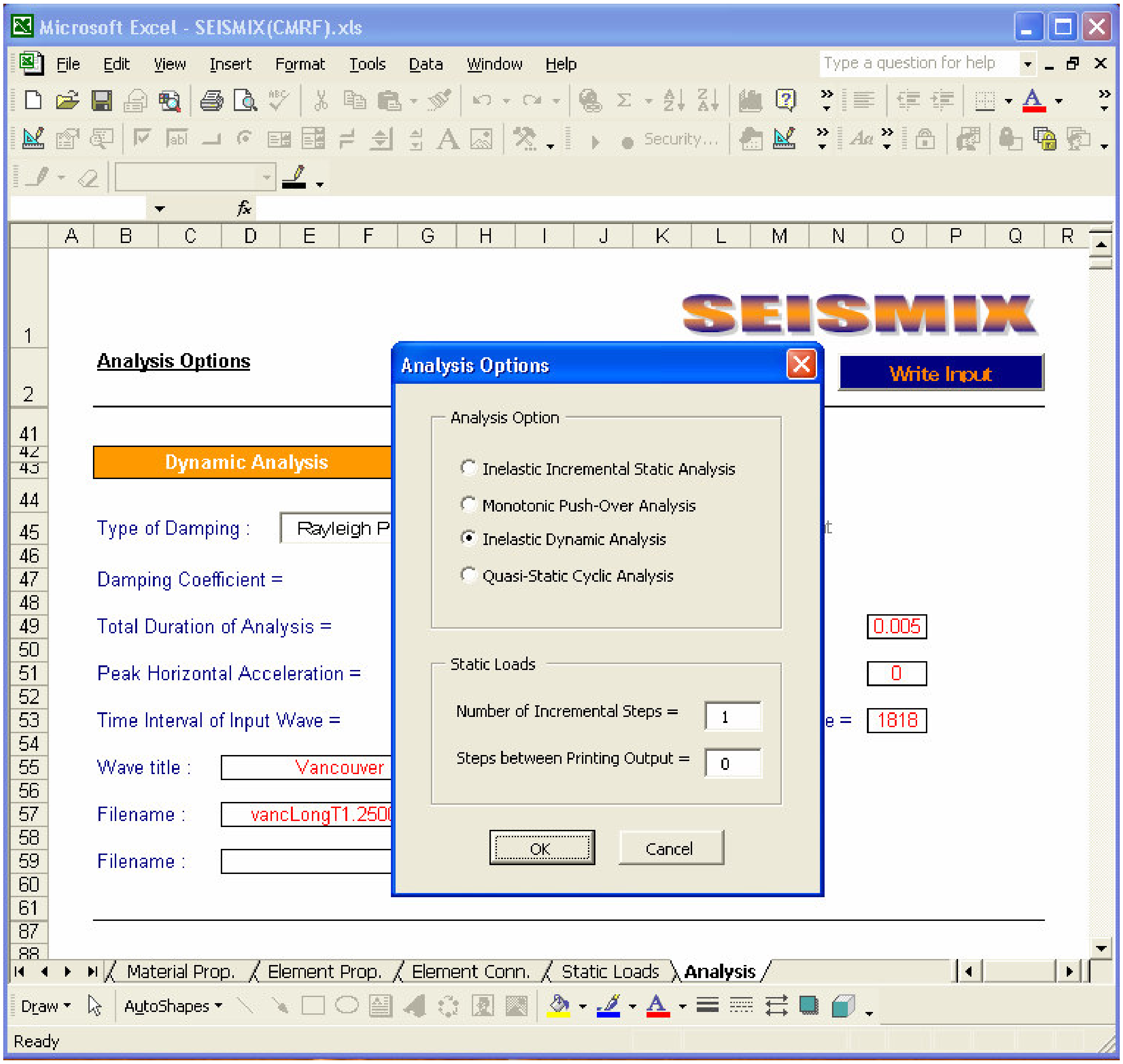
INTRODUCTION

Seismic loading provisions in most existing building codes focus on the minimum lateral seismic forces for which the building must be designed. Specifying the lateral forces alone is not enough to ensure that the desired level of performance will be achieved. In Canada the seismic design of buildings is performed according to the relevant provisions of the National Building Code of Canada (NBCC). A technical overview of the seismic provisions of NBCC 2005 is available in the special issue of the Canadian Journal of Civil Engineering (CJCE 2003). The 2005 edition of NBCC seismic design provisions continue to rely on the specification of minimum lateral seismic forces for which the building must be designed and the acceptable drifts under such forces. However, the code is presented in an objective-based format where an acceptable solution needs to be achieved for a specified objective, rather than just satisfying the minimum requirements (CJCE 2003). This is a step-forward towards the performance-based design. Performance-based design (Vision 2000 Committee, 1995) requires an accurate evaluation of performance of a structure at various stages in the design process, and it requires reliable analysis of structures subjected to the design levels of loads. Although seismic design of buildings is performed based on the equivalent static loads method, NBCC 2005 strongly recommends the use of dynamic analysis for the purpose of refinement in the design. Carrying out a detailed dynamic analysis of a structure using a number of earthquake ground motion records, and constructing the performance profile of the structure in probabilistic terms, require enormous computing effort. Although the computing power of the modern computers is astounding, significant manual effort is needed in organizing the input and output data from a given analysis tool and extracting meaningful information out of the huge quantity of analysis data. It is necessary to develop simple tools to automate such analysis and extract relevant information from a large set of analysis data.

Although there are a number of general purpose software packages available for structural analysis and design, special purpose software tools are often necessary to particular research needs. IDARC2D, a special purpose software tool for modeling the dynamic behaviour of reinforced concrete (RC) buildings subjected to earthquake ground motion is used in this study. IDARC2D has the capability of analyzing earthquake damage in multistory, reinforced concrete buildings (IDARC2D 2006). The problem with IDARC2D is that the input is written manually by the user in a text file and the output is also given in text form to be read by the user. This method of data input could be cumbersome to the user, especially if one plans to conduct dynamic analysis involving a large number of earthquake ground motion records, and multiple building configurations and design choices. A set of interface tools have been developed in the present study to simplify the data input and interpretation of the analysis data. The tools presented herein can be used for automating the input process and post processing the output data to conduct a large scale simulation of earthquake response of multi story RC frame buildings. As a case study, a six story RC frame building designed for Vancouver using the seismic provisions of the NBCC 2005 has been presented. The seismic performance of the building has been evaluated for a suite of eight simulated earthquake ground motion records compatible with the seismic hazard at Vancouver.

DESCRIPTION OF THE AUTOMATION TOOL FOR ANALYSIS AND DESIGN

The computer program, IDARC2D is an inelastic dynamic structural analysis tool used for detailed modelling of reinforced concrete building frames. For example, the user has the option of specifying the hysteretic behavior of the different elements of the structure. The use of infill panels, transverse beams, shear walls, different brace types is also another example of the many options available in this software. The user can choose to perform time-history, push-over or quasi-static analysis on the structure.



Analysis Options

Type of Damping : Rayleigh P
Damping Coefficient =
Total Duration of Analysis =
Peak Horizontal Acceleration =
Time Interval of Input Wave =
Wave title : Vancouver
Filename : vancLongT1.250
Filename :

0.005
0
e = 1818

Analysis Options

Analysis Option
○ Inelastic Incremental Static Analysis
○ Monotonic Push-Over Analysis
● Inelastic Dynamic Analysis
○ Quasi-Static Cyclic Analysis

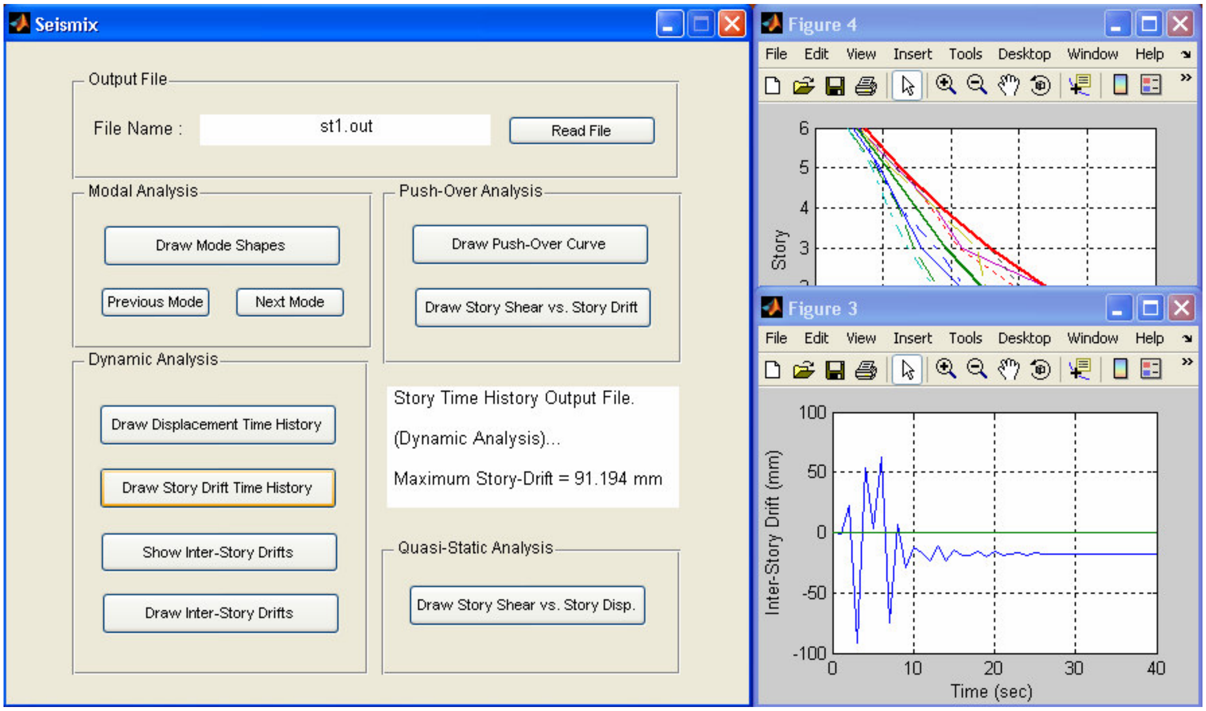
Static Loads
Number of Incremental Steps = 1
Steps between Printing Output = 0

OK Cancel

Figure 1: The user interface for IDRAC2D pre-processor

The pre-processor unit has been built using the Excel (Microsoft Corporation) and Visual Basic scripts. All input data are gathered in the Excel sheel which provides with appropriate forms with appropriate data labels to fill out with necssary data. The user can edit and change the editable fields and finally when the complete set of data for structural model definition, material properties, analysis options etc. are entered into the preprocessor, the user can instruct the pre-processor to prepare the IDRAC2D input files in text format by clicking on the "Write Input" button from the user interface (Figure 1). After the input file is written, the user may run the IDARC2D program to generate the output files. The excel file contains seven worksheets where all data should be filled.

Dealing with output files on the other hand requires reading a lot of data and generating graphs for visualising the response of the structure. This is done here using a graphical user interface developed in MATLAB as shown in Figure 2. The post-processing interface developed in MATLAB scans through the output files generated by IDARC2D and provides tools for plotting a number of response quantities. The program can plot push-over curves, mode shapes, inter-story drifts and time-history graphs.



File Name : st1.out

Story Time History Output File.

(Dynamic Analysis)...

Maximum Story-Drift = 91.194 mm

Figure 2: The user interface for IDRAC2D post-processor

Figure 3 shows the schematic architecture of the pre and post processing units as described earlier. The pre-processor engine is based on Visual Basic scripts or macros for manipulating an Excel workbook that gathers the input data necessary fot IDARC2D. The input form and data cells in Excel are dynamically organized based on the type of analysis or the problem size. Once the data is gathered through the preprocessor, the user can instruct it to make appropriate data files in text format for IDARC2D. IDARC2D produces a number of output text files with general information and specific structural response, such as, story drift, story hysteris etc.The MATLAB based post-processor scan through the IDARC2D output files and produces necessary graphical output in order to visualize the analysis results, such as mode shapes, push-over curve, time-history of displacement or drift etc.

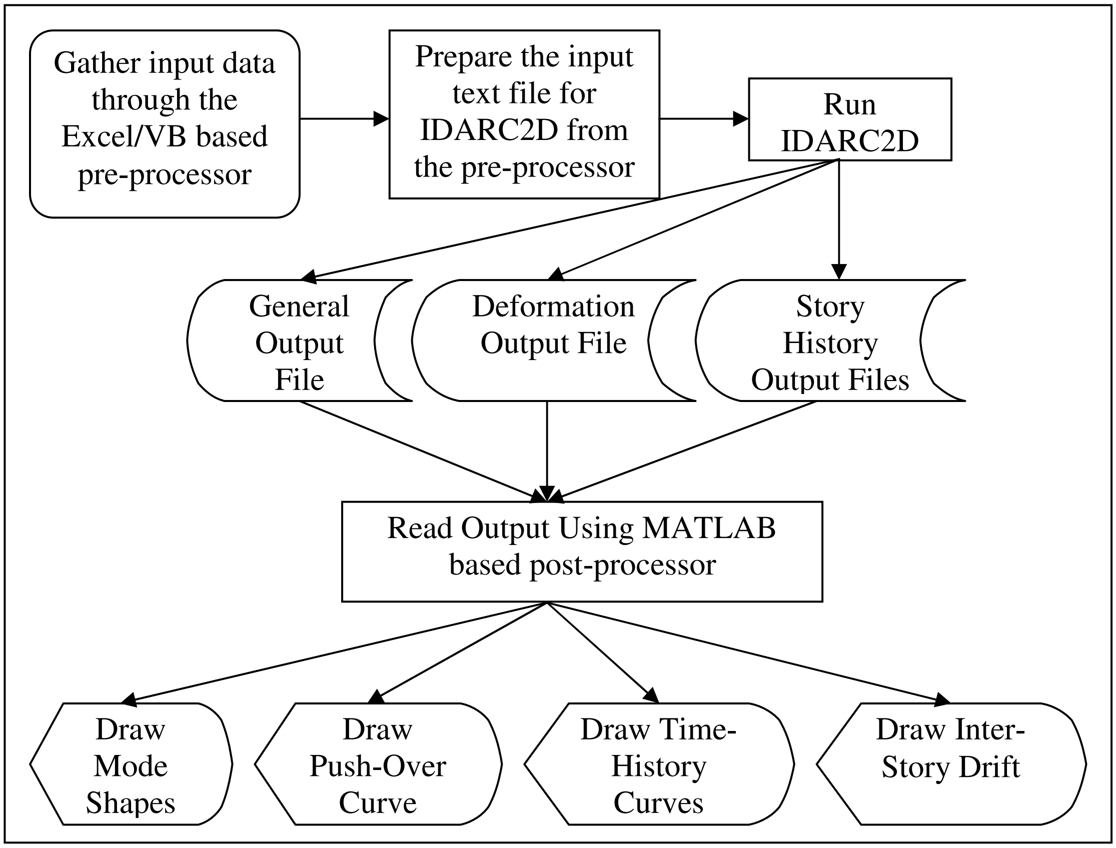


Figure 3: Schematic architecture of the analysis automation system for IDARC2D

CASE STUDY – A SIX STORY RC FRAME BUILDING IN VANCOUVER

The use of the pre and post processor has been demonstrated in the following example. A six story building in Vancouver has been designed using the NBCC 2005 seismic provisions. The geometric details of the building are shown in Figure 4. The building has several six-meter bays in the N-S direction and 3 bays in E-W direction. The E-W bays consist of two nine-meter office bays and a central six-meter corridor bay. The story height is 4.85 m for the first story and 3.65 m for all other storys. The building is composed of a set of parallel frames equally spaced 6 meters apart. The design is done for a typical intermediate frame as shown in Figure 4. The chosen cross sections resulting from the design are shown in Table 1.

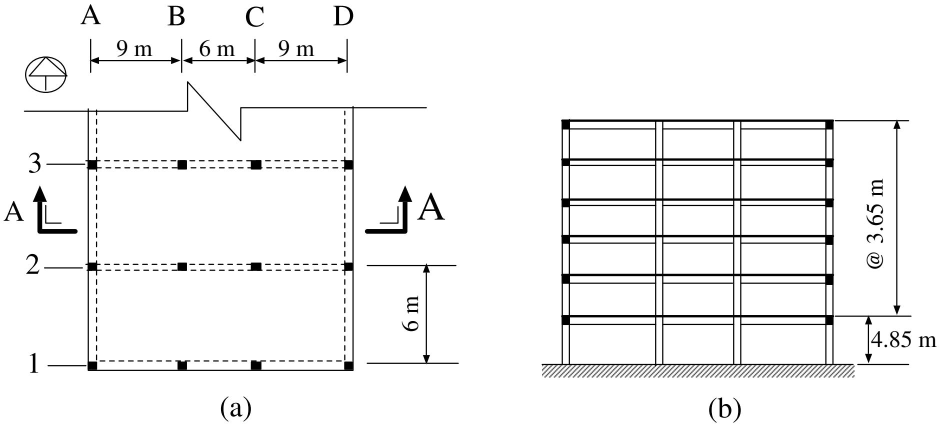
SEISMIC PROVISIONS OF NBCC 2005

The 2005 edition of NBCC allows the use of the equivalent static load method in the structural design against earthquake excitations. The seismic hazard is expressed in terms of a uniform hazard spectrum (UHS), which provides the maximum expected spectral acceleration S_a of a single-degree-of-freedom (SDOF) system with 5% damping. The elastic base shear, V_e for a single-degree-of-freedom building can be obtained by multiplying the spectral acceleration value $S(T)$ corresponding to the fundamental period of the building T_a

with the weight of the building *W*. Considering the ductility capacity, the over-strength, the higher mode effects, and the importance of the structure, the design base shear is given by

$$V = \frac{S(T_a)M_v I_e W}{R_o R_d} \geq \frac{S(2.0)M_v I_e W}{R_o R_d} \tag{1}$$

where M_v accounts for higher mode effect, I_e is the importance factor, and R_d and R_o account for ductility and overstrength, respectively. The design base shear is distributed along the height of the building according to provisions that are similar to those in (NBCC 1995).



(a) (b)

Figure 4: Building layout: (a) plan, and (b) elevation

Table 1: Beam & Column Sections

Element	Size	Reinforcement
Beam	400 x 600	7 #20 bars at top, 5 #20 bars at bottom, and 4L #10 stirrups @ 100
External Column	500 x 500	12 #25 bars and 4L #10 ties @ 100
Internal Column	550 x 550	16 #25 bars and 4L #10 ties @ 100

DESIGN OF THE BUILDING FRAME BASED ON NBCC 2005

The building has been designed to resist the effect of the equivalent lateral loads combined with gravity loads; dead and live. The elements of the structures are designed based on the most critical load combination. The following load combinations have been used in the design: (a) the lateral load combination (D + 0.5 L + E), and (b) the gravity load combination (1.25*D*+1.5*L*), where D is the dead load, L is the live load and E is the equivalent static earthquake force. The design base shear based on the NBCC 2005 provisions is 424 kN and the ductility and overstrength factors are 4 and 1.7 respectively. The yield stress, f_y for reinforcing steel, and the 28-day concrete compressive stress, f_c' are assumed to be 400 MPa and 30 MPa, respectively. Live load on the roof is assumed to be 2.2 kN/m^2; on other floors it is 4.8 kN/m^2 on the corridor bay and 2.4 kN/m^2 on the other bays.

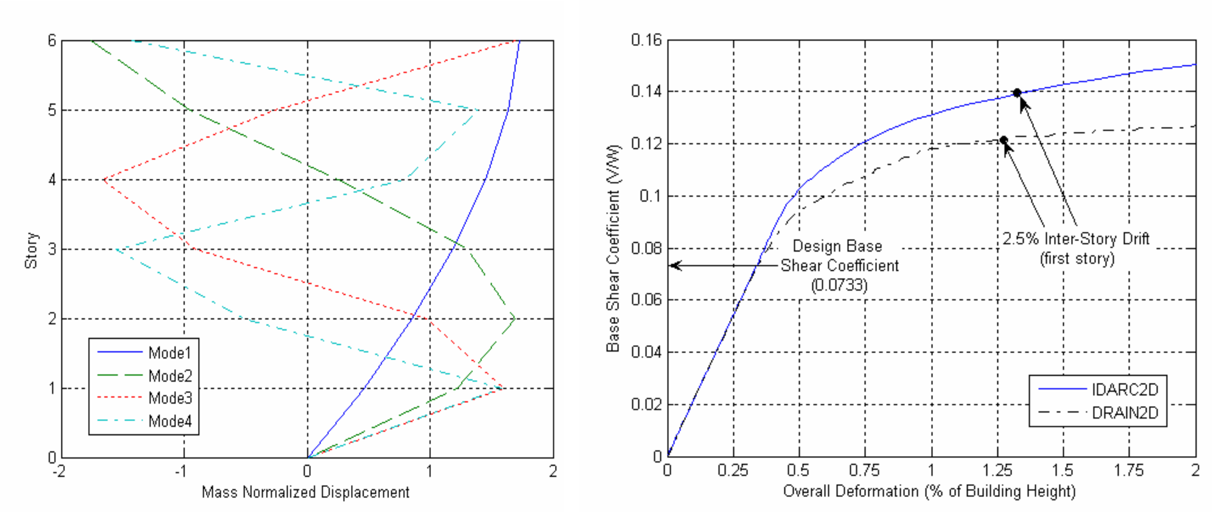
The static design however involves a few iterations until a safe and economic cross section is reached for all elements. Since the calculation of the base shear according to the NBCC 2005 requires the fundamental period of the structure, which is calculated using an empirical formula, the fundamental period should be checked using modal analysis after the first design iteration. Usually the modal analysis of the bare frame structure gives a longer period for the fundamental mode of vibration as compared to the period computed using the empirical formula suggested in the code. If the fundamental period obtained from modal analysis is greater than the one obtained from the empirical formula, then according to NBCC 2005, the design base shear needs to be revised to achieve a more realistic design load. The revision of the base shear should be based on a period which is 50% higher than that obtained from the emipirical formula of NBCC 2005 or the one obtained from the modal analysis, whichever is less. In this case, the code defined formula ($T = 0.075(h_n)^{3/4}$) gives a period of 0.78 s, while the modal analysis gives a value of 1.68 s, which is more that 1.5 times the code defined value (1.17 s). Thus the building needs to be redesigned for the base shear calculated using a period of 1.17 s. First four mode shapes of the building are shown in Figure 5(a) and the corresponding periods are 1.68 s, 0.54 s, 0.3s, and 0.2 s.

PUSH-OVER ANALYSIS

A force controlled push-over analysis is performed to simulate the structure's response to incremental lateral loading. The push-over analysis serves as an important tool for estimating the strength and ductility capacities of the structure and is performed here twice; once using IDARC2D and another time using DRAIN2D. The push-over curve obtained from the IDARC2D analysis is then compared with that obtained from DRAIN2D, both curves are shown in Figure 5(b).

The base shear coefficient is defined as the ratio of the base shear to the total tributory weight corresponding to a building frame, V/W. In this case, the design base shear coefficient is equal to 0.0733. The resulting push-over curves show that first occurence in hinge formation in a frame element corresponds to a base shear coefficient of approximately 0.1 when IDARC2D is used, and 0.09 when DRAIN2D is used. This result is acceptable since the design base shear is in the linear zone of the curve and is less than the base shear corresponding to the first hinge formation.

It's clear from Figure 5(b) that both programs give almost the same initial response, however there's a difference between the results in the post-yielding zone. Also shown on both curves is the point where the maximum inter-story drift reaches 2.5% (in this case this occurs at the first story level). The maximum inter-story drift corresponds to a base shear coefficient value of 0.139 and a roof drift (overall deformation) of 1.33% when using IDARC2D. The corresponding base shear coefficient is 0.123 and the roof drift is 1.26% when DRAIN2D is used.



(a) (b)

Figure 5: Analysis results: (a) Mode shapes, and (b) Push-over curve

DYNAMIC ANALYSIS

A dynamic analysis is performed using eight artificial ground motion records compatible for the seismic hazard at Vancouver (Tremblay et al. 2001). Four of those records are longer in duration, while the other four records are shorter in duration. The properties of these ground motions are displayed in Table 2. The roof drift and inter-story drift are important parameters to describe the overall deformation and performance of the structure. The total drift is expressed as a percentage of the total height of the building, while the interstorey drift is expressed as the percentage of story height. The maximum inter-story drifts of all floors along with the envelope and mean values have been compiled and plotted for all eight records (Figure 6(a)). The maximum inter-story drift occurs at the first story level, specifically due to the first short ground motion record (S1) and is equal to 2.3% while the mean value is 1.61%. The time-history of the first story produced by the ground excitation (S1) is also plotted (Figure 6(b)) to show the displacement of this story during the earthquake period and a few seconds later. The total duration of the earthquake is 8.53 seconds. It's clear from the time-history graph that the response of the first floor is maximized during the excitation period. However, after the ground motion stops, a plastic deformation of almost 0.37% (17 mm) is observed.

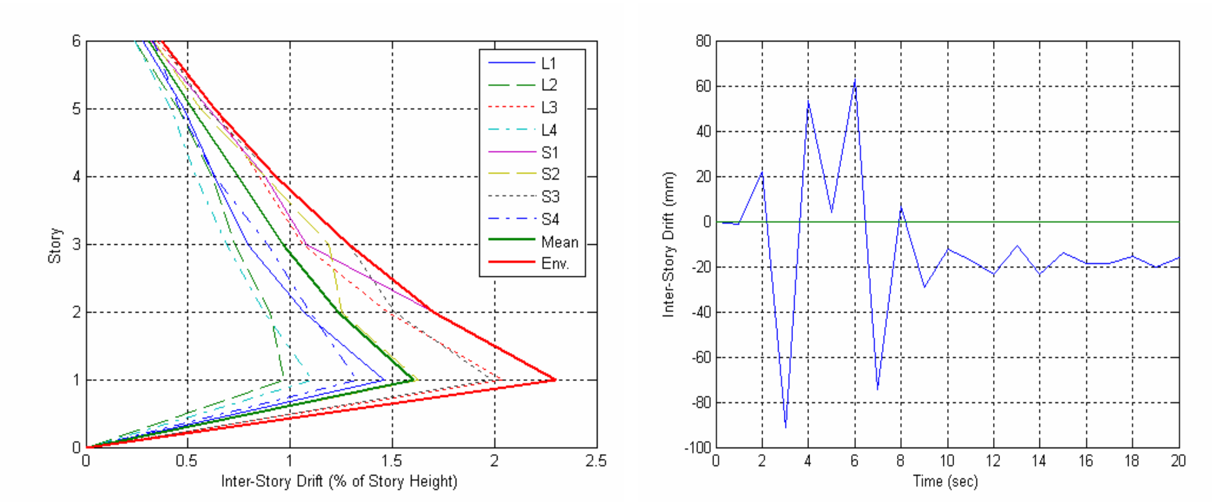
Table 2: General Properties of the Ground Motion Records

Ground Motion Record	L1	L2	L3	L4	S1	S2	S3	S4
Total Duration (s)	18.18	18.18	18.18	18.18	8.53	8.53	8.53	8.53
Peak Acceleration (g)	0.25	0.23	0.25	0.25	0.53	0.42	0.58	0.35

It should be noted that the ground floor is almost a third longer than the rest of the floors, and the ground floor columns have the same cross section as the rest of the building columns. Increasing the ground floor column cross sections could reduce the resulting drift to some extent. The maximum roof drift is also calculated for all eight records and shown in Table 3. The envelope value is found to be 0.98%, which occurs due to ground motion record (S3).

Table 3: Maximum Roof Drifts

Ground Motion Record	L1	L2	L3	L4	S1	S2	S3	S4
Max. Roof Drift (% of Total Height)	0.65	0.52	0.46	0.53	0.91	0.86	0.98	0.59



(a) (b)

Figure 6: Results: (a) Maximum Inter-Story Drifts, and (b) Time-History Curve (Story 1, S1)

DISCUSSION AND CONCLUSIONS

- The article presents a pre and a post processor for the IDARC2D computer program that is used for inelastic dynamic analysis of reinforced concrete buildings. The tools developed herein are simple and easy to use, so that the user can concentrate on the analysis rather than troubleshooting the data file construction for the analysis program.
- The preprocessor has been developed using Visual Basic scripts operated on an Excel workbook, while the post-processor is based on the MATLAB environment.

- Design and analysis of a six story RC frame building have been carried out to demonstrate the progrtams presented here. The building is assumed to be located in Vancouver representing a high level of seismic hazard. NBCC 2005 seismic provisions have been used in the design. After the design phase, the building has been analyzed against eight ground acceleration records corresponding to UHS-2500. The building should be able to resist collapse when subjected to this level of seismic hazard and the maximum inter-story drift value should not exceed 2.5%. Since no inter-story drift values exceeds 2.5 % and the structure didn't collapse, then the design is satisfactory.
- The IDARC2D output files contain a lot of data, not all of it is actually read by the post-processor, further automation should be considered to be able to get a full assessment of the design performance and damage indices.

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