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Computer Aided Design and Analysis of Reinforced Concrete Frame Buildings for Seismic Forces

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Abstract: For earthquake resistant design, evaluation of the seismic performance of buildings is essential to determine if an acceptable solution in terms of capacity and performance is achieved. Seismic performance evaluation requires static, modal and dynamic response analysis of a structure. The dynamic response history analysis often requires a large number of simulations using a number earthquake Ground Motion Records (GMR). Specialized computer programs for such analysis and design often lack the flexibility in user interaction as many of them come from research environments having focus only on the advanced analysis features. The study presents a user interface design and a scheme for automating the analysis process for evaluating the seismic performance of RC building frames. Such simulations involving a large number of earthquake GMR produce a huge amount of data that needs to be post processed in order to extract meaningful information about the behavior of a building under earthquakes. The study also discusses the development of such post processor. The software tools developed here have been demonstrated through a case study, where a six storey RC frame building has been designed based on the seismic provisions of the current edition of the National Building Code of Canada and analyzed to determine its seismic performance. The building is assumed to be located in Vancouver in western Canada. A set of eight simulated and sixteen actual ground motion records have been used in the inelastic dynamic time history analysis and a summary of the results have been presented.

Key words: Computer assistance, building frames, concrete, earthquake resistant design, seismic performance

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. A performance-based approach is desired in structural design where the structure is provided not only with adequate strength, but also appropriate deformability and damage tolerance for a given level of seismic hazard. Performance-based design (SEAOC, 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, current codes (NBCC, 2005) strongly recommend 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 (GMR) 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 and this study presents a general scheme for that with the implementation to a particular analysis software, namely IDARC2D (2006), a special purpose software tool for modeling the dynamic behavior of Reinforced Concrete (RC) buildings subjected to earthquake ground motion.

Although there are a number of general purpose software packages available for structural analysis

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and design, special purpose software tools are often necessary to particular research needs. Since RC framed buildings are used in the study, IDARC2D is used here as it is a specialized software with the capability of analyzing earthquake damage in multistory RC buildings and has a number of advanced analysis and modeling features which are not available in general purpose analysis software (IDARC2D, 2006). However, IDARC2D lacks a user interface and consequently, the input is written manually by the user to the text format and the output is also given in text form to be read by the user. This method of data input is cumbersome, 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 here 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 storey RC frame buildings.

To demonstrate the automation process developed here, a case study comprising a six storey RC frame building designed for Vancouver, Canada 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. To validate and compare the results obtained using IDRAC2D, the analyses have also been carried out using DRAIN2DX (Prakash *et al*., 1993) a well known program for inelastic dynamic analysis of two-dimensional frames. However, DRAIN2DX is more general purpose seismic response analysis software as compared to IDARC2D. Modeling RC frames using DRAIN2DX is difficult and a simplified model using the two-dimensional beam-column elements has been used here.

DESCRIPTION OF THE AUTOMATION TOOL FOR ANALYSIS AND DESIGN

As discussed earlier, a typical automation scheme for structural analysis comprises the following three main components; pre-processor, analysis module and the post-processor, as shown in Fig. 1. The pre-processor provides the user interface, preferably a graphical one through which the user can define the structural model, loads and support conditions. The pre-processing module then validates the models and conveys necessary information to the analysis module or engine. Once the analysis is completed, the output of that is processed by the post-processor which is designed to present the results in desired format. The post-processor may also be

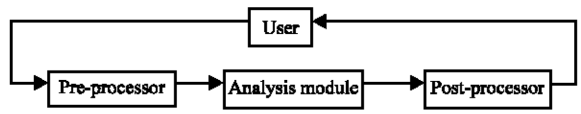

Fig. 1: Schematic representation of a typical scheme for analysis automation

designed to process the output data from multiple sessions of analysis, which is typical the dynamic analysis using multiple GMR and compile the results to present the summary.

In this study, this scheme has been implemented using the computer program IDARC2D, which is an inelastic dynamic structural analysis tool used for detailed modeling of reinforced concrete building frames. One of the important features IDARC2D includes is automatic generation of the moment-curvature (M-Φ) relation for beam and the axial force-moment (P-M) interaction curves for columns given the section size and reinforcement details. It also 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.

IDARC2D pre-processor: The pre-processor unit has been built using the Excel (Microsoft Corporation) and Visual Basic scripts. All input data are gathered in a Excel Workbook which provides appropriate forms with appropriate data labels to fill out with necessary 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 (Fig. 2). 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.

IDARC2D post-processor: 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 Fig. 3. 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

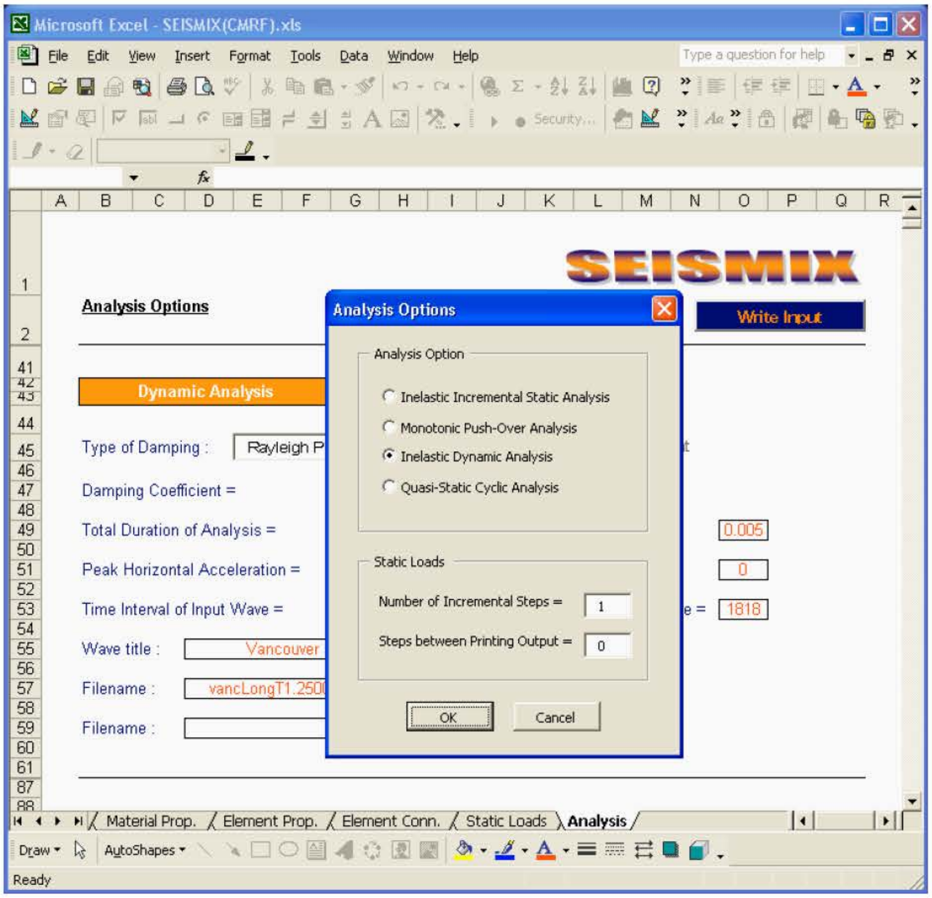

Fig. 2: The user interface for IDRAC2D pre-processor

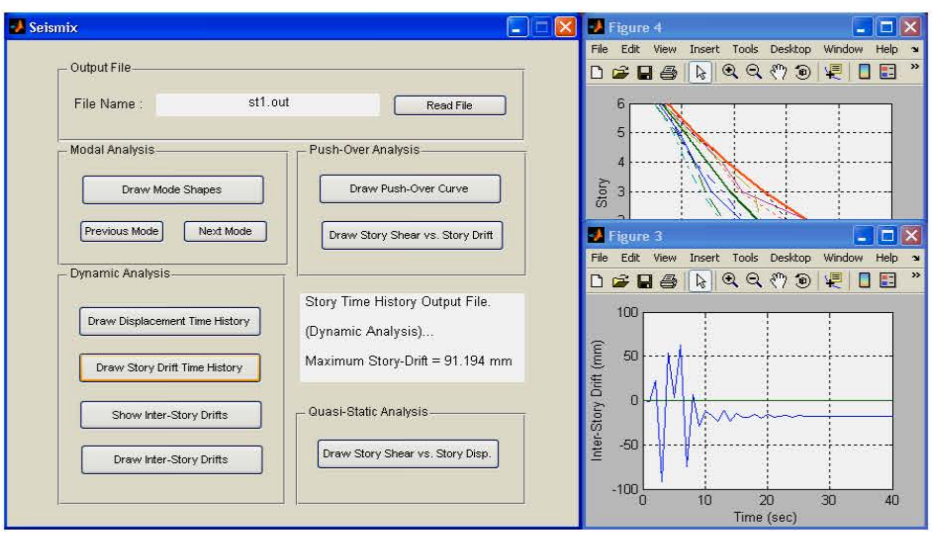

Fig. 3: The user interface for IDRAC2D post-processor

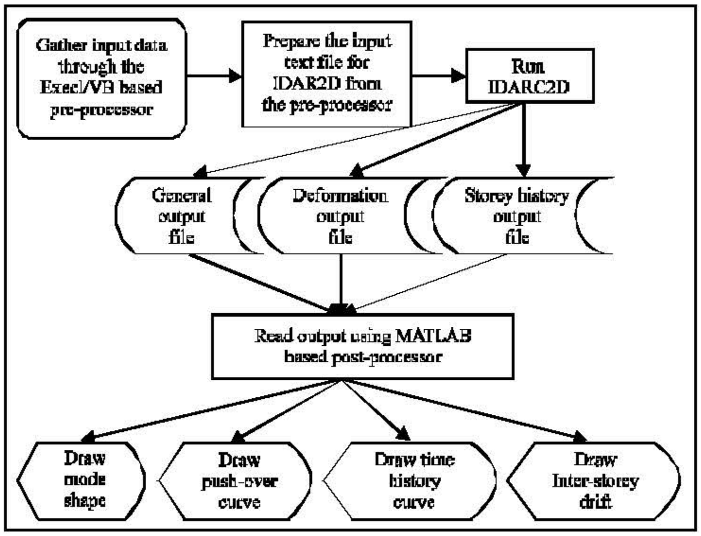

Fig. 4: Schematic architecture of the analysis automation system for IDARC2D

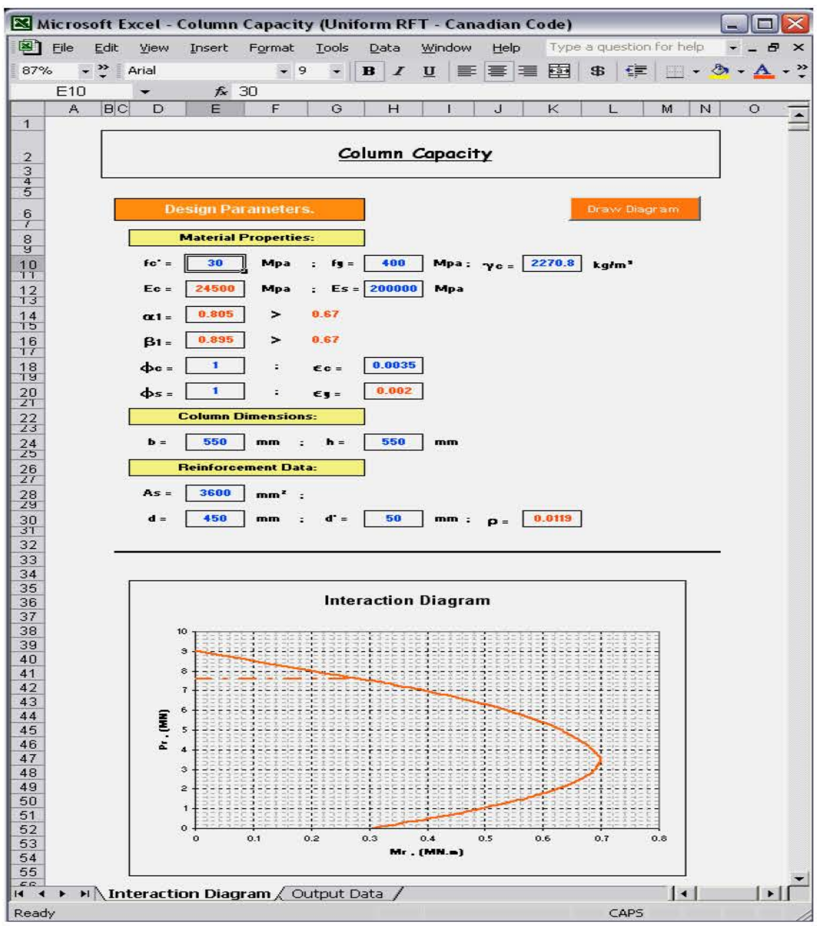

Fig. 5: P-M Interaction curve generator excel worksheet

shapes, inter-storey drifts and time-history graphs. It also organizes the output from multiple sessions of dynamic analysis with a number of earthquake GMR into summary tables or graphs as shown in Fig. 3 (top right corner). The data processed by the post-processor can also be presented in the Excel format.

Figure 4 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 for 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, storey drift, storey 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.

Generating beam-column properties: Two Excel files are created specifically for designing and calculating the capacity of rectangular reinforced concrete sections subjected to simple bending. Another Excel file is designed with the aid of VB scripts to generate the Axial Load-Bending Moment (P-M) interaction curves for rectangular reinforced concrete sections with uniform reinforcement. The input to these programs are the section size, reinforcement details, materials strength and resistance factors as defined in NBCC (2005). It must be noted that these tools are not required for IDARC2D analysis as the information produced by them can be internally generated by IDARC2D based on the section size, material properties and the reinforcement details. These tools are meant to be used with DRAIN2DX which does not have the capability to generate them internally.

Figure 5 shows a screens hot of the Excel worksheet to generate the interaction diagram. The advantage of this worksheet is that the user has the freedom of choosing the strength reduction factors for concrete and steel. The modulus of elasticity of concrete and steel are also specified by the user. The sectional dimensions and reinforcement are among the input parameters as well as position of the reinforcing steel. The stress-strain distribution of concrete is represented by an equivalent stress block and the crushing strain of the concrete is specified by the user. After all the data are entered, the P-M interaction curve is generated automatically by pressing the Draw Diagram button. First, the output data is written in another worksheet labeled Output Data which is linked to the interaction diagram.

CASE STUDY-A SIX STOREY RC FRAME BUILDING IN VANCOUVER

The use of the pre and post processor has been demonstrated in the following example. A six storey building in Vancouver has been designed using the NBCC (2005) seismic provisions. The geometric details of the building are shown in Fig. 6. The building has several 6 m 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 6 m corridor bay. The storey height is 4.85 m for the first storey and 3.65 m for all other storeys. The building is composed of a set of parallel frames equally spaced 6 m apart. A typical intermediate frame as shown in Fig. 6 has been considered for the detailed design and analysis. The chosen cross sections of the columns and primary beams resulting from the design are shown in Table 1. All secondary beams are assumed to be of size 300×500 and the slab thickness is 120 mm.

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 building with the single-degree-of-freedom system can be obtained by multiplying the spectral acceleration 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 V is given by Eq. 1:

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

where:

M_v = Accounts for higher mode effect,
I_e = The importance factor
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 NBCC (2005).

Table 1: Beam and column sections

Element	Size	Reinforcement
Beam	400×600	7 #20 bars at top, 5 #20 bars at bottom and 4L #10 stirrups at the rate of 100
External column	450×450	12 #20 bars and 4L #10 ties at the rate of 100
Internal column	500×500	12 #25 + 4 #20 bars and 4L #10 ties at the rate of 100

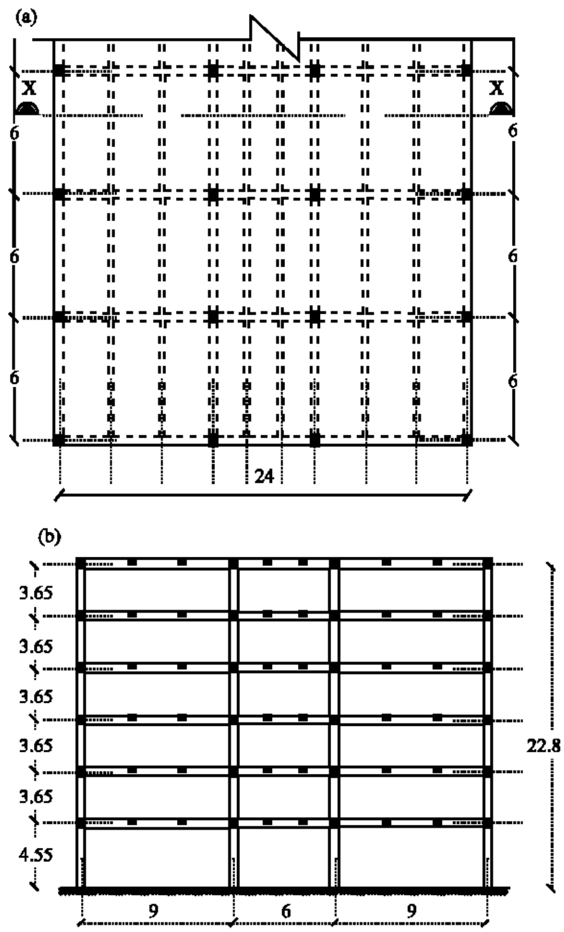

Fig. 6: Building layout: (a) plan and (b) elevation

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 + 0.5L + E) and (b) the gravity load combination (1.25D+1.5L), 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 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 against the one obtained from the 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, 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 empirical 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 sec, while the modal analysis gives a value of 1.68 sec, which is more that 1.5 times the code defined value (1.17 sec). Thus the building needs to be redesigned for the base shear calculated using a period of 1.17 sec. The reinforcement details of the primary beams and columns are given in Table 1. First four mode shapes of the building are shown in Fig. 7a and the corresponding periods are 1.68, 0.54, 0.3 and 0.2 sec.

Push-over analysis: A force and displacement 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. The push-over curve obtained using the IDARC2D and DRAIN2DX are shown in Fig. 7b.

In the push-over curves as shown in Fig. 7b, the base shear coefficient (V/W) is defined as the ratio of the base shear, V to the total tributory weight, W for the building frame. In this case, the design base shear coefficient is equal to 0.0733. The resulting push-over curves show that first occurrence of hinge formation in the frame element corresponds to a base shear coefficient of approximately 0.1 when IDARC2D is used and 0.09 when DRAIN2DX is used.

It's clear from Fig. 7b that both programs give similar initial response, however there is a difference between the results in the post-yielding zone. The point where the maximum inter-storey drift reaches 2.5% (in this case this occurs at the first storey level) is marked on

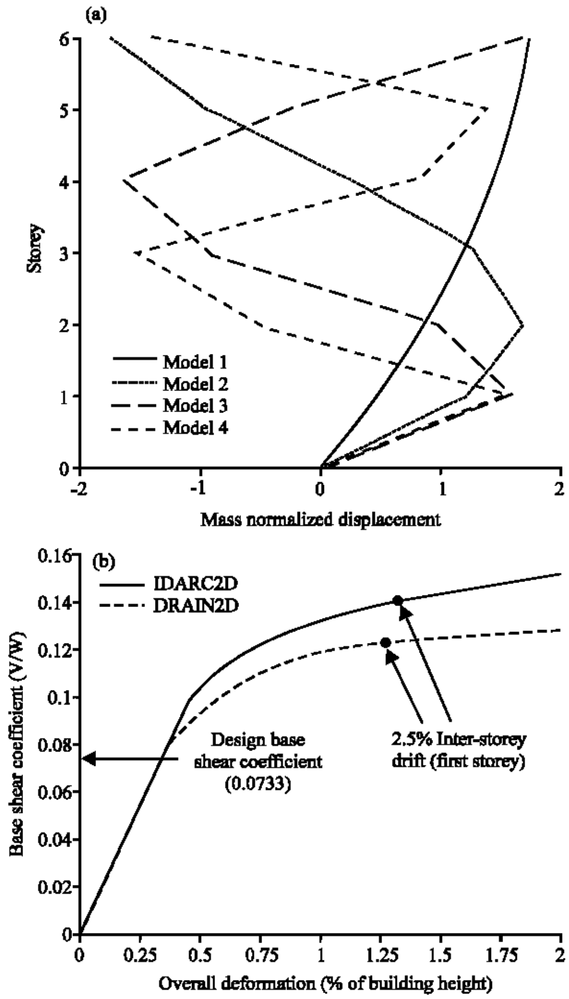

Fig. 7: Analysis results: (a) Mode shapes and (b) Push-over curve

both the curves. This point indicates the inter-storey drift limit in NBCC 2005 for collapse prevention performance. The maximum value of the inter-storey drift of 2.5% corresponds to a base shear coefficient of 0.139 and a roof drift (overall deformation) of 1.33% when IDARC2D is used and the corresponding base shear coefficient is 0.123 and the roof drift is 1.26% when DRAIN2DX is used.

Dynamic analysis: The roof drift and inter-storey drift are important parameters to describe the overall deformation and performance of the structure. The roof drift or the total drift is the roof displacement expressed as a percentage of the total height of the building, while the interstorey drift is the differential displacement between current level to the one immediately below and expressed as the percentage of storey height. A dynamic analysis is

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

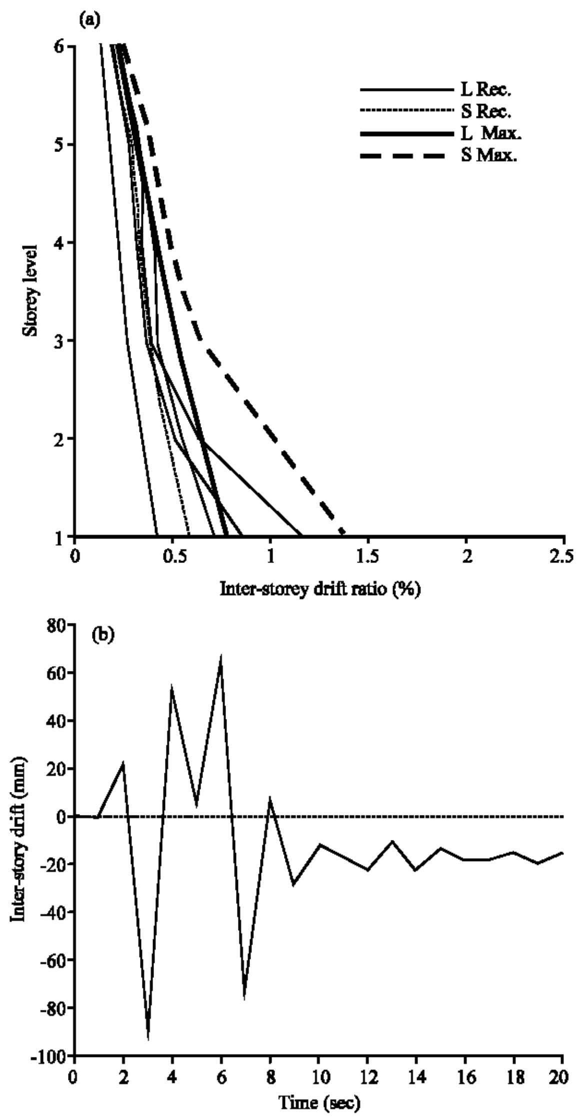

Fig. 8: Results: (a) Maximum inter-storey drifts and (b) Time-history curve (Storey 1, S1)

performed using eight artificial ground motion records compatible with the seismic hazard at Vancouver (Tremblay and Atkinson, 2001). Four of those records of long duration, while the other four records are of short duration. The properties of these ground motions are shown in Table 2. The maximum inter-storey drifts of all floors along with the envelope and mean values have been compiled and plotted for all eight records (Fig. 8a). The maximum inter-storey drifts also occur at the first storey level and are equal to 2.07 and 1.46% due to the long duration and short duration records, respectively. The time-history of the first storey produced by the ground excitation, S1 is also plotted (Fig. 8b) to show the displacement of this storey during the earthquake period and a few seconds later. The total duration of the earthquake is 8.53 sec. It is 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.

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).

A collection of sixteen actual records are used in the nonlinear dynamic analysis. Some of these records were selected form the seismic database of McMaster University, Canada (Naumoski *et al*., 1988) and other records were selected from the database of Pacific Earthquake Engineering Research Center (PEER, 2007). The records were selected based on the peak spectral acceleration to peak velocity ratio (A/V ratio) similar to the seismic motion is Vancouver, which is close to 1. These records are scaled based on the seismic hazard spectrum for Vancouver. The characteristics of the actual records used in the analysis before scaling are shown in Table 4, where, A and V represent the spectral acceleration and velocity of a GMR, respectively. As scaling affects the dynamic response of the structure (Naumoski *et al*., 2004), the following two methods of scaling are used here to identify the sensitivity of the response to scaling: the ordinate method and the partial area method (Fig. 9). First, spectral analysis is performed for each record. The response spectrum is then scaled to match the design spectrum of Vancouver.

The ordinate method of scaling is performed based on the fundamental period of vibration of the structure, as explained here with reference to Fig. 9a. The response spectral acceleration corresponding to the fundamental period (Sa_2) is scaled to the value of the design spectral acceleration (Sa_1) corresponding to the same period. In other words all data points of the record are scaled based on the factor Sa_1/Sa_2.

On the other hand, the partial area method of record scaling (Fig. 9b) is based on the first and second period of vibration of the structure. The area (A_2) under the response spectral acceleration curve between 1.2 times the fundamental period value and the second period value is scaled to the corresponding area (A_1) under the design spectral acceleration curve between the same periods. All the data points of the record are scaled based on the factor A_1/A_2. The response spectra of the real GMRs scaled using the above two methods for the six-storey building is shown in Fig. 10 and compared with the NBCC 2005 design spectrum.

Figure 11 shows the maximum inter-storey drifts of the building frame produced by IDARC2D. The maximum Mean+SD values of the inter-storey drift are 1.23 and 1.26% for the ordinate method and partial area method scaled records, respectively, which occur at the first storey level. Similar values have been produced using DRAIN2DX program as shown in Fig. 12, which follow the same trend and orders of magnitudes for the inter-storey drift (mean+SD). The difference in the maximum dynamic drift demand values calculated

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

Table 4: Ground Motion Records (GMR) from past earthquakes

Record	Location/Record No.	Date	A_{max} (g)	V_{max} (m sec^{-1})	A/V ratio	Duration (sec)
1	Imperial valley	18/05/1940	0.350	0.330	1.04	53.74
2	Kern county	21/07/1952	0.180	0.180	1.01	54.40
3	Kern county	21/07/1952	0.160	0.160	0.99	19.16
4	Borrego mountain	08/04/1968	0.050	0.040	1.10	45.00
5	Friuli, Italy	15/09/1976	0.110	0.102	1.08	26.39
6	San Fernando	09/02/1971	0.150	0.150	1.01	65.18
7	San Fernando	09/02/1971	0.210	0.210	1.00	79.48
8	San Fernando	09/02/1971	0.170	0.170	0.99	62.58
9	San Fernando	09/02/1971	0.180	0.200	0.88	43.00
10	San Fernando	09/02/1971	0.200	0.170	1.19	47.08
11	Gazli, USSR	17/05/1976	0.608	0.654	0.93	16.27
12	Coalinga	22/07/1983	0.217	0.181	1.20	19.50
13	Monte Negro	15/04/1979	0.170	0.190	0.88	40.40
14	SUCH850919AL.T	19/09/1985	0.110	0.110	0.94	120.00
15	VILE850919AT.T	19/09/1985	0.090	0.110	0.83	128.00
16	Coyote Lake	06/08/1979	0.271	0.263	1.03	27.19

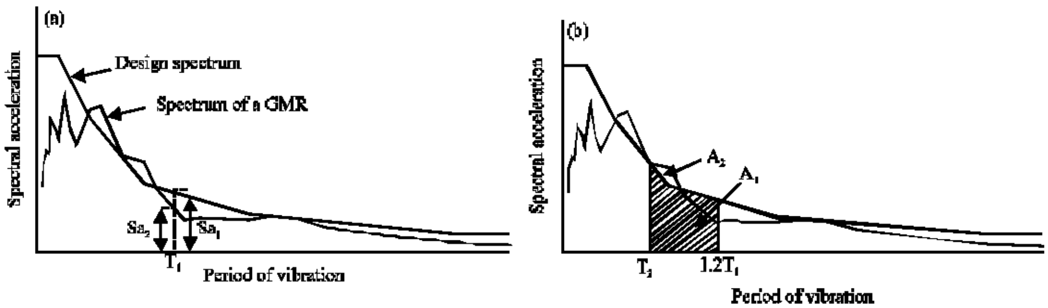

Fig. 9: Methods used for scaling the ground motion records: (a) Ordinate method, (b) Partial area method

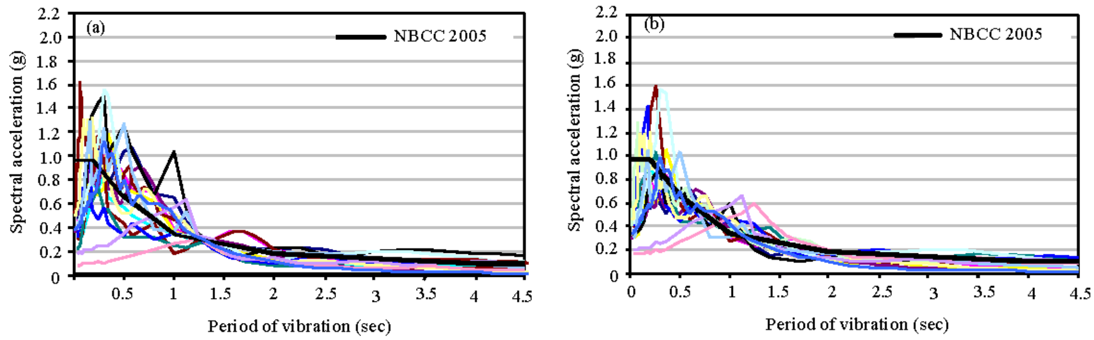

Fig. 10: Comparison of the response sdpectra of scaled actual GMRs with the NBCC 2005 spectrum: (a) Ordinate scaling and (b) Partial area scaling

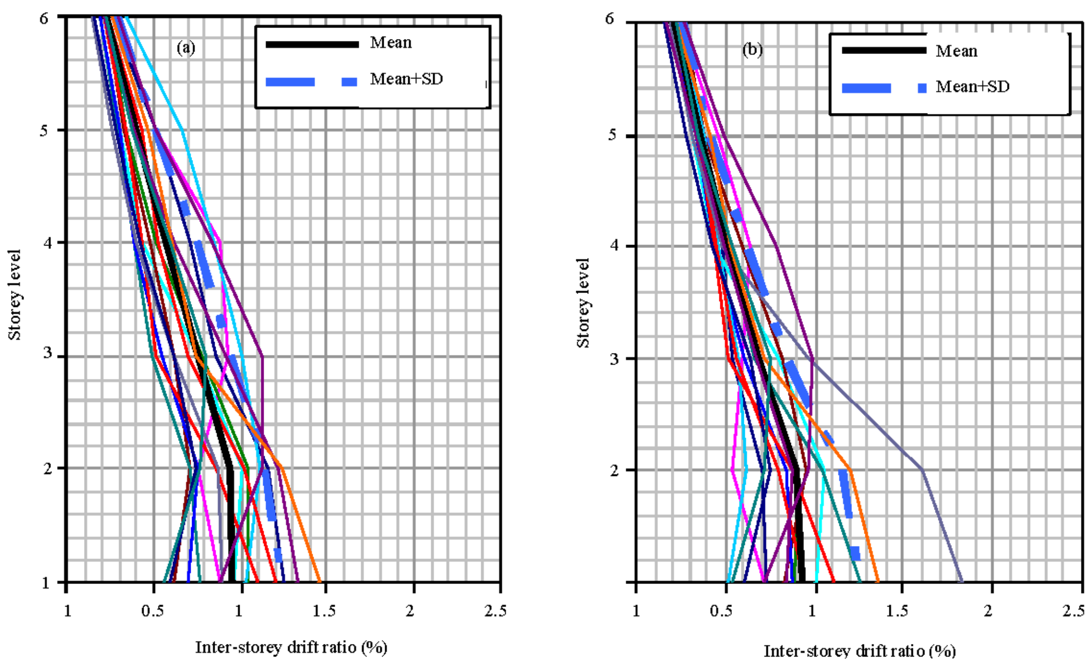

Fig. 11: Inter-storey drift envelops using actual GMRs: (a) Ordinate scaling and (b) Partial area scaling (IDARC2D results)

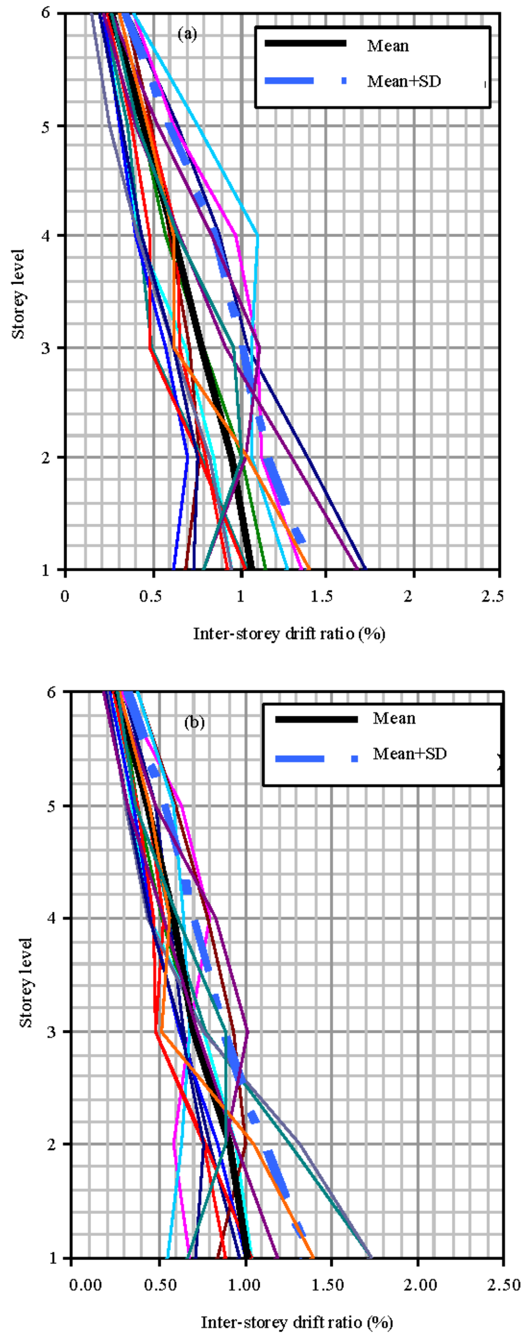

Fig. 12: Inter-storey drift envelops using actual GMRs: (a) Ordinate scaling and (b) Partial area scaling (DRAIN2DX results)

using IDARC2D and DRAIN2DX are within 10% in all cases. The results are consistent with that using the synthesized records presented earlier.

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 pre-processor has been developed using Visual Basic operated on an Excel workbook, while the post-processor is based on the MATLAB environment.
- The pre and post processing tools developed here have been demonstrated through a six storey RC frame building which has been designed according to the National Building Code of Canada.
- 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 synthetic and sixteen real ground acceleration records corresponding to the seismicity in Vancouver to determine its performance characteristics.
- The building is expected to resist collapse when subjected to this level of seismic hazard and the maximum inter-storey drift value should not exceed 2.5%. Since no inter-storey drift values exceeds 2.5% and the structure did not collapse then the design is satisfactory.
- The IDARC2D results have been verified with that produced by DRAIN2DX. For DRAIN2DX analysis, the RC elements have been modelled using simple beam-column elements and to generate the properties of these elements based on the section size and reinforcement details, a VB-Excel tool has been developed. The results produced by IDARC2D and DRAIN2DX have been found to be comparable.

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