AUTOMATED ANALYSIS AND PERFORMANCE EVALUATION OF EARTHQUAKE RESISTANT STEEL FRAME BUILDINGS

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

ABSTRACT

Special purpose structural analysis programs often lack the user interfaces and the flexibility the way modern software offers in terms of dynamic libraries and Application Programming Interfaces. This paper discusses the development of a pre and post processing tool for DRAIN-2DX, a program for seismic response analysis of building frames. The paper focuses on the earthquake resistant design of steel frame buildings. The tool developed here is used for automating the dynamic analysis process such that a large scale simulation for the evaluation of seismic performance of steel frame buildings could be carried out easily. Such large scale simulations produce a huge amount of data which would be handled by the post-processor in order to extract meaningful information about the behaviour of a building under earthquakes. As a case study, a ten storey moment resisting steel frame building designed based on the NBCC 2005 seismic provisions are analyzed using the software tools discussed here. The building is assumed to be located in Vancouver ion western Canada. 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 response history analysis. A set of eight simulated ground motion records that are compatible with the seismic hazard spectrum of Vancouver have been used in the dynamic analysis. Seismic excitation causes damage in a structure, which is reflected in the response of the structure. The results are discussed in detail to demonstrate the advantages of the tools developed herein.

KEY WORDS

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

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INTRODUCTION

While 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. The seismic design of buildings in Canada is performed according to the relevant provisions of the National Building Code of Canada (NBCC). The seismic design provisions of the current edition of the code (NBCC 2005) 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. An overview of the seismic provisions of NBCC 2005 is available in CJCE (2003). 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. 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.

Now-a-days automated software systems have become an essential for civil engineering computation. Any kind of complicated analysis and design can easily be done now with less time effort than before. Thus a handy, easily available and less complicated tool is always in demand. Analysis and design of an earthquake resistant building frame is always as complicated as earthquake itself. To perform this kind of job several commercial and non-commercial software are available such as, DRAIN-2DX (Prakash et al. 1993), DRAIN-BUILDING (NISEE, 2005), DRAIN-RC (DRAIN-RC 2006), IDARC2D (IDARC2D 2006), SAP-2000 (SAP 2000, 2006), ETABS (NISEE 2005), to name a few. DRAIN-2DX is a simple, flexible and widely used for academic research on seismic design and evaluation of buildings. In this paper the analysis automation process has been inmplemented for DRAIN-2DX software and demonstrated through a building with Steel Moment Resisting Frames designed according to NBCC 2005. The building is assumed to be located in Vancouver representing a location of potentially high level of seismic hazard.

DRAIN-2DX is a general purpose computer program for static and dynamic analysis of plane structures (Prakash et al. 1993). Linear and non-linear static and dynamic analysis can be carried out by this tool. But this is not user-friendly software, and the preparation of input data file for different type structure for various analysis is cumbersome. Because of the lack of a graphical user interface , it is also difficult to use the output file to interpret the results and draw different graphs (pushover, base shear vs interstorey drift, mode shapes). Calculation of base shear from dynamic analysis by DRAIN-2DX is also not a very easy task. So, some automation for the pre-processing and post-processing of this software is necessary to make it user-friendly and more effective.

AUTOMATION OF DRAIN-2DX

PRE-PROCESSOR

To analyze a frame with DRAIN-2DX program an input file named DRAIN.INP is necessary and the input data should be formatted as suggested in the program's manual. Writing a DRAIN.INP file for various types of analysis with varying frame characteristics and different earthquake records is quite cumbersome and time consuming. A MATLAB-based pre-processing program is developed to collect information about the frame geometry and analysis information such as data for STATIC analysis, DYNAMIC analysis etc. The preprocessor prepares the input file DRAIN.INP according to the specification given in the user's manual of DRAIN-2DX. Post-processing program has been developed using MATLAB programming language, this program is also able to draw the frame's geometric shape from the input file to check the accuracy of the co-ordinates in the input data files.

POST-PROCESSOR

Designing a member by collecting data manually from the DRAIN-2DX output files is a laborious task and probability of error in transferring data is high. So, it demands some automation in collecting data from the output file and visualizind it. For this part of processing system several MATLAB functions been developed to perform the following tasks by scanning the DRAIN-2DX out put file:

- Calculation of the base shear from dynamic analysis.
- Calculation of the maximum, mean and average interstorey drift.
- Draw storey level shear versus interstorey drift graph.
- Draw pushover (base shear versus roof displacement) graph from pushover analysis and mode shapes from modal analysis.

The name of the output file of DRAIN-2DX is input to the post-processor to perform the abovementioned tasks. In some cases, the header lines under which the output data corresponding to special analysis, such as time history, pushover etc. are stored is necessary as input data in the program. The schematic details of the pre and post processing modules are shown in Figures 1 and 2.

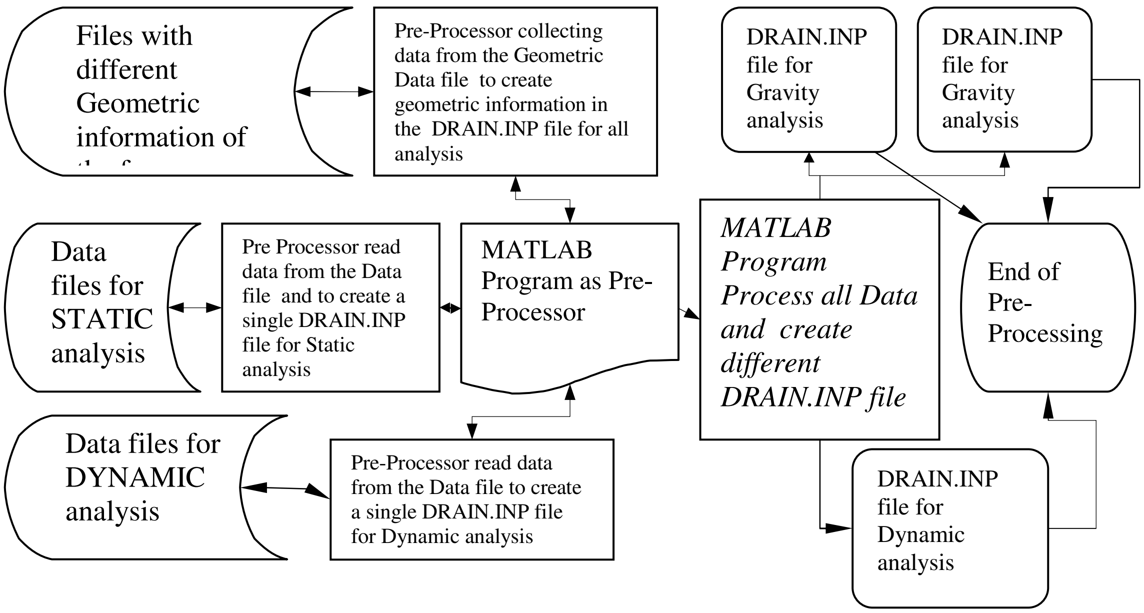


Figure 1: Flow chart of the pre-processor

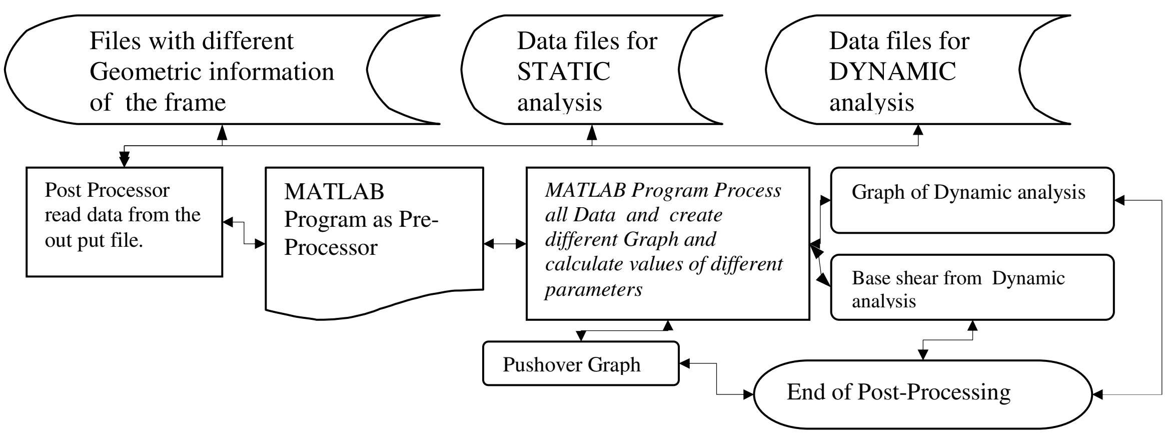


Figure 2: Flow chart of the post-processor

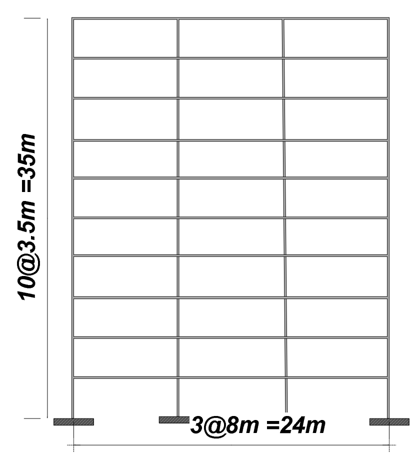
BACKGROUND ON NBCC2005

The provisions of NBCC 2005 is based on uniform hazard spectra corresponding to 2% probability of exceedance in 50 years where the NBCC 1995 was based on 5% probability of exceedance in 50 years. The NBCC 2005 seismic design provisions continue to rely on the specification of the minimum lateral seismic forces for the building must be designed and the acceptable drifts under such forces. In 2005 edition of NBCC 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.

CASE STUDY: A TEN STOREY STEEL FRAME BUILDING IN VANCOUVER

PROBLEM DEFINITION

For this study a simple ten storey building with steel moment resisting frames is considered here and it is assumed to be situated in Vancouver in the western Canada. The geometric details are shown in Figure 3. The building has a series of eight-meter bays in the E-W direction and 3 bays in the N-S direction. Also the frames assumed to be fixed to the ground.The specified minimum yield strength of steel (F_y) is 345 MPa and steel type is CSA G40.21 350W**.** The plan of the building and elevation of the frame is shown in Figure 3.



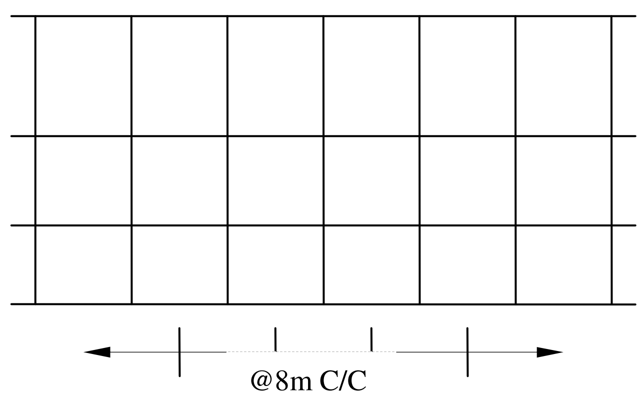


Figure 3: Layout of the building

The building considered here can be modeled by a series of transverse frames connected by rigid links. For simplicity the exterior and interior ductile frames are kept similar. Thus a single frame along with the floor mass tributary to it can be used in the analysis, and the analysis procedure becomes two-dimensional. For consistency with this procedure, accidental torsion is not considered in obtaining the design forces.

DESIGN DETAILS

The frame is designed for lateral loads which is calculated using the equivalent static load method as described in CJCE (2003). The design base shear (V) is determined according to NBCC 2005 by using the Equation 1. The elastic base shear V_e for a single-degree–of-freedom system is obtained from the spectral acceleration value $S(T)$ corresponding to the fundamental period of the building T_a and the weight of the building W. Ductility value $R_d = 5.0$ and force modification factor $R_o = 1.5$ are taken to modify the elastic base shear (V_e) for calculation of design base shear as suggested in NBCC 2005, and the design base shear for the given building has been found to be 324.8 kN. The base shear is distributed across the height of the frame, using the procedure suggested by NBCC 2005 to obtain the floor level forces (inverted triangle). A major challenge to performance-based design is to develop an efficient and effective general methodology for the design of structures at multiple performance and hazard levels (Humar et al. 2005). Modal analysis has performed to calculate the modal period and effect of modal period on the calculation design base shear.

$$V = \frac{S(T_a)M_v I_E W}{R_0 R_d} \geq \frac{S(2.0)M_v I_E W}{R_0 R_d} \qquad (1)$$

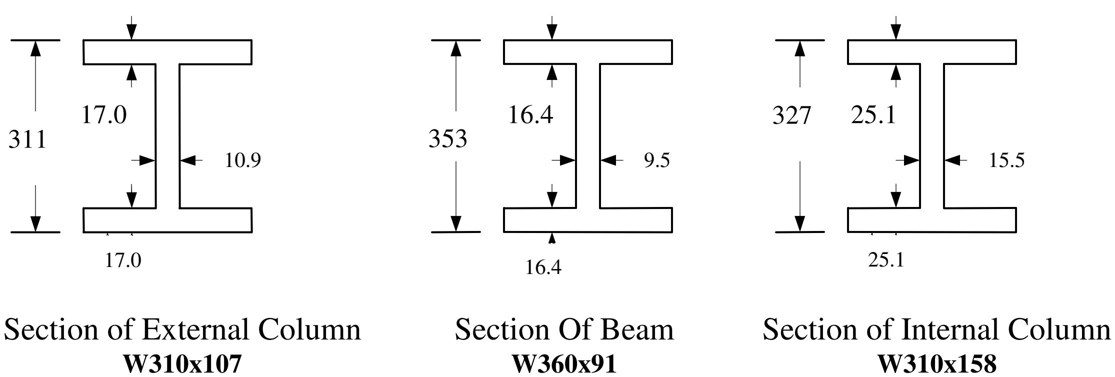
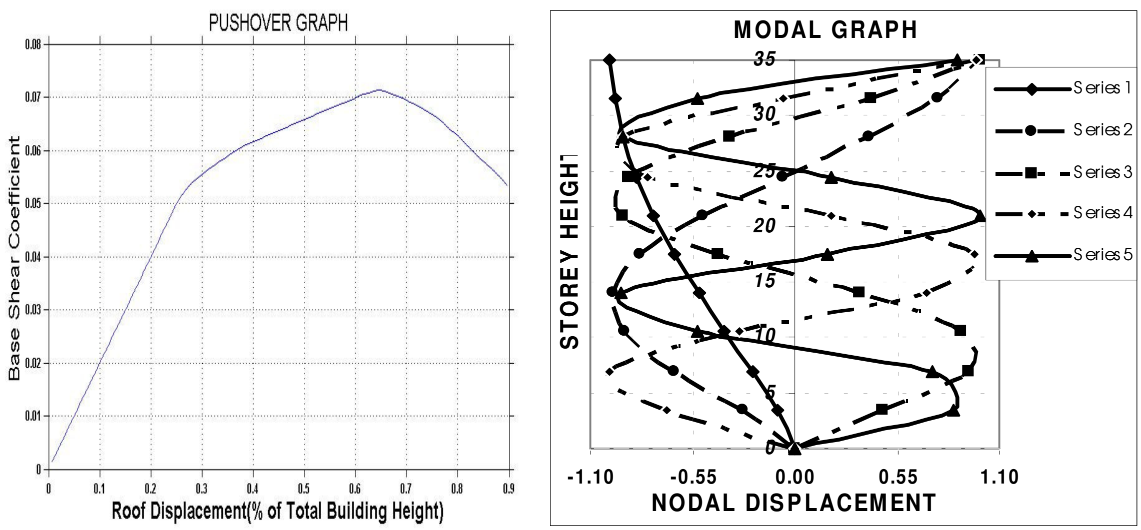


Figure 4: Details of the teel section used in the design

The section properties of the beams and column of the frame are taken from the 'Handbook of Steel Construction' (CISC 2004). Member forces are calculated through GRAVITY and STATIC analysis of DRAIN-2DX program and design member forces have been determined from various combinations of Dead Load, Live Load and Earthquake Loads according to NBCC 2005 guidelines. The sections of beam and column are designed according to the guidelines given in 'Handbook of Steel Construction' and details of the sections are shown in the Figure 4.

ANALYSIS

The evaluation of seismic performance of any structure requires the estimation of its dynamic characteristics and the prediction of its response to the ground motions to which it could be subjected during its service life. In this case static pushover and non-linear dynamic analysis have been performed using DRAIN-2DX program. The pushover analysis has been done by considering P-• effect and 3% strain hardening. Pushover analysis provides the base shear for a given interstorey drift, which is an important damage parameter and the pushover curve is shown in the Fig. 5(a). The dynamic characteristics, namely the periods and mode shapes have been obtained through an eigenvalue analysis. Figure 5(b) shows the mode shapes.



(a) (b)

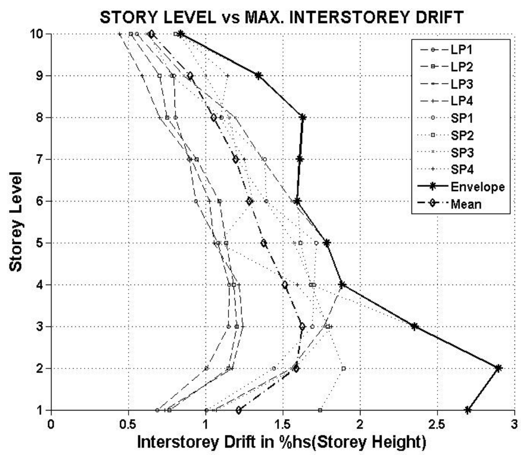
Figure 5: Analysis: (a) Pushover Graph, and (b) Mode Shapes

Inelastic time history analyses provide the damage states of the building when it is subjected to various levels of ground motion. In this study dynamic time history analysis has been conducted for a set of eight artificial ground motion records compatible with the seismic hazard spectrum for for Vancouver, Canada (Tremblay et al. 2001). Among these data four are for long period and four are short period. From the dynamic analysis the maximum interstorey drift of each record for each storey level and the maximum of all the maximum interstorey drifts (envelope values) have been calculated and shown in

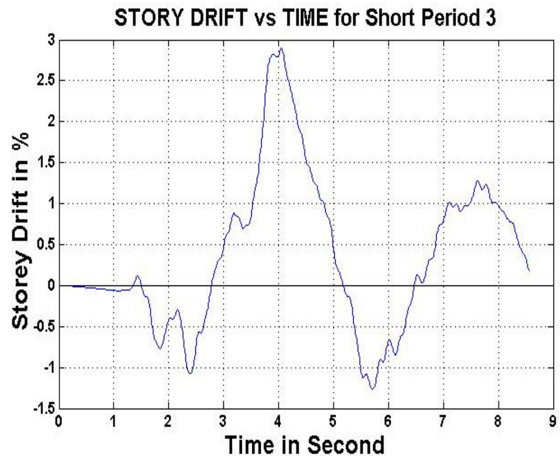
Figure 6(a). The mean values of all the maximum interstorey drift are also presented in the same figure. The maximum roof displacement for each set of data has been calculated and shown in Table 1.

Table 1: Maximum roof displacement (% H) for different data

LP1	LP2	LP3	LP4	SP1	SP2	SP3	SP4
0.2257	0.2887	0.4319	0.2640	0.3744	0.3800	0.4506	0.2741



(a)



(b)

Figure 6: Analysis: (a) Storey level vs Maximum Storey Drift, and (b) Time History Graph (Storey 2 drift)

DISCUSSION AND CONCLUSIONS:

The paper discusses a set of MATLAB based computer programs for pre-processing the data file for DRAIN-2DX, a widely used seismic analysis tool for plane frames, and a postprocessor for interpreting and visualizing the output data. As a case study, a ten storey steel moment resiting frame building designed according to NBCC 2005 has been presented. The design base shear for a typical transverse frame of the building is estimated as 324.8 kN and the base shear calculated from the dynamic analysis is 231.5 kN. So, it has been shown that the building is safe for the above mentioned acceleration records. From the time history analysis the recorded maximum roof displacement is 0.451% of building height and it has happened for 3rd data set of short period. The calculated maximum interstorey drift is 2.8% of total building height and it occur at 2rd storey level for 3rd acceleration record of short period. So, it has been observed that the maximum roof displacement and the maximum interstorey drift are occuring in the time history analysis of the same set of ground excitation. The interstorey drift appears to be high (more than 2.5%) from the building's collapse prevention point of view and performance may not be acceptable. Thus the building should be redesigned for an acceptable level of seismic performance (i.e., collapse prevention for an earthquake with 2% probability of exceedance in 50 years)

From the time history graph it is observed that the excitations of the structure is high at the mid of the time range, so, major damage of the structure occurred at this time range. The maximum storey drift graph reflect that that the lower storeys have more interstorey drift than the upper ones.

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