Number of Yield Excursion Cycles versus Performance Based Seismic Design

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SUMMARY:
The content of the paper is to emphasis the need of yielding some of the components of a building structure in order to absorb sufficient amount of energy during severe earthquake ground motions in such a manner that the concerned building structure should not dislodge structural integrity in fail safe manner. In order to accomplish the objectives of this paper, some referred steel building frameworks have been modeled using the performance based seismic design criterion laid down in FEMA's 273, 350. Analysis results for the number of yield excursion cycles have been used for the further investigations for performance evaluation under varying earthquake ground motions.

Key words: Performance based seismic design, Yield excursion cycles, hysteretic loops, etc.

1. INTRODUCTION

Performance based seismic design has undergone critical appraisal in the recent past due to enhanced capability of nonlinear modeling with guidelines in the current state of art [1,2,3,4,5,6,7,8]. Recently performance of building structures has been questioned in spite of high life safety but with types of damage patterns, which were not accepted even to the developed economy of USA and Japan during Northridge and Kobe earthquakes. A number of performance indicators are available in literature to mark performance objectives, however, number of yield excursion cycles has been found to be more comprehensive in the recent past [10].

The aim of this paper is to formulate a problem of steel building framework and the same has been analyzed for performance objectives. The responses in terms of number of loops resulting into number of yield excursion cycles indicate damages in terms of hysteretic energy. Higher the number of yield excursion cycles, more will be damages to the concerned structural members, hence such information's are useful tool for performance indicators.

2. PROBLEM FORMULATION

2.1. Relation between Energy (E_D) and Number of Hysteretic Loops

Hysteretic energy through yielding is the outcome of the severe ground motion, when a structure yield and takes the advantage of ductility. Elasto-plastic behavior of steel frames has been considered since such a behavior is closely related with the steel frame actual behavior.

$$E_{hi}=4k\delta_y^{\,2}(\mu_i-1)=8E_s(\mu_i-1) \tag{2.1}$$

During successive loop under varying earthquake ground motions, the total energy dissipated for displacement ductility = 2, 3, 4, 5, 6, 7 etc. is following:

$$E_D = \sum_{i=1}^{n} E_{hi} = 8E_s + 16E_s + 24E_s + 32E_s + 40E_s \tag{2.2}$$

The above equation (2.2) forms the arithmetic progression with the resultant values.

i.e., $$E_D = 8n \times \frac{(n+1)}{2} E_s \tag{2.3}$$

Where E_D is the total energy dissipated, n is the total number of loops and E_s is the strain energy. For performance based criteria the equation (2.3) is an important equation since, elastic strain energy (E_s) presents IO/OP performance levels and the successive values of total hysteretic energy reveals the other performance levels (LS, CP etc.)

2.2. Number of Yield Excursion Cycles and PBSD

Number of yield cycles (NEYC) is an effective comparative index of the severity of ground shaking. For each cycle under reversal of stresses, a structural component yields in tension and compression. While a component undergoes reversal of stresses without yielding, the input energy is stored as strain energy and during reversal it is dissipated as damping energy. However, reversal of stresses beyond yielding directly dissipates energy and as a result the capacity decreases tending towards collapse if the components are directly taking the loads e.g., a column undergoes reversal of loads in the yielded portion, the chances of collapse increases. If a horizontal components like beam yields and undergoes reversal of stresses, and the input seismic energy is dissipated in safe mode. The number of yields while a structure or the structural components passes from tensile to compression and from compression to tension are important for quantifying the damages, because the functionally of the structure is adversely affected by the number of yield excursions.

The most important parameters for number of yield excursions are the well defined yield point, and steel components have such a characteristics. Demand on components through capacity design can be met through the limited number of members. In this regards weak beam and strong column is fully established. During severe earthquake ground motions allowing some components into the inelastic region in desirable manner are well documented and needs simplicity for code based applications. Significant inelastic deformation before a component releases from tension and comes into compression and vice-versa, which is important for documentation for control of energy dissipation in the definite manner. Such kinds of the above possibility of the formation of yielding and changing from tension to compression and vice-versa are the key points of identification and quantification of damages. Number of yield and yield excursions are not required to be same because some of the yield may not participate for yield excursion. Such a possibility may be very close to the collapse zone. Number of loops has the relation with the number of yielding. In one complete loop the numbers of yield excursions are:

$$2N + 1 \text{ or } 2N \tag{2.4}$$

Where N is the number of loops. If the loop is complete and tends to the next loop, the number of yield is 2+1=3, otherwise the loop is tending to complete the loop, and the yield excursions are 2. Performance of a component depend upon the number of loops which can be possible without detrimental any consequences which results into collapse procedures. The size of the loop is also important because the larger the area the larger will be damage.

3. MODELING AND ANALYSIS

For performance based seismic design development, it is the first task to assess the performance capability of the structural systems for the performance objectives assigned. Identification and quantification of damage at global and local locals is the key element for an effective analysis procedure under seismic loading. Analysis of response for the determination of damages at various performance levels depends upon the modeling and their corresponding analysis procedures. Analysis procedures require the requisite nonlinear model of the building frames along with the loading on the structures. In order to accomplish the desired objectives of this study, nonlinear static pushover analysis and time history analysis have been conducted on the building frames modeled in Perform 3D, 2006 [17] under varying seismic loading. Five steel frames building have been taken from the literature, where these frames have been used for performance evaluations. These frames have been modeled using RAM Perform 3D [17]. Using FEMA 273 [3, 7], base shear corresponding to performance objectives have been estimated and were applied to the respective building frames. Accelerograms in-built to this software have been used for time history analysis. Nonlinear static pushover analysis and time history analysis for the modeled building frames have been conducted. Subsequently analysis results were recorded for performance assessment. Various steps for modeling and analysis in this study are listed below:

3.1. Development of Performance Objectives

The main objective of performance based seismic design is to evaluate the performance of a system at different seismic hazards. Selection of performance objectives is the first task of performance based seismic design. A comprehensive performance assessment needs to be taken care from the conceptual phase of design procedure in order to reduce the number of iterations for achieving the assigned performance. Using FEMA-273 [3], a generalized format of performance objectives corresponding to various performance levels have been developed for the present study. A set of earthquake ground motions in-built in RAM Perform 3D have been used further for evaluation and data base, as required for damage assessment in this study.

3.1.1. Design Spectra Parameters

Using the site parameters and the guidelines by FEMA 273 (1997), the following table 3.1, has been developed in order to get the base shear corresponding to four performance levels.

Table 3. 1. Performance level site parameters [3, 7]

Site Location	Site Class	Performance Level	Earthquake Level	S_s (g)	S_1 (g)	F_a	F_v
Latitude 36.9^{0}N Longitude 120^{0}W	D	OP	50%/50	0.126	0.061	1.60	2.40
		IO	20%/50	0.209	0.100	1.60	2.40
		LS	10%/50	0.290	0.140	1.57	2.24
		CP	2%/50	0.500	0.230	1.40	1.94
Latitude 41^{0}N Longitude 115.2^{0}W	D	OP	50%/50	0.109	0.035	1.60	2.40
		IO	20%/50	0.180	0.0580	1.60	2.40
		LS	10%/50	0.250	0.080	1.60	2.40
		CP	2%/50	1.100	0.410	1.06	1.59

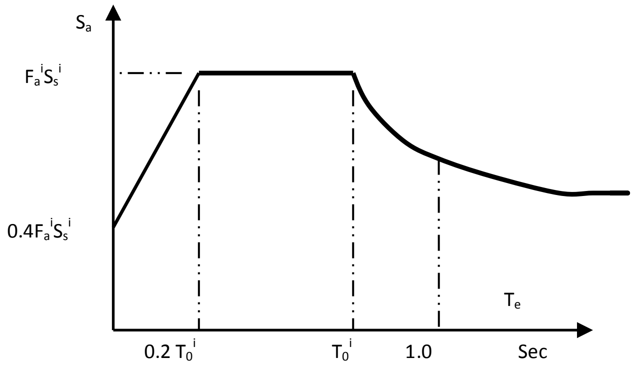

Figure 3. 1. Earthquake acceleration response spectrum

Estimation of $T_O = \dfrac{F_v S_1}{F_a S_s}$ (3.1)

$$T_O^i = \frac{F_v S_1}{F_a S_s} \tag{3.2}$$

i = OP, IO, LS, CP

$$Sa^i = \begin{cases} Fa^i Sa^i\left(0.4 + \dfrac{3T_e}{Ta^i}\right) & 0 < T_e \le 0.2T_0^i \\ Fa^i Sa^i & 0.2T_0^i < T_e \le T_0^i \\ \dfrac{F_v^i S_1^i}{T_e} & T_e > T^i{}_O \end{cases}$$

Using equation (3.2) and the values of parameters from the table 3. 1 the value of T_O are to be calculated and tabulated corresponding to their performance levels. T_0 is the period corresponding to specific performance level and T_e is the time period of the structure. S_s, S_1 F_a and F_v are site parameters required for the evaluation of T_0.

3.2. Evaluation of Seismic Response of Building Frames in the Present Study

Recent advances in computational skill and the software's that may analyze 2D as well as 3D structures to a larger number of earthquake records with different characteristics can now be carried out to enable building response. Using the environment of the software's [12], which enable to automate nonlinear analysis for performance based seismic evaluation, selected steel building frames have been modeled for linear and nonlinear response analyses in RAM Perform 3D. Frameworks modeled for nonlinear response were run for nonlinear static and nonlinear dynamic analysis using the estimated base shear under desirable earthquake ground motions. Details of the building frameworks are listed below:

3.2.1. Example problem: Nine Storey Five Bays 2D Frame Building

The building frame has been used for performance evaluation under earthquake ground motions in the mentioned literature [5, 19]. The frame consists of 99 members. All five bays span is 9.14m (centerline dimensions) and storeys are 3.96 m high. All the columns use wide flange sections of 345 N/mm^2 steel (expected yield strength =397 N/mm^2), while all the beams use wide flange sections 248 N/mm^2 steel (expected yield strength =339 N/mm^2. All beams at the same floor levels are same sections. Details of the sections are given separately. Constant gravity load of 32 kN/m is applied to the beams in the first to eighth storey, while gravity loads of 28.7 kN/m are applied to the roof beams. The seismic weight is 4942 kN for the first storey, 4857 kN for each of the second to the eight storey, and 5231 kN for the roof.

Table 3.2. Base shear for nine storey 2D frame for performance levels

Performance Levels	T_O^i (sec)	S_a^i (g)	V_B^i (kN)
OP	0.744	0.07	3092
IO	0.735	0.12	5106
LS	0.688	0.15	6670
CP	0.637	0.21	9493

Table 3.3. Base shear distribution for nine storey 2D frame

Story no. from top	Height from base of the structure (meter)	Uniform pushover (kN)	Triangular pushover
09	35.64	1054.78	1898.36
08	31.68	1054.78	1687.68
07	27.72	1054.78	1476.72
06	23.76	1054.78	1265.96
05	19.80	1054.78	1054.80
04	15.84	1054.78	843.84
03	11.88	1054.78	632.88
02	07.92	1054.78	421.92
01	03.96	1054.78	210.96
00	00.00	0000.00	000.00

Table 3.4. Details of beam and columns of nine storey 2D frame

Beams details	Columns details
W_{24x68}, W_{27x87}, W_{30x99} W_{36x135}, W_{36x160}	W_{14x233}, W_{14x257}, W_{14x283}, W_{14x370}, W_{14x455}, W_{14x500}

4. RESULT DISCUSSIONS

4.1. Number of Yield Excursion Cycles (NYEC) and PBSD

The number of yield excursion cycles under reversals of stresses is defined as the number of times a structural system yields in one direction and subsequently yields in the opposite direction in the successive cycles. The number of yielding reversals is more for strong motion, while for low ground motion, the NYR is smaller. NYR spectra indicate that low cycle fatigue may be the problem for structures subjected to long duration earthquake if they are designed for only C_y resulting from the use of the assumed ductility ratio μ.

Table 4.1. Number of loops, number of yield excursions, and cumulative ductility for three storey steel building .

Input Seismic Energy (kNm)	Strain Energy (kNm)	Hysteretic Energy (kNm)	Number of Loops	NYEC	Cumulative Ductility
3379.83	51.70	2098.86	2.72	5.00	6
10730.48	89.89	7598.35	4.12	8.00	10
21684.70	142.75	15139.74	4.67	9.30	15
32860.40	333.16	24665.64	3.83	7.66	10

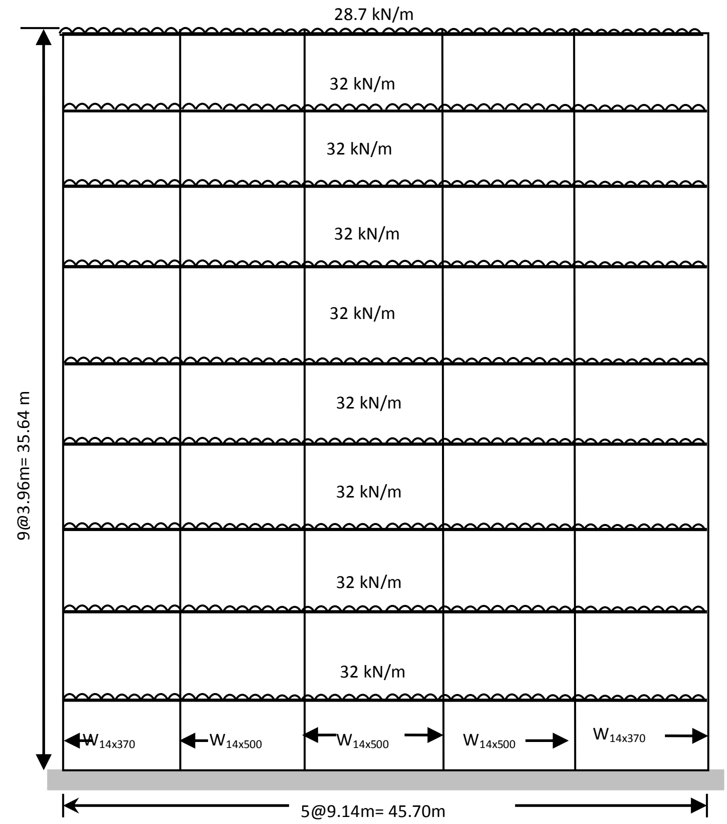

Figure 4.1. Nine storey 2 D Steel Building Framework

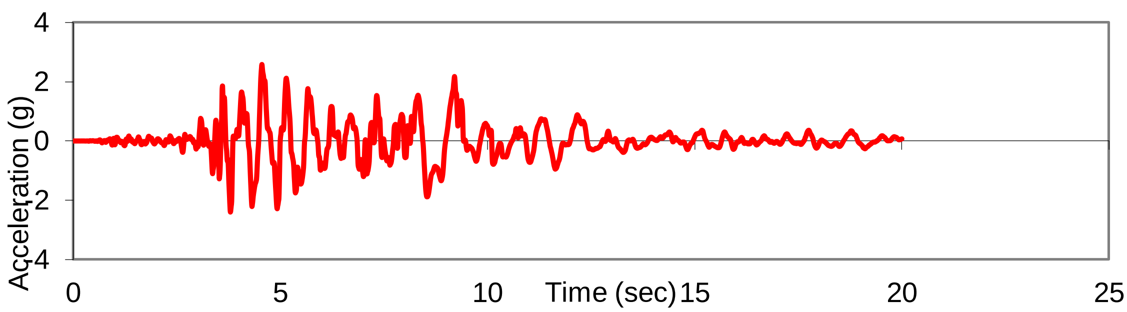

Figure 4.2. Accelerogram of Northridge E-W (0.5165g) with scale factor 5

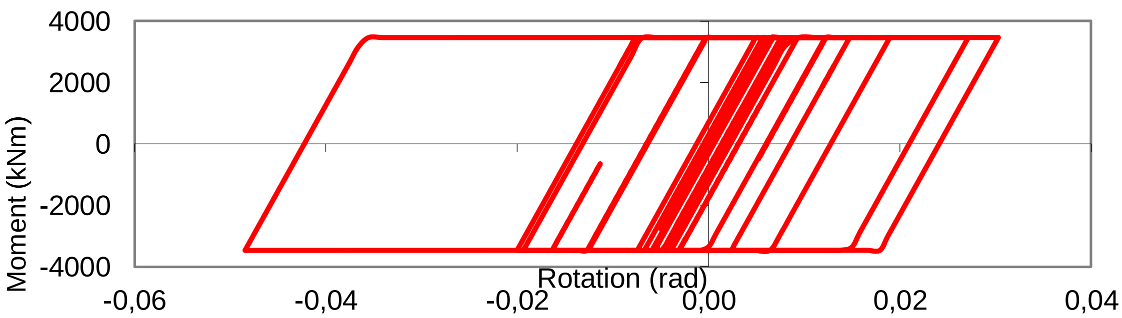

Figure 4.3. Time history of beam one on ground floor of nine storey 2D frame

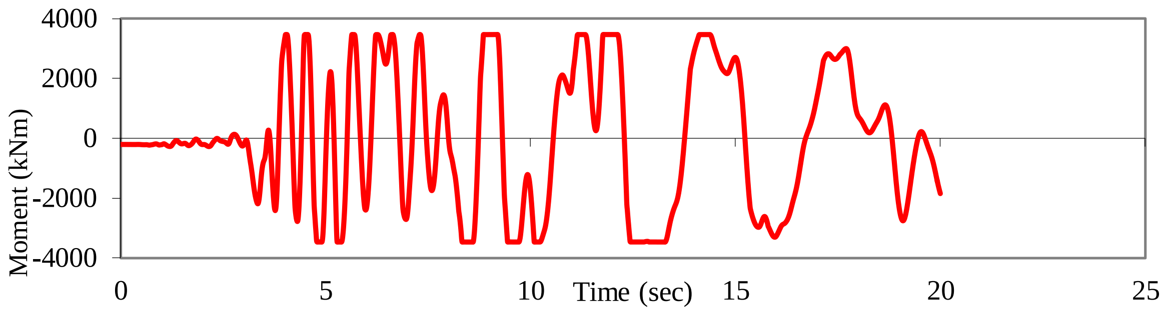

Figure 4.4. Time history of beam two on ground floor of nine storey 2D frame

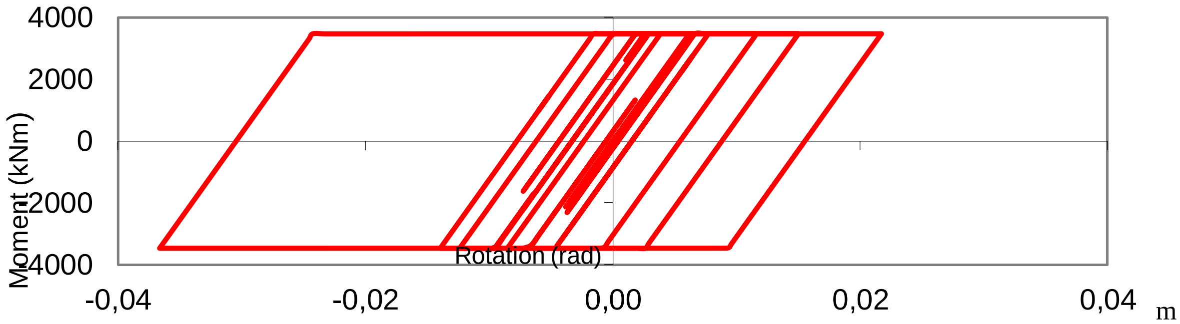

Figure 4.5. Hysteretic loop of beam two on ground floor of nine storey 2D frame

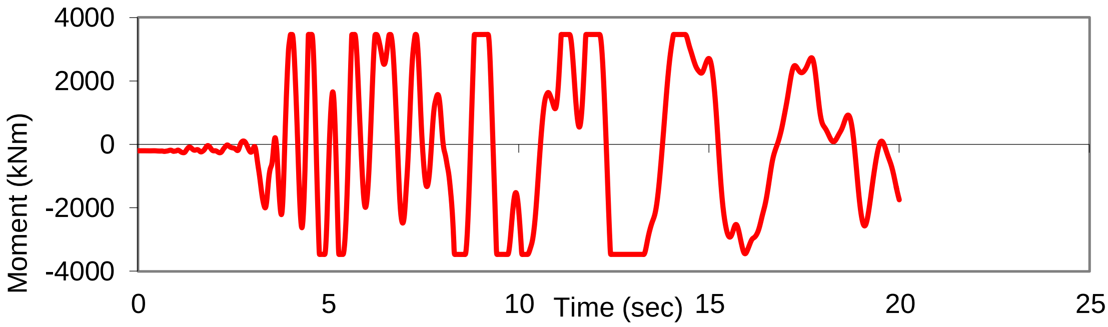

Figure 4.6. Time history of beam three on ground floor of nine storey 2D frame

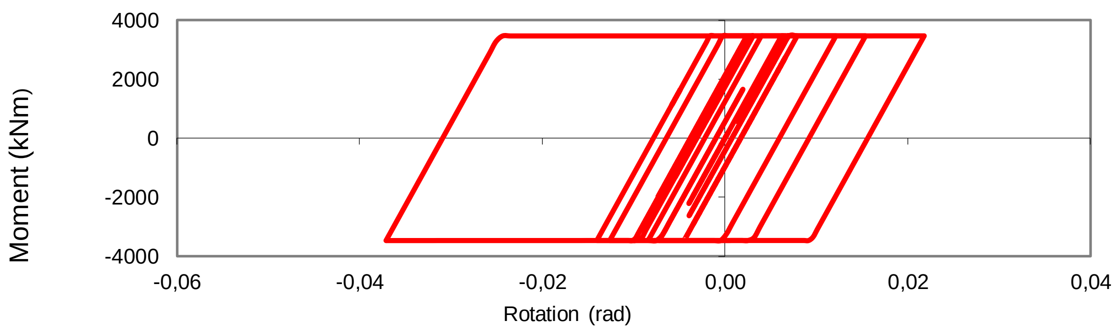

Figure 4.7. Hysteretic loop of beam three on ground floor of nine storey 2D frame

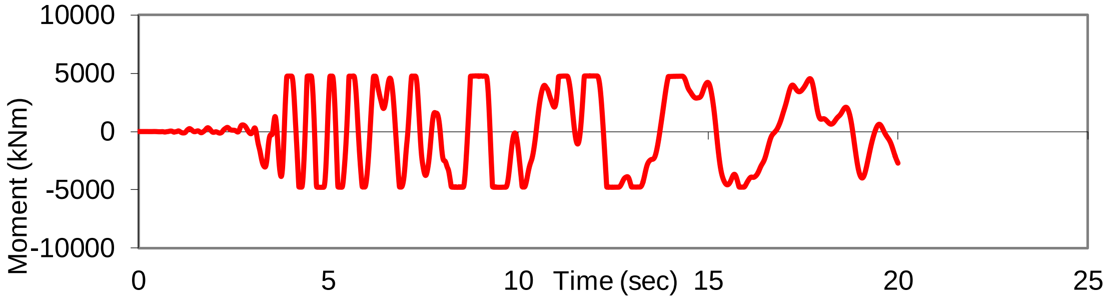

Figure 4.8. Time history of 2nd column on ground floor of nine storey 2D frame

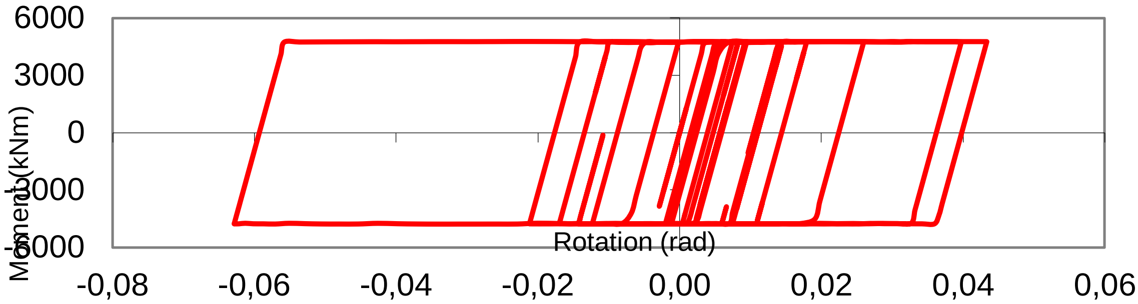

Figure 4.9. Hysteretic loop of 2nd column on ground floor of nine storey 2D frame

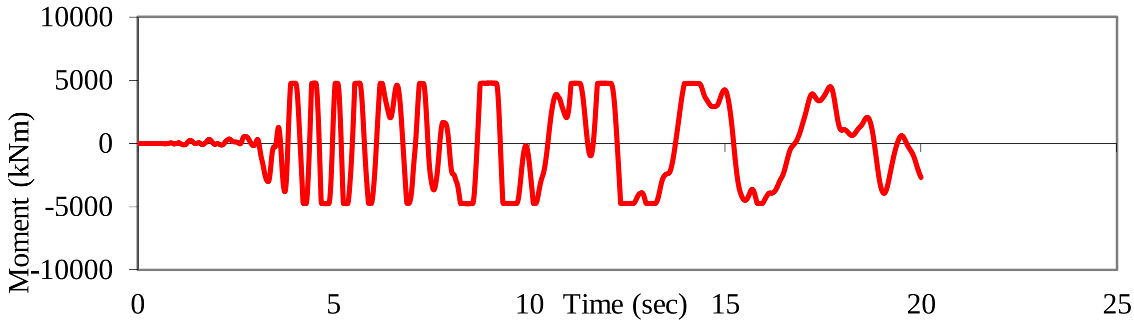

Figure 4.10. Time history of 3rd column on ground floor of nine storey 2D frame

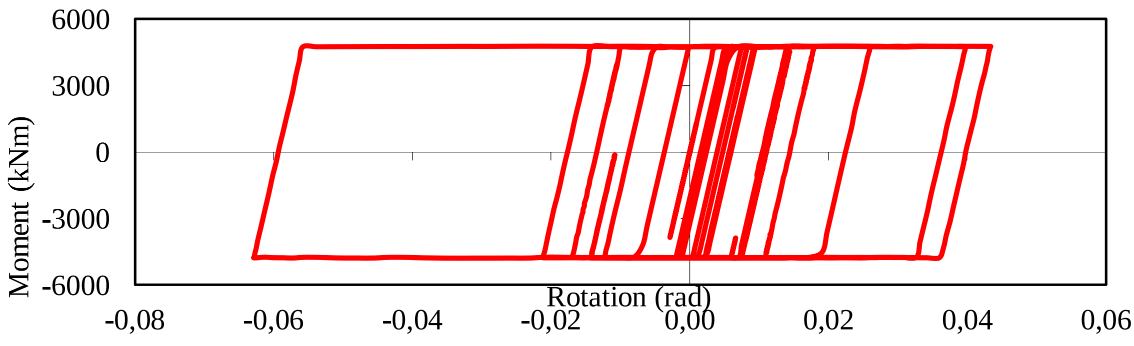

Figure 4.11. Hysteretic loop of 3rd column on ground floor of nine storey 2D frame

Table 4.2. Hysteretic energy, number of loops, NYEC, and cumulative ductility for nine storey 2 D framework.

Sl. No	E_H	E_S	No. of loops	NYEC (Theoretical	NYEC (Experimental)	Ratio of Th. & Exp. NYEC Columns 6 /7	Cumulative ductility
01	1632.7	18.80	6.1	13	18	1.385	21
02	999.2	17.18	7	15	17	1.133	28
03	1051.5	16.5	6.3	13	18	1.385	21

5. CONCLUSIONS AND FUTURE RECOMMENDATIONS

Performance based seismic design and number of yield excursion cycles has been addressed in this paper. A performance objective which is the combination of performance levels corresponding to the seismic hazards has been formulated. 2 D steel frame building were generated for the assigned performance objectives. Modeling for linear and nonlinear analyses procedure under the guidelines of FEMA'273 were done using the software RAM Perform 3D. For the prescribed gravity and the earthquake ground motions, programs were run in batch mode. Further, concluding remarks in this context were made. Number of yield excursion cycles of structural members under the reversal of stresses due to severe earthquake ground motions has been a true representation of damages. In this regard, the trend of the variation of the number of yield excursion cycles with the increase of the input seismic energy reveal the possibility of expressing performance objectives as the design philosophy of the performance based seismic design. Dissipation of energy through the hysteretic loop has been attractive due to modeling and analysis of the related members due to the wealthy environment of software's and the fast speed computers on the effective cost benefit ratio.

However, such kind of the findings need further investigation in terms of space and time including the types of construction materials and the most important is nonlinearity of the materials and the geometry. Identification and quantification of damages while the structure is typically loaded under varying earthquake loadings has been the subject matter of the present research activities. The strength and opportunity of such approach has potentiality due to advanced technology in the area of analysis and design.

The aim of the present work remained to focus on the simplicity of the analytical procedures involved for expressing performance based design objectives with the number of yield excursion cycles under the critical types of earthquake ground motions. Use of derived energy based relations has been found to be useful for further derivations in order to trace out the performance objectives achieved by a structures.

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