Damage Indices using Energy Criterion for Seismic Evaluation of Steel Frame Buildings

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SUMMARY
The content of the paper is based on the premises that indices in terms of damages are effective methods of evaluation of building structures under earthquake loadings. Energy based criterion has been found effective tools in the present state of art because energy being the capacity of a structure to resist any seismic demand in more stable manner. The main focus of this paper remains with the formulation of damage indices using the energy based evaluation using some reference steel building structures under varying earthquake loadings. Damage implies the reduction of resisting capacity, which may be loss of strength or loss of energy absorption due to cyclic loading arising during earthquakes. The analytical expressions derived in terms of energy capacity have been validated through the data acquired as response analysis in the present work. The conclusion of the findings may be further investigated through changing the structures, types of materials and the loading combinations etc.

Keywords: Energy based seismic evaluation, Steel frame buildings, Damage indices etc

1. INTRODUCTION

Seismic evaluation of steel building structures has undergone critical reappraisal in the recent past [SEAOC, 1995; ATC-40, 1996; FEMA-273, 1997; Gong, 2003; Akiyama, 1985]. Various numerical approaches have been recently employed to trace out the simplicity for the evaluation of the response of steel building structures under seismic loading. However, the approach of the energy based balance criterion as effective methodology has been addressed [Park & Ang, 1985; Housner, 1956; Bozorgnia & Bertero, 2004] in the recent past. In order to quantify the damage indices referred in this paper, steel building frames have been modeled for linear and nonlinear analysis procedures with the guidelines of modeling of software's: ETABS, SAP-2000, RAM PERFORM 3D. With the optimum conditions of the building performance criterions, the loading has been assigned under the seismic actions. Programs were run under batch modes. The database of the response parameters have been incorporated for the validation of the damages indices developed in the content of this paper. The objectives of the paper remained with the development of trouble-free approach in terms of normalization of energy with the strain energy for better seismic evaluation tools. Due to fast nonlinear analysis procedures, local to global behavior of structural and non structural members have been found a better tool with promising opportunity and in this direction, the use of fast speed and high memory computer systems have made possible to think and go ahead for further investigations.

2. PROBLEM FORMULATION

Change of internal energy capacity of a structure is responsible for the disturbance resulting into partial or total damage; hence it is important for identification and quantification of various types of energy in order to pacify simple methodology for seismic resistant design. In order to achieve such objectives as the content of this paper, the following approach has been made

2.1. Distribution of Input Seismic Energy

Left side of the energy balance equation (2.1**)** is input seismic energy and right side represent the energy distributed among energy components. A component is capable to absorb a significant amount of energy as elastic strain energy and dissipates energy through damping in the elastic region. Rest of the energy is dissipated through yielding in the inelastic region. Therefore, distribution of energy among its components is the first task for further proceeding to design.

$$E_i = E_S + E_K + E_D + E_{h\xi} \tag{2.1}$$

Dividing equation (2.1) by the input seismic energy to both sides of the equation

$$1 = E_S/E_i + E_K/E_i + E_D/E_i + E_{h\xi}/E_i \tag{2.2}$$

Equation (2.2**)** is in the normalized form, where the normalizing parameter is input seismic energy itself. Expanding the various energy parameters on the right side of the equation (2.2**)**, the following simple normalized values, we get.

2.1.1 Normalized Strain Energy $= \dfrac{ku^2}{2} \Big/ \dfrac{1}{2} m s_{pv}^{\,2} = \omega^2 \left(\dfrac{u}{s_{pv}}\right)^2 = \left(\dfrac{u}{s_d}\right)^2$ (2.3)

Where u is the relative displacement and S_d is the spectral displacement.

2.1.2 Normalized Kinetic Energy $= \left(\dfrac{\dot{u}}{s_{pv}}\right)^2$ (2.4)

Where the numerator is relative velocity and the denominator is the pseudo velocity.

2.1.3 Normalized Damping Energy $= 2\xi\omega_n \left(\dfrac{\dot{u}}{s_{pv}}\right)^2$ (2.5)

Equations (2.5) and (2.4) reveal that normalized damping and kinetic energy ratio is $2\xi\omega_n$

2.1.4 Normalized Hysteretic Energy $= (\mu_i - 1) \times \left(\dfrac{u}{s_d}\right)^2$ (2.6)

This implies that normalized strain energy is related with the normalized hysteretic energy by a factor equal to cumulative ductility minus 1.As discussed above distribution of input seismic energy among its components is required for making the design decision. Validation of normalized energy components from equations (2.3) to (2.6) requires time history analyses analysis and spectral velocity of the concerned ground motions.
Response parameters in terms of energy after nonlinear analysis of representative steel building frames under varying earthquake ground motions will be the contents of the next chapter: modeling and analysis. Some more investigations based on the structure and ground motion interaction in terms of energy input and mechanical characteristics has been formulated as following.

2.2. Relation between Hysteretic Energy (E_D) and Strain Energy (E_s)

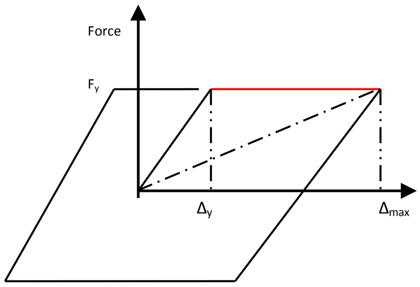

Figure 2.1. Hysteretic loop for elasto-plastic system

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.

$$E_{hi} = 4k\delta_y^{\,2}(\mu_i - 1) = 8E_s(\mu_i - 1) \tag{2.7}$$

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

$$E_D = \sum_{i=1}^{n} E_{hi} = 8E_s + 16E_s + 24E_s + 32E_s + 40E_s \tag{2.8}$$

The above equation (2.8) forms the arithmetic progression with the resultant values.

$$\text{i.e., } E_D = 8n \times \frac{(n+1)}{2} E_s \tag{2.9}$$

Where E_D is the total energy dissipated, n is the total number of loops and E_s is the strain energy. For damage evaluation, the equation (2.9) is an important equation. The values of the successive hysteretic energy are normalized by the total hysteretic energy, which has been recognized an effective damage index.

A damage index through normalizing the successive hysteretic energy with the sum of hysteretic energy is the proposed damage index as the content of present study. The normalized values provide a trend of continuous damage spectrum

2.3. Simplification of Park and Ang Damage Model

Park and Ang damage model is simplified for overall damage index in order to correlate the local damage index to the global performance as one of the derivative of the present study.

Damage models accounting for the combination of maximum deformation and dissipated energy have been introduced [Park & Ang, 1995]. The model proposed by Park and Ang model uses damage index D_e defines by

$$D_e = \frac{U_{max}}{U_u} + \frac{\beta \int dE_H}{R_y U_y} \tag{2.10}$$

U_u = ultimate deformation under monotonic loading

U_y = yield deformation, $\int dE_H$ =cumulative hysteretic energy

β = non-negative parameter =0.025 for steel structures

$$\frac{U_{dyn}}{U_{mon}} = \frac{\max imum - deformation - in - dynamic - loading}{\max imum - deformation - in - monotonic - loading}$$

A structure under equivalent loading will yield more than the actual dynamic loading

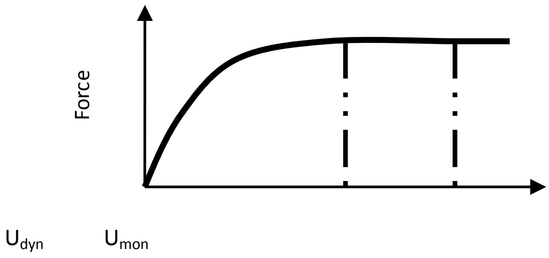

Figure 2.2 Force vs. deformation relation for monotonic and dynamic loading [Akiyama, 1985]

A structure under equivalent loading will yield more than the actual dynamic loading Extension of equation (2.10) for a generalized form, where the damage at component levels may directly be incorporated for the overall damage index. Rearranging the eqn. (2.10**),** we get the following expression

$$\frac{(D_e U_{mon} - U_{dyn})}{U_{mon}} \times \frac{R_y U_{mon}}{\beta} = \int dE_H$$, Using $\alpha = \frac{R_y}{Mg}$ and $\mu = \frac{U_{mon}}{U_y}$

$$\alpha Mg(D_e U_{mon} - U_{dyn}) = \mu\beta \int dE_H \tag{2.11}$$

Putting $\frac{U_{dyn}}{U_{mon}}$ =0.6 as suggested by researchers Park and Ang [Park & Ang, 1995] the maximum damage under unidirectional dynamic loading normalized with the max deformation under monotonic loading.

$$\int dE_H = E_H{}^i = \frac{\alpha U_y Mg(5D_e - 3)}{5\beta} \tag{2.12}$$

$$D_e{}^i E^i{}_H = \frac{\alpha U_y Mg D_e{}^i (5D^i{}_e - 3)}{5\beta} \tag{2.13}$$

$$\frac{D_{1e}E_{1H} + D_{2e}E_{2H}}{E_{1H} + E_{2H}} = \text{Overall} - \text{Damage} - \text{Index} = \frac{D_{e1}{}^2 + D_{e2}{}^2 - 0.6(D_{1e} + D_{2e})}{D_{e1} + D_{e2} - 1.2}$$

The generalized expression for overall damage index (D_{Tn})

$$D_{Tn} = \frac{D_{1e}{}^2 + D_{2e}{}^2 + D_{3e}{}^2 + D_{4e}{}^2 + \ldots\ldots - 0.6(D_{1e} + D_{2e} + D_{3e} + \ldots.)}{D_{1e} + D_{2e} + D_{3e} + \ldots\ldots.. - (0.6 + 0.6 + 0.6 + \ldots..).} \tag{2.14}$$

The expression (2.14) of damage index is the extension of Park and Ang damage index for overall damage, which includes the damage index at the element level to the global level. D_{ie} is the damage index at the element level.

3. MODELING AND ANALYSIS

Steel building frames have been modeled for linear and nonlinear analysis in the environment of RAM PERFORM 3D. Building frames have been subjected lateral loads due to seismic action in addition to its gravity loading. Time history analyses were also performed on the respective building frames.

4. RESULT AND DISCUSSIONS

Results have been tabulated after analysis of the respective building frames and discussions were made in step wise as follows:

4.1. Normalized Hysteretic Energy

Result: The value of hysteretic energy and strain energy are known from the response history for energy for the building frames in the study for a set of earthquakes. Tables 4.2 to 4.3 contain the hysteretic energy normalized with the strain energy for the building frameworks. Table 4.1 gives details of normalized hysteretic energy for the varying ground motions with higher peak ground accelerations.

4.1.1. Result Discussions

The major task of seismic design is to incorporate stiffness, strength and ductility degradation under the severe earthquake ground motions in analytical expressions. Hysteretic energy in the normalized form consists of this entire factor into a single equation. As found the data for normalized hysteretic energy in the table. 4.1, the value is nearly constant for varying ground motions. The next attribute of seismic design is to consider the stable parameter or such attribute which can be stable when any drastic change takes place. Normalized hysteretic energy where the base is strain energy and the numerator is hysteretic energy is useful for such design development. One of the problem formulations is normalized hysteretic energy in terms of hysteretic energy and normalized yield strength as a content of this program. Tables 4.2 to 4.3 have been used for the interpretation of normalized hysteretic energy for those frames which have dissipated significant amount of input seismic energy through yielding of beams/columns at various floors reveal the pattern of energy consumed by the structures as strain, kinetic and hysteretic energy. Hysteretic energy as the major source of consumption of input seismic energy under severs earthquake ground motions provides stable and promising response while a structure has no other alternatives for fail safe design.

Table 4.1. Energy distributions (%) for three storey 3D building framework.

Input Energy (kNm)	Strain Energy (kNm)	Kinetic Energy (kNm)	Hysteretic Energy (kNm)	% E_S	% E_K	% E_h	Earthquake ground motions
3379.83	51.69	157.66	2098.86	1.53	4.67	62.1	Northridge, (0.5165g)
10730.48	89.89	57.86	7598.12	0.84	0.54	70.8	Northridge(2x0.5165g)
21684.70	142.75	31.83	15142.00	0.66	0.15	69.8	Northridge(3x0.5165g)
32860.40	333.16	54.13	24667.90	1.01	0.16	75.1	Northridge(4x0.5165g)

Table 4.2. Normalized hysteretic energy for three storey 2D building frame.

Sl. No	Elastic strain energy	Hysteretic Energy	Ratio of hysteretic and elastic strain energy	Earthquake ground motions
1	50.57	389.70	7.71	Northridge E-W,(0.5165g)
2	40.20	381.34	9.48	Northridge E-W,(2x0.5165g)
3	38.66	635.92	16.45	Northridge N-S,(2x0.4158g)
4	39.06	1326.80	39.96	El Centro E-W,(0.2148g)
5	36.84	943.72	25.61	El Centro E-W,(2x 0.2148g)

Table 4.3. Normalized hysteretic energy for three storey 3D building frame.

Sl. No	Elastic strain energy	Hysteretic Energy	Ratio of hysteretic energy and elastic strain energy	Earthquake ground motions
1	104.1	2120.45	20.37	Northridge E-W, (0.5165g)
2	70.85	3179.37	44.87	Northridge E-W,(2x0.5165g)
3	177.87	7727.84	43.45	Northridge N-S,(2x0.4158g)
4	133.00	254.15	1.91	El Centro E-W,(0.2148g)
5	160.70	2571.43	16.02	El Centro E-W,(2x 0.2148g)

4.2. Hysteretic Energy (E_D) and Strain Energy (E_s)

Equation (2.9) relates the total hysteric (E_D) and strain energy (E_S) i.e., $E_D = 8\boldsymbol{n} \times \frac{(\boldsymbol{n}+1)}{2}\boldsymbol{E_s}$, Where E_D is the total energy dissipated, n is the total number of loops and E_s is the elastic strain energy. E_D represents damage, which has the relation with elastic strain energy through the number of loops, when a component yields and dissipates energy during reversal of stresses arising due to severe earthquake loadings. For single hysteretic loop, hysteretic energy is related with the strain energy through cumulative ductility. Since displacement approach for performance evaluation is poorly rated because the cumulative ductility is not easily accessible. However, for the known values of successive loop, the hysteretic energy is related with the cumulative ductility and can be estimated through the simple relation. Further, the same expression has been used for finding total energy dissipated (H_i) during reversal of stresses due to varying earthquake ground motions.

Table 4.4. Hysteretic energy for the successive loop

Sl. No.	μ_i	1	2	3	4	5	6	7
01	$E_{ih} = \frac{\mu_i - 1}{\mu_i} \times \mu_i E_s$	0	E_s	$2E_s$	$3E_s$	$4E_s$	$5E_s$	$6E_s$
02	$H_i = \sum_{i}^{2} E_{ih}$	0	E_s	$3E_s$	$6E_s$	$10E_s$	$15E_s$	$21E_s$

Table 4.5. Damage index

Sl.	μ_i	1	2	3	4	5	6
01	Damage Index (DI)= $\frac{\sum_{1}^{n} \boldsymbol{E_{ih}}}{\boldsymbol{H_i}}$	1/21 =0.067 Immediate Occupancy	3/21 0.2 Damage	6/21 0.4	10/21 0.47 Control	15/21 0.71 Life Safety	21/21 1.0 Collapse

Table 4.6. Hysteretic energy for elasto-plasto loop for successive displacement ductility

Sl. No.	Displacement Ductility (μ)	(μ-1)	4(μ-1)/(μ)	E_h =…..Eso E_{so} =μ x E_s	Remarks
01	1	0	0	0	Algebraic sum of the hysteretic energy for successive cycles may be economically used for prediction of energy to be dissipated during continuous spectrum of damages
02	2	1	2	4	
03	3	2	8/3	8	
04	4	3	3	12	
05	5	4	16/5	16	
06	6	5	20/6	20	

With the known value of strain energy used for Operational occupancy, the relation of various performance objectives on the continuous spectrum of damage spectrum to be predicted. Such a kind of relation in between the hysteretic energy and the strain energy is unique in its characteristics and can be used for the simplest formulation of performance index.

Table 4.7. Theoretical and experimental damage ratio for three story 3D frame: Northridge Earthquake (0.6g)

Sl	Displacement	Cumulative	Theoretical damage	Experimental damage
1	1	1	0	0
2	2	3	0.2	0.06
3	3	6	0.4	0.33
4	4	10	0.67	0.42
5	5	15	1.00	1.00

Table 4.8. Theoretical and experimental damage ratio for three story 3D frame: El Centro Earthquake (0.6g)

Sl.No.	Displacement	Cumulative	Theoretical damage	Experimental damage
1	1	1	0	0
2	2	3	0.06	0.02
3	3	6	0.13	0.29
4	4	10	0.22	0.34
5	5	15	0.33	0.43
6	6	21	0.47	0.52
7	7	28	0.62	0.81
8	8	36	0.80	0.96
9	9	45	1.00	1.00

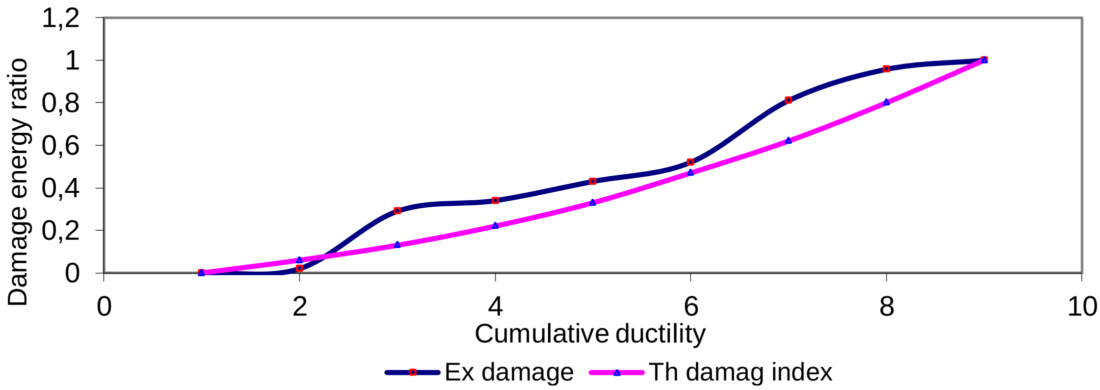

Figure 4.1. Theoretical and experimental damage ratio: Cumulative ductility

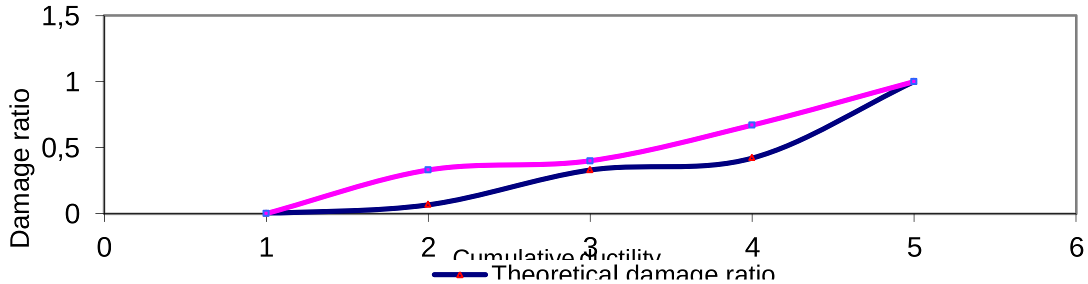

Figure 4.2. Theoretical and experimental damage ratio vs. Cumulative ductility

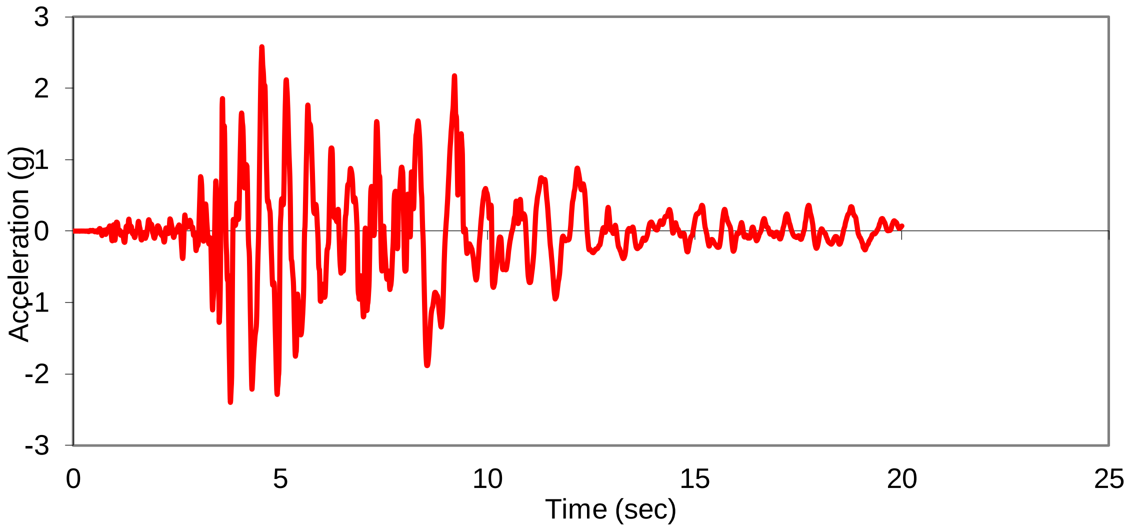

Figure 4.3. Accelerogram of Northridge E-W (0.5165g) with scale factor 5

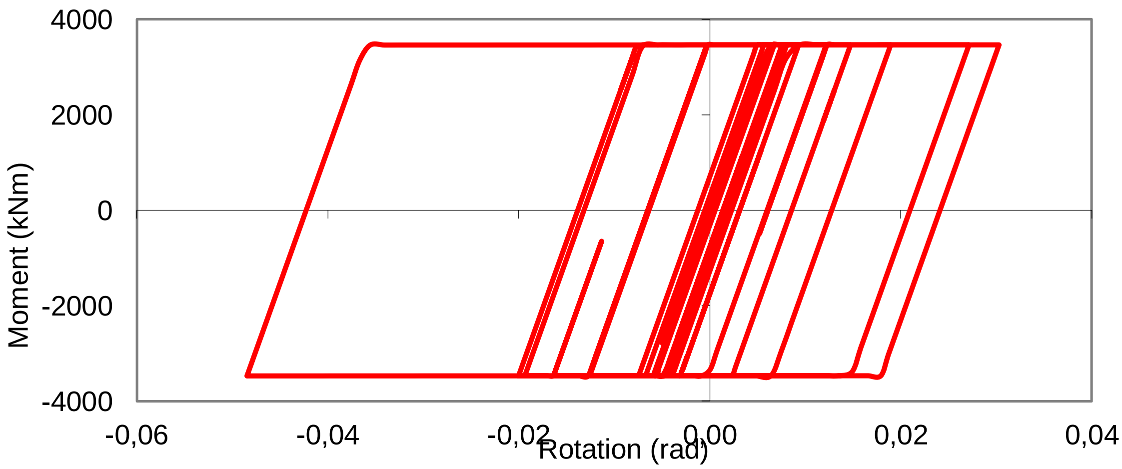

Figure 4.4. Time history of beam two on ground floor of nine storey 2D frame

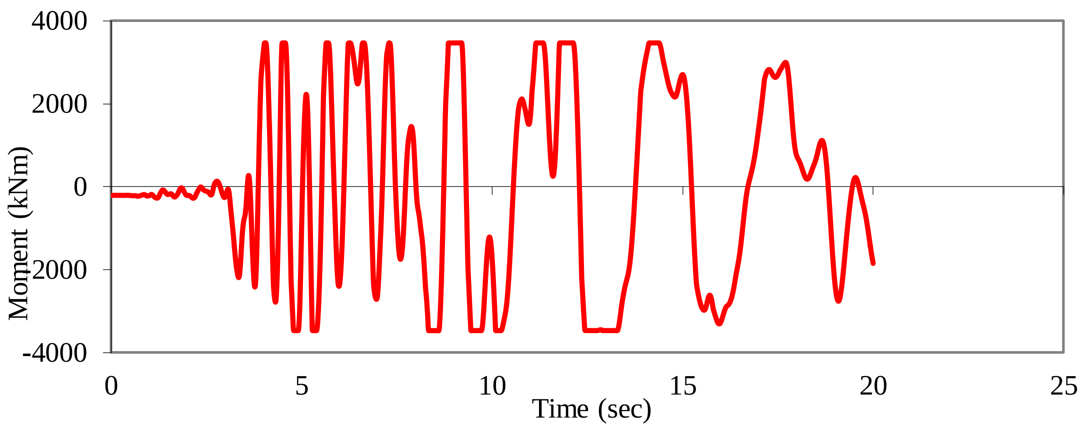

Figure 4.5. Time history of beam one on ground floor of nine storey 2D frame

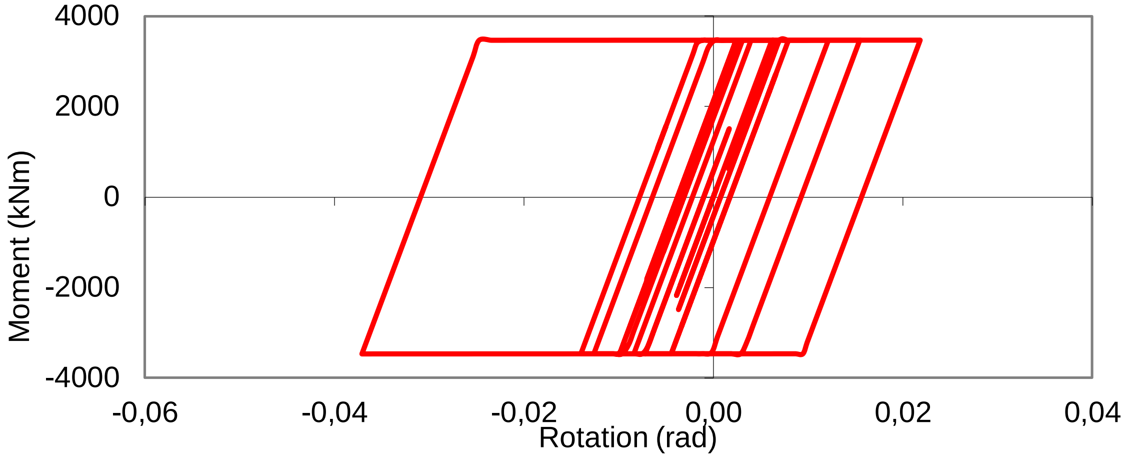

Figure 4.6. Hysteretic loop of beam fourth on ground floor of nine storey 2D frame

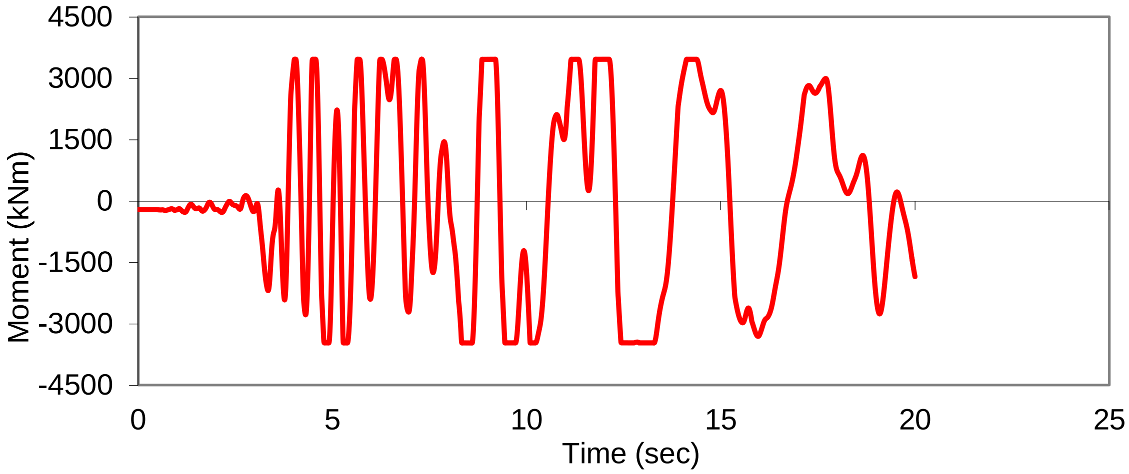

Figure 4.7. Time history of fifth beam on ground floor of nine storey 2D frame

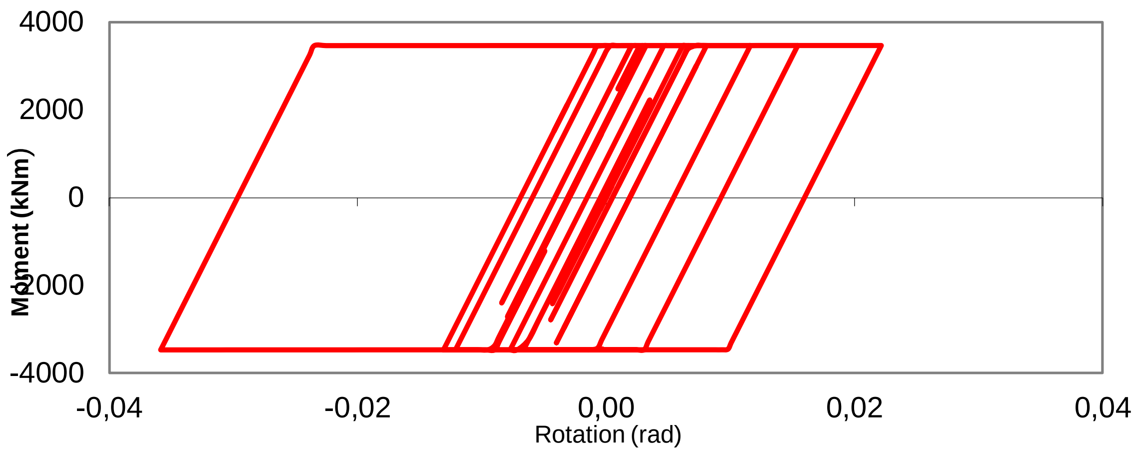

Figure 4.8. Hysteretic loop of fifth beam on ground floor of nine storey 2D frame

5. CONCLUSION

Ductility is associated with damage. In this regard, cumulative ductility corresponding to the displacement ductility as estimated in this program is relevant to the damage identification and quantification. Theoretical damage is the ratio of cumulative ductility corresponding to the displacement ductility divided by the equivalent largest available cumulative ductility using the analytical result. Experimental damage ratio is ratio of hysteric energy corresponding to the displacement ductility to the highest hysteretic energy capacity. Both values have been validated using three story 3D & 2D steel building frames under varying earthquake ground motions.

Energy based evaluation for damage evaluation has been found to be a stable approach for analysis under earthquake ground motions. The paper discusses the characteristic of damages under varying earthquake ground motions as they have been addressed with simplicity once formulated and designated in terms of damage indices using the energy balance criterion. The scope of the content of the paper remain focused on the further possibility of simplicity through more and more investigations using various types of construction materials, types of structures and the most important is the nature of the earthquake ground motions.

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