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Energy based Design as an Alternative Intuitive Criterion to the Drift Criterion

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***Abstract:** Structural integrity with smaller structural plan density is doubtful under earthquake loading, while the structure is supposed to undergo inelastic deformation. Recent past damages under moderate earthquakes have raised a lot of questionnaires to the existing seismic design procedures. Drift controlled damage indices are consistently under reappraisal because of our better understanding of dynamic loading. Hence, energy based concept is suggested in an effort to explicate the response of building systems during earthquake loading. In this paper, explicit expressions for various components of energy i.e. strain, kinetic, damping and inelastic energy versus drift have been derived and discussed with the post processing results of building systems under varying strong earthquake motions. The incremental dynamic analysis is used in our study and the results show that the energy criterion analysis gives better one than the drift criterion for the structures subjected to earthquake ground motions.*

***Keywords:** Energy based design, Incremental dynamic analysis, earthquake, undergo inelastic deformation, strain, kinetic, damping and inelastic energy.*

I INTRODUCTION

Earthquake-resistant design philosophy anticipates that the structures to be designed has to resist low level earthquakes with no damage, medium level earthquakes with light damage levels for non-structural elements and moderate or significant structural damage, whereas the high level earthquakes with significant damage to both non-structural and structural elements without overall or partial collapse of the structure in order to avoid human life loss. The current seismic design codes use strength based design concept in which the demand is calculated by linear analysis and it intends the building should remain elastic up to the factored load demand. It is not feasible to design the structure based on this concept for earthquakes and lead to the deformation based design. A structure hence designed by this method is anticipated to go through huge inelastic deformations when a strong earthquake ground motion strikes and the structure collapse depends mainly on the structural system tolerance to the cyclic inelastic deformations. Even trustworthiness of deformation based seismic design is not as we expect from structural behavior under probable demand. In order to cater the need of structural behavior, energy based design criterion has been recently necessitated. The content of the paper is based on the fundamental of drift and energy bifurcation of likely damages under earthquake loading. Outcome of the present finding shows that energy based damage indexing is better approach with respect to drift controlled study.

II LITERATURE REVIEW

The energy based concept was given by many researchers as early as 1950s and it gained importance from thereon. Some of the notable contributions are given by G. Housner, G.V. Berg et al. [1] [2] as they formed energy relations of a SDOF system and elasto-plastic structure exposed to strong earthquakes. S.C. Goel et al. [3] focused on the impact of the significant earthquake record parameters and its characteristics when subjected to inelastic response parameters for structures. B. Kato et al. [4] considered the energy based concept to evaluate the ground motion damage in buildings and also a steel building model was designed based on energy theory. He tailed the theory that a building can securely resist a strong earthquake motion when its capacity of energy absorption for the structure is larger than the energy input imparted by ground motion. Uang et al. [5] explored the corporeal sense of the absolute energy and relative energy of building systems. Those were the two energy relation equation given that time between the structures. Zahrah et al. [6] and P. Fajfar et al. [7] focused on seismic energy absorption and energy demand for structures in SDOF systems. A. Nurtug et al. [8] developed procedure for linear single degree of freedom system to calculate seismic energy in that structure. F.Mollaioli et al. [9] studied much into the energy theory especially with the focus on the energy demand. Leelataviwat et al. [10] estabilshed design methods for steel buildings based on the energy theory. These designs were easy to follow and it clearly explained the energy based concept. Chou et al. [11] established an empirical equation for the multistory buildings to estimate the absorbed energy with the use of energy spectra established for single degree of freedom systems. Li et al. [12] and Ye et al. [13] also formulated the procedures for finding hysteretic energy of MDOF systems from equivalent SDOF systems and later gave the procedures for the concept of energy-based seismic design with the help of input energy and hysteretic energy relationship and also explained its application for braced frame systems.

The fundamental and main concept of energy based seismic design is that the structure should dissipate the input seismic energy of the earthquake ground record motions in a safe manner.

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For this, study on collapse behavior of building systems is to be fully known and it is crucial when we consider under large and 2% return period earthquakes. Some researchers showed that its essential importance as a well-designed structural system with good energy-dissipating mechanisms are supportive in order to decrease the collapse probability of building systems under large earthquakes. As a result, the structure design has to be improved and this became the main objective of energy-based design concept against large and 2% return period severe earthquakes by applying more reasonable energy-dissipating mechanisms, which may be external energy dissipated devices or through internal hinge formation/ inelastic energy dissipation.

Displacement based design concept:

It is recognized that strength has lesser importance than deformation for seismic actions, because no a building structures is conceived elastic under higher seismic forces. Thus, a well-designed structure with adequate ductility can deform in elastically to required deformation without much loss of strength. Displacement beyond yield point of a structural element is required for understanding of the concerned structure because strength gives false impression when yielding has started in order to quantify the performance as shown in Fig.1 However, displacement provides a better indicator for damage assessment in terms of displacement ductility. Displacement ductility (μ) is defined as the ratio of the maximum absolute displacement to its yield displacement, $\mu = \frac{max|u|}{u_y}$ where u is displacement; and u_y is yield displacement of the system. Identification of capacity of a structure in terms of energy may be visualized as strain, kinetic, damping, inelastic strain and hysteretic energy. Each component of energy has their own role for quantifying damages. Energy approach for Energy based seismic design is developed as it lends freedom to structural engineers in their selection of a mechanism to dissipate the input energy, and therefore to quantitatively control the damage.

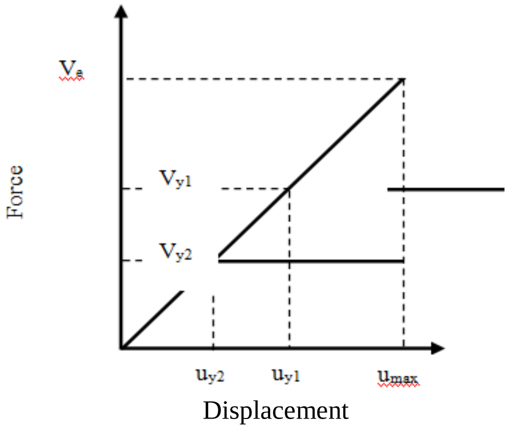

Fig 1: Displacement based design

Energy balance concept:

The effect of seismic action in terms of both force and displacement demands, as well as the cumulative effect of damage produced by cyclic loading is taken into account in the energy based seismic design concept. Energy demand is the product of the force and displacement demands of the structure and the bilinear hysteretic relationship of a SDOF system can be estimated mathematically when the forcing function is identified. Intended for practical purposes in design and evaluation of structural systems, several researchers sush as Miranda and Bertero [14], Newmark and Hall [15] gave equations in the form of the displacement ductility, strength reduction factor, and/or displacement of the corresponding elastic system. [16]

Energy balance concept for Multi-degree of freedom system (MDOF):

The equation of motion of a MDOF system subjected to horizontal base excitation $\ddot{u}_g(t)$ is,

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = -M\ddot{u}_g(t) \qquad (1)$$

Where, m is mass matrix; k is stiffness matrix of structure; c is damping matrix.

u is lateral displacements of the floors relative to the base;

$\ddot{u}_g(t)$ is ground motion acceleration.

The displacement vector in terms of the free vibration mode shapes (ϕ_n)

$$u = \sum_{n=1}^{N} \phi_n q_n(t) \qquad (2)$$

The expression of the displacement vector in terms of the mode shapes allows the governing equation to be uncoupled in terms of modal coordinates using orthogonal property and $q_n(t) = \Gamma_n D_n(t)$ as

$$\ddot{D}_n(t) + 2\xi_n\omega_n\dot{D}_n(t) + \omega_n^2 D_n(t) = -\ddot{u}_g(t) \qquad (3)$$

Where ξ_n is the damping ratio, ω_n is the natural vibration frequency and

Γ_n is modal participation factor which is given by

$$\Gamma_n = \frac{\phi_n^T.m.1}{\phi_n^T.m.\phi_n} \qquad (4)$$

The base shear of multi-degree of freedom system, $V_{bn,}$ is

$$V_{bn} = f_n^T.1$$

$$= (\phi_n^T.k.1)\Gamma_n D_n$$

$$(\because \phi_n^T.k.1 = \omega_n^2 \phi_n^T.m.1 \;\& V_n = D_n \omega_n^2)$$

$$V_{bn} = (\phi_n^T.m.1)\Gamma_n V_n \qquad (5)$$

By substituting the value of modal participation factor,

$$V_{bn} = M_n^* V_n$$

Where M_n^* is effective modal mass of the system which corresponds to the nth mode of MDOF system and given by

$$M_n^* = \frac{(\phi_n^T.m.1)^2}{\phi_n^T.m.\phi_n}$$

Then a displacement u_n* is defined in the MDOF system such that the total work done by the base shear V_{bn} in a small virtual displacement du_n* is the same as the total work done by the lateral restoring forces over the entire structure.

$$V_{bn} du_n{}^* = f_n^T . \phi_n \left(\frac{du_n{}^*}{\phi_n^*}\right)$$

Where, ϕ_n^* is value of the element in the ϕ_n vector at the u_n^* level

$$\phi_n^* = \frac{f_n^T . \phi_n}{V_{bn}} = \frac{f_n^T . \phi_n}{f_n^T . 1} = \frac{\phi_n^T . m . \phi_n}{\phi_n^T . m . 1} = \frac{1}{\Gamma_n}$$

The displacement $u_n{}^*$ and the displacementof the SDOF system D_n can be related as

$$u_n{}^* = \phi_n^* \Gamma_n D_n = D_n$$

So at yield point, $u_{ny}{}^* = D_{ny}$; $V_{bny} = M_n^* V_{ny}$

Where, D_{ny} and $u_{ny}{}^*$ are the displacements of SDOF and MDOF system at yield stage. V_{ny} and V_{bny} are the yield base shear of the SDOF system and the corresponding MDOF systems. Hence the energy balance equation of the MDOF system is given by equation 6 as

$$\frac{1}{2} M_n^* S_v^2 = \frac{1}{2} V_{ny} u_{ny}{}^* + V_{ny}(u_{nm}{}^* - u_{ny}{}^*) = E_e + E_p \quad (6)$$

$$E_i\,(t) \qquad = E_e\,(t) + E_k\,(t) + E_d\,(t) + E_h\,(t) \qquad (7)$$

In equation 7, the input energy E_i (t) is the demand of the system, which defined as work done by the actual seismic force (i.e. mass multiplied by ground acceleration) over the system deformation. The right hand side terms [E_e(t), E_k(t), E_d(t), Eh(t)] are the capacity of the structure. E_e(t), an instantaneous quantity dependent on the existing elastic displacement level at time *t* is known as the elastic strain energy. The kinetic energy E_k(t) is only associated to the immediate response of the system which are at a time *t* proportional to its relative velocities of masses. The energy dissipated by the structure through inherent viscous damping is the cumulative quantity damping energy E_d(t), which is an ever increasing one with respect to the time during the period of vibration. E_h(t), which is a collective quantity of the plastic displacement throughout the whole period of the vibration which are directly correlated to the structural component's cyclic inelastic deformation capacity and if the structure remains elastic, hysteretic energy or inelastic dissipated energy will be zero. The elastic strain energy and instant kinetic energy are of low percentage of the energy input at any time during the period of vibration whereas, the hysteretic energy and cumulative damping energy are the chief contributors for the input energy dissipation.

III STRUCTURAL MODEL AND GROUND MOTIONS

To illustrate the application of the seismic energy as design criterion, irregular steel building of 2 stories (MODEL- I) and regular steel building of 5 stories (MODEL-II) were chosen and its 3D model is shown in fig 2 and fig 3. The structural configuration and detailing of the main structures corresponded to typical buildings located in the seismicity part of India. The gravity loads and the lateral loads are applied according to the Indian code. The earthquakes chosen are El-Centro and Northridge ground motions with different scale factors ranging from 0.2 to 2. These earthquakes are scaled accordingly such that the frames won't collapse and/or cause excessive distress but yields. The building consists of three bays of 4.0 m width in the longitudinal direction and 5 m width in the transverse direction. The dead load consists of self-weight of structural and non-structural members. The live load is assumed to be 1.5 kN/m^{2}for roof and 3.0 kN/m^2 for floors. Other types of loads such as wind loads, snow loads etc. are not taken into the account. The input parameters as specified by BIS for the area are: Zone (V), importance factor (I) of 1.0, response reduction factor (R) of 5.0 (SMRF), and soil type (hard soil site, and spectral acceleration(Sa) for 5% damped spectra).Initially the above said models are analyzed by equivalent static analysis for validation in SAP 2000, then the non-linear time history analysis was performed for the models using PERFORM 3D with the scaled ground motion records (i.e) Incremental dynamic analysis. The Maximum inter-story drift and various energies E_e(t), E_k(t), E_d(t), E_h(t) found from the analysis results are tabulated and used for further interpretation as targeted for the outcome of the present paper. The energy dissipation capacities of structure is shown in fig 4.

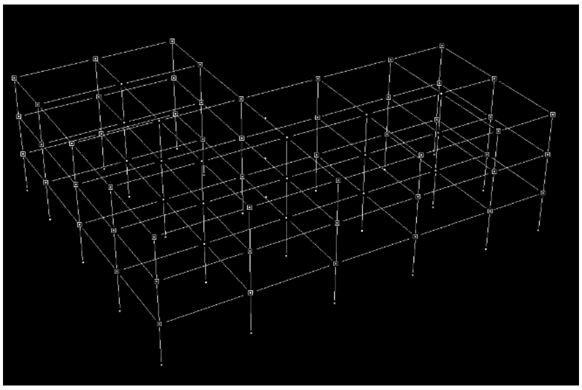

Fig 2: Model-I (Irregular structure 3D model)

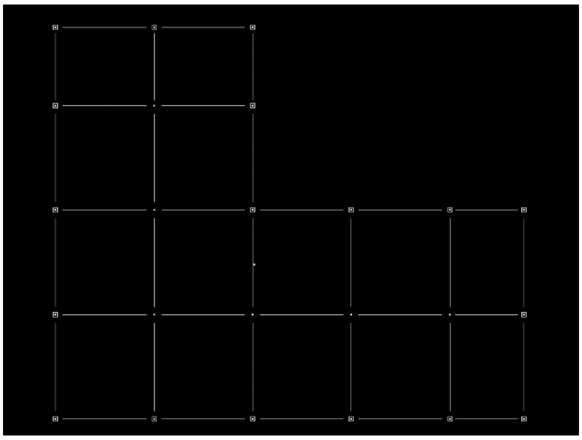

Fig 2a: Plan of Model-I

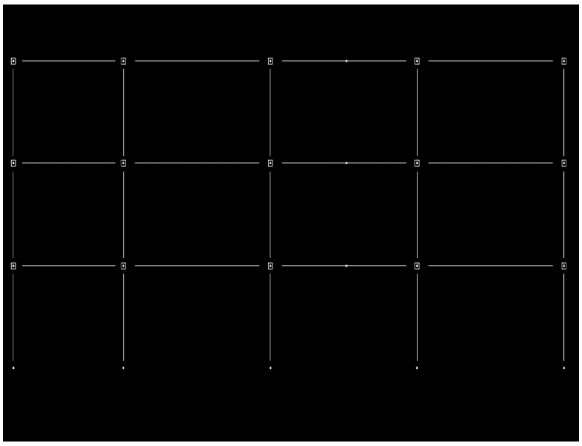

Fig 2b: X-direction frame of Model-I

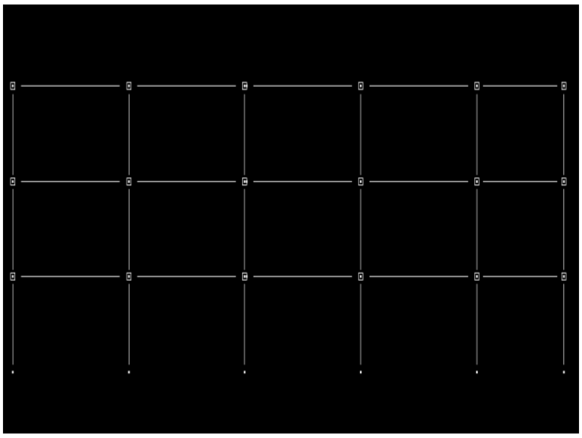

Fig 2b: Y-direction frame of Model-I

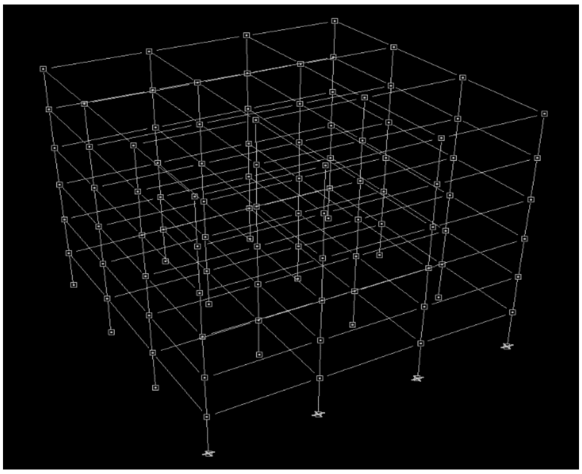

Fig 3: Model-II (Regular structure 3D Model)

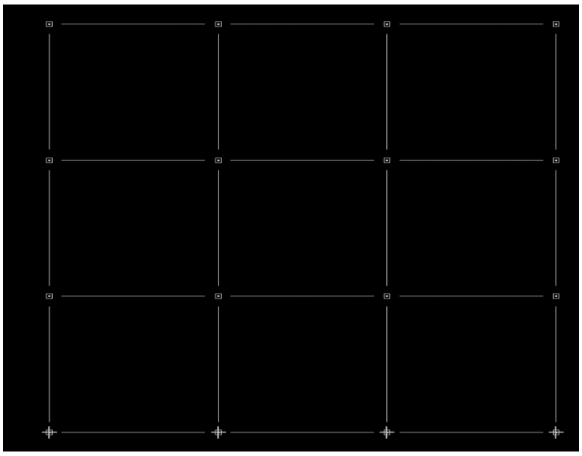

Fig 3a: Plan of Model-II

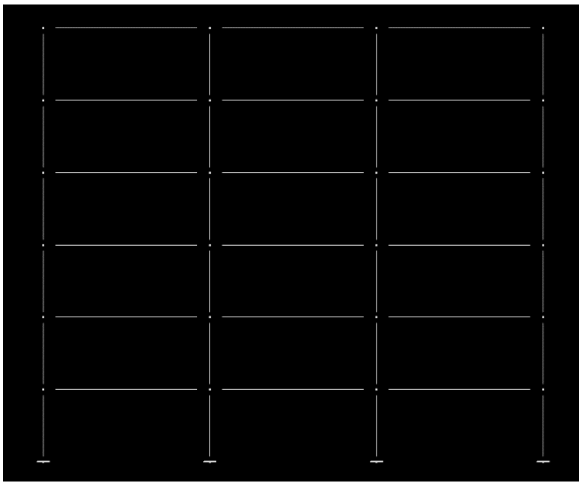

Fig 3: X & Y direction frame of Model-II

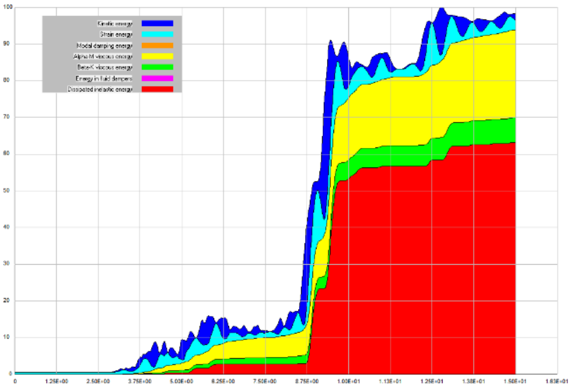

Fig 4: Energy dissipation of various energies

III RESULTS AND DISCUSSIONS

The results are tabulated as shown in the following as table 1a to table 8b. The incremental dynamic analysis curves (IDA) for the maximum inter-story drift, various energies are plotted for different ground motions and are shown in the following figures as figure 5a to figure 12b. The figure plotted shows the comparison of the maximum inter-story drift and the various energies of the structure. From the results we can observe for the irregular structure the inter-story drift values are more than the hysteretic energy, strain energy, kinetic energy and the modal damping energy for the first ground motion record (Elcentro). The strain energy value is more for the second ground motion record than the story drift but as expected the hysteretic energy, kinetic energy and the modal damping energy values are less than the inter-story drift for second ground motion record (Northridge). For regular structure it shows us the mixed results for both ground motions, especially for strain energy. Overall the results indicate that the energy criterion analysis gives better results than the drift criterion for the considered structures subjected to earthquake ground motions. Also, some of the results shows that the drift is better when compared to the strain energy.

Model 1: Irregular Structure

Table 1a: Drift & Inelastic Energy dissipated Values of El Centro

Scale Factor	Drift	Inelastic Energy Dissipated (N.mm)
0	0	0
0.2	0.006419	13.79206
0.4	0.012812	12948061
0.6	0.016014	29330862
0.8	0.018382	40787523
1	0.020288	53780778
1.2	0.024362	76942668
1.4	0.02945	91257846
1.6	0.03445	1.31E+08
1.8	0.038495	1.6E+08
2	0.041429	1.89E+08

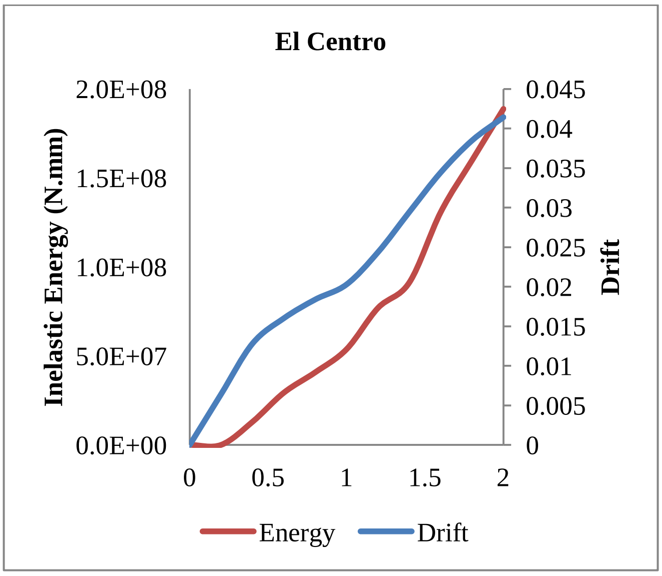

Fig 5a: IDA Curve for Drift & Inelastic Energy dissipated for El Centro

Table 1b: Drift & Inelastic Energy dissipated Values NR Mulholland

Scale Factor (PGA)	Drift	Inelastic Energy Dissipated (N.mm)
0	0	0
0.2	0.013093	13.79206
0.4	0.015957	34333830
0.6	0.01978	83179431
0.8	0.025226	1.31E+08
1	0.032709	1.64E+08
1.2	0.040356	1.91E+08
1.4	0.048252	2.36E+08
1.6	0.055843	3.02E+08
1.8	0.063158	3.53E+08
2	0.070676	4.01E+08

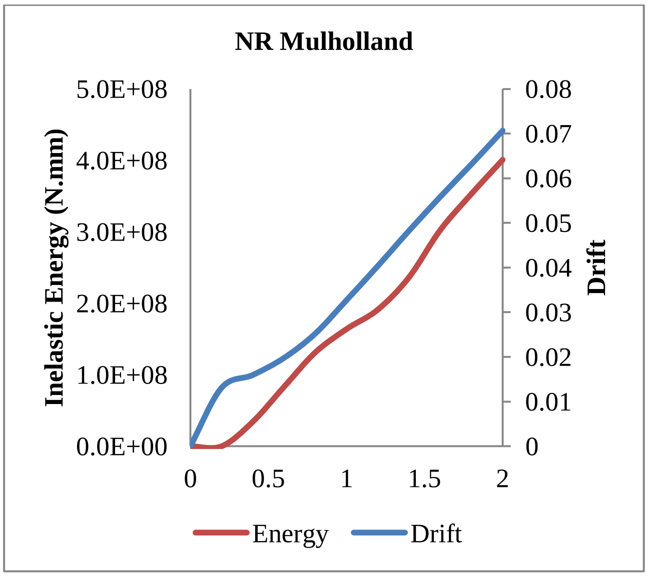

Fig 5b: IDA Curve for Drift & Inelastic Energy dissipated NR Mulholland

Table 2a: Drift & Strain Energy Values of El Centro

Scale Factor (PGA)	Drift	Strain Energy (N.mm)
0	0	0
0.2	0.006418	1.52E+08
0.4	0.012812	4.08E+08
0.6	0.016013	5.42E+08
0.8	0.018382	6.65E+08
1	0.020288	8.16E+08
1.2	0.024362	9.46E+08
1.4	0.02945	1.06E+09
1.6	0.034449	1.17E+09
1.8	0.038494	1.26E+09
2	0.041428	1.37E+09

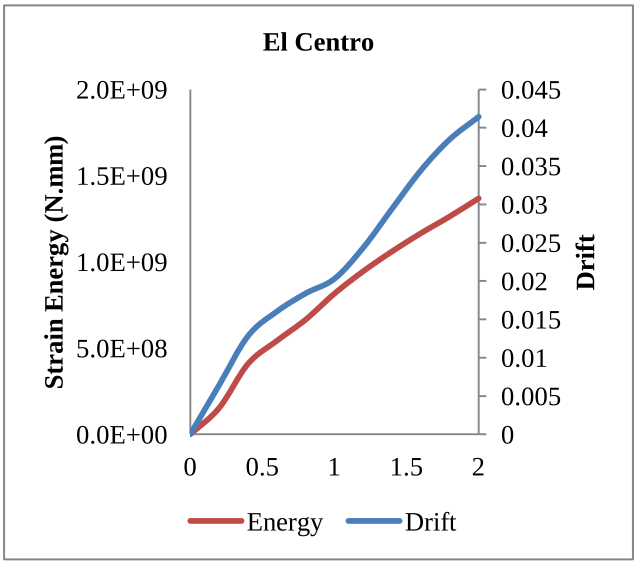

Fig 6a: IDA Curve for Drift & Strain Energy for El Centro

Table 2b: Drift & Strain Energy Values of NR Mulholland

Scale Factor (PGA)	Drift	Strain Energy (N.mm)
0	0	0
0.2	0.013092	2.96E+08
0.4	0.015957	7.69E+08
0.6	0.01978	9.62E+08
0.8	0.025225	9.52E+08
1	0.032709	1.13E+09
1.2	0.040355	1.33E+09
1.4	0.048252	1.55E+09
1.6	0.055842	1.76E+09
1.8	0.063158	1.98E+09
2	0.070675	2.18E+09

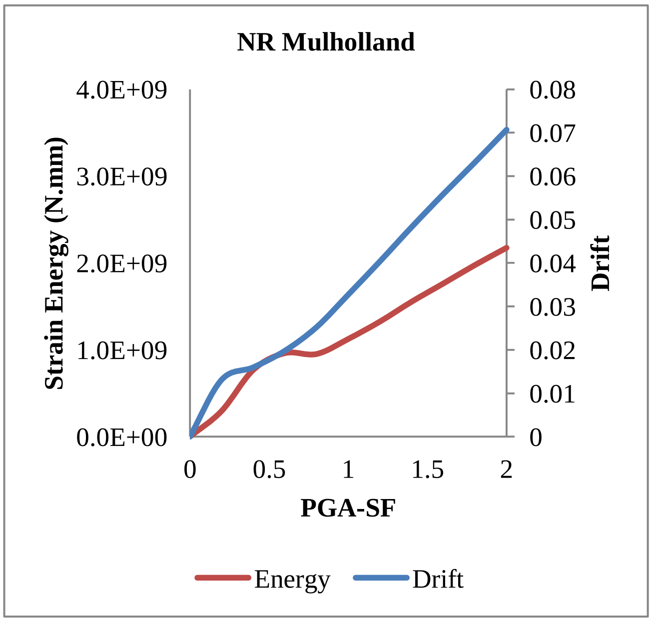

Fig 6b: IDA Curve for Drift & Strain Energy for NR Mulhollan

Table 3a: Drift & Kinetic Energy Values of El Centro

Scale Factor (PGA)	Drift	Kinetic Energy (N.mm)
0	0	0
0.2	0.006418	1E+08
0.4	0.012812	3.43E+08
0.6	0.016013	5.67E+08
0.8	0.018382	7.89E+08
1	0.020288	1.02E+09
1.2	0.024362	1.22E+09
1.4	0.02945	1.49E+09
1.6	0.034449	1.86E+09
1.8	0.038494	2.25E+09
2	0.041428	2.61E+09

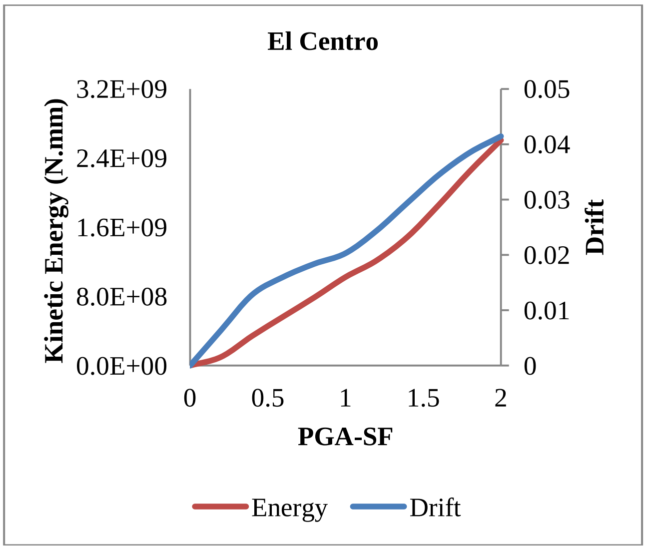

Fig 7a: IDA Curve for Drift & Kinetic Energy for El Centro

Table 3b: Drift & Kinetic Energy Values of NR Mulholland

Scale Factor (PGA)	Drift	Kinetic Energy (N.mm)
0	0	0
0.2	0.013092	2.67E+08
0.4	0.015957	7.87E+08
0.6	0.01978	1.47E+09
0.8	0.025225	1.94E+09
1	0.032709	2.39E+09
1.2	0.040355	2.79E+09
1.4	0.048252	3.12E+09
1.6	0.055842	3.77E+09
1.8	0.063158	4.66E+09
2	0.070675	5.58E+09

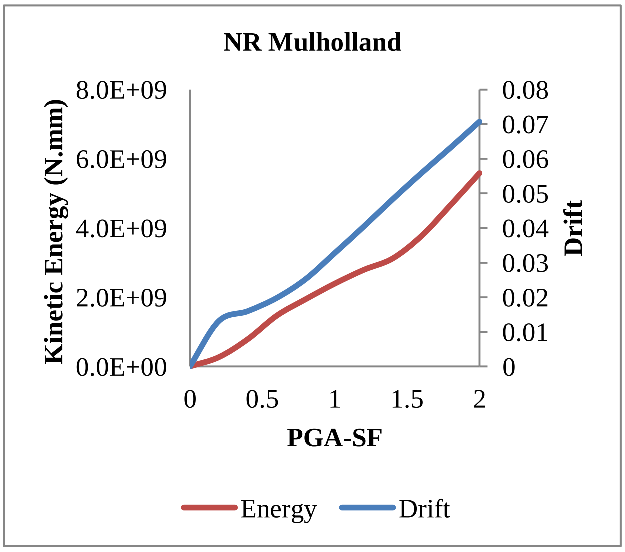

Fig 7b: IDA Curve for Drift & Kinetic Energy for NR Mulholland

Table 4a: Drift & Modal Damping Energy Values of El Centro

Scale Factor (PGA)	Drift	Modal Damping Energy (N.mm)
0	0	0
0.2	0.006418	2.15E+08
0.4	0.012812	7.95E+08
0.6	0.016013	1.43E+09
0.8	0.018382	1.98E+09
1	0.020288	2.4E+09
1.2	0.024362	2.83E+09
1.4	0.02945	2.99E+09
1.6	0.034449	3.76E+09
1.8	0.038494	4.29E+09
2	0.041428	4.87E+09

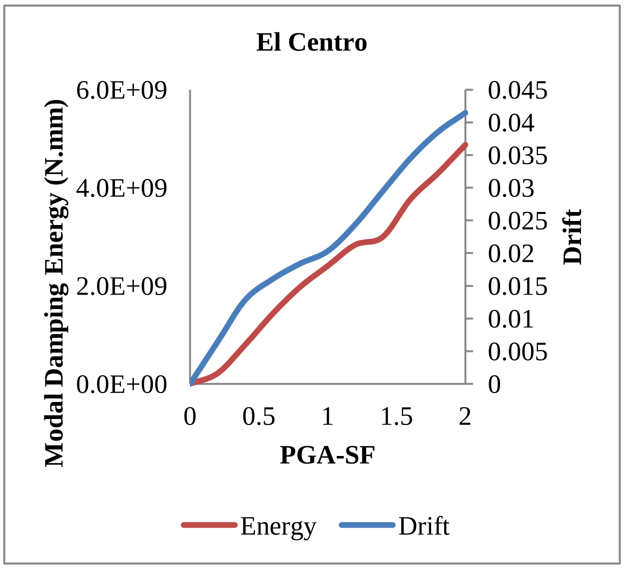

Fig 8a: IDA Curve for Drift & Modal Damping Energy for El Centro

Table 4b: Drift & Modal Damping Energy Values of NR Mulholland

Scale Factor (PGA)	Drift	Modal Damping Energy (N.mm)
0	0	0
0.2	0.013092	2.46E+08
0.4	0.015957	7.03E+08
0.6	0.01978	1.16E+09
0.8	0.025225	1.63E+09
1	0.032709	2.11E+09
1.2	0.040355	2.63E+09
1.4	0.048252	3.21E+09
1.6	0.055842	3.83E+09
1.8	0.063158	4.5E+09
2	0.070675	5.19E+09

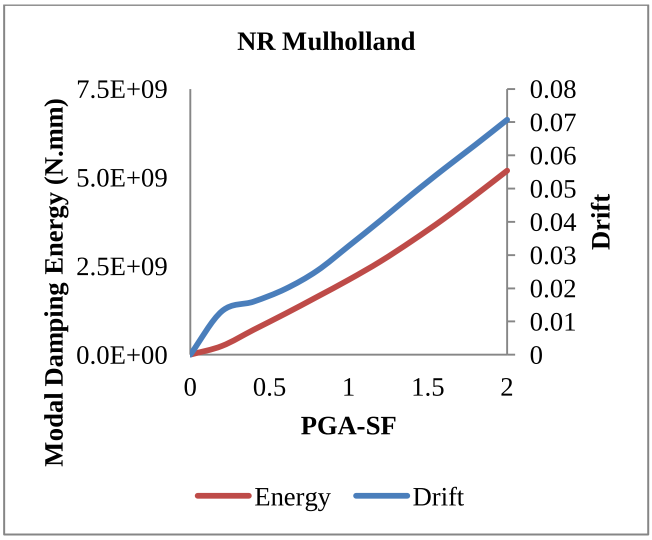

Fig 8b: IDA Curve for Drift & Modal Damping Energy for NR Mulholland

Model 2: Regular Structure

Table 5a: Drift & Inelastic Energy dissipated Values of El Centro

Scale Factor (PGA)	Drift	Inelastic Energy Dissipated (N.mm)
0	0	0
0.2	0.0045	16
0.4	0.0058	10490000
0.6	0.00731	31200000
0.8	0.00896	58100000
1	0.01013	90200000
1.2	0.01108	1.16E+08
1.4	0.01396	1.4E+08
1.6	0.0171	1.7E+08
1.8	0.0192	2.02E+08
2	0.02159	2.45E+08

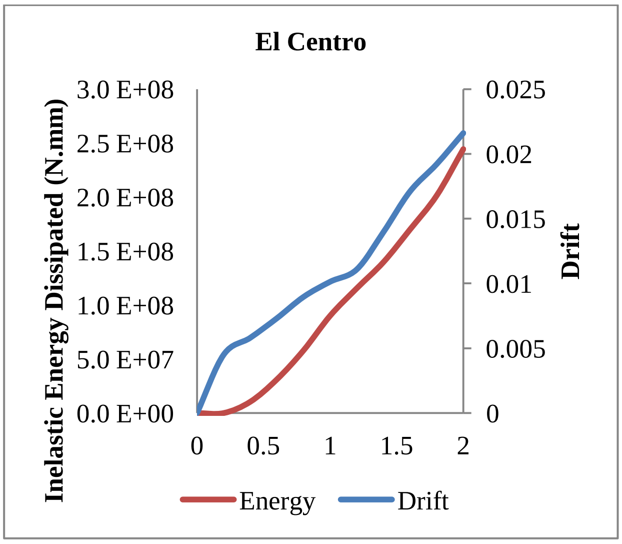

Fig 9a: IDA Curve for Drift & Inelastic Energy dissipated for El Centro

Table 5b: Drift & Inelastic Energy dissipated Values NR Mulholland

Scale Factor (PGA)	Drift	Inelastic Energy Dissipated (N.mm)
0	0	0
0.2	0.0045	32
0.4	0.00871	24800000
0.6	0.011	92710000
0.8	0.01351	1.95E+08
1	0.01767	2.85E+08
1.2	0.02225	3.74E+08
1.4	0.02678	4.41E+08
1.6	0.03136	5.13E+08
1.8	0.03565	5.78E+08
2	0.04029	6.4E+08

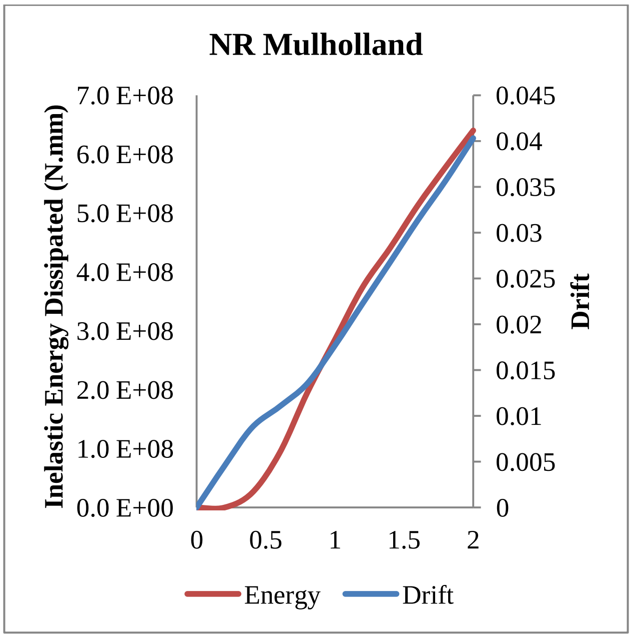

Fig 9b: IDA Curve for Drift & Inelastic Energy dissipated NR Mulholland

Table 6a: Drift & Strain Energy Values of El Centro

Scale Factor (PGA)	Drift	Strain Energy (N.mm)
0	0	0
0.2	0.0045	16877000
0.4	0.0058	54100000
0.6	0.00731	95310000
0.8	0.00896	1.48E+08
1	0.01013	1.92E+08
1.2	0.01108	2.28E+08
1.4	0.01396	2.62E+08
1.6	0.0171	2.8E+08
1.8	0.0192	3.21E+08
2	0.02159	3.62E+08

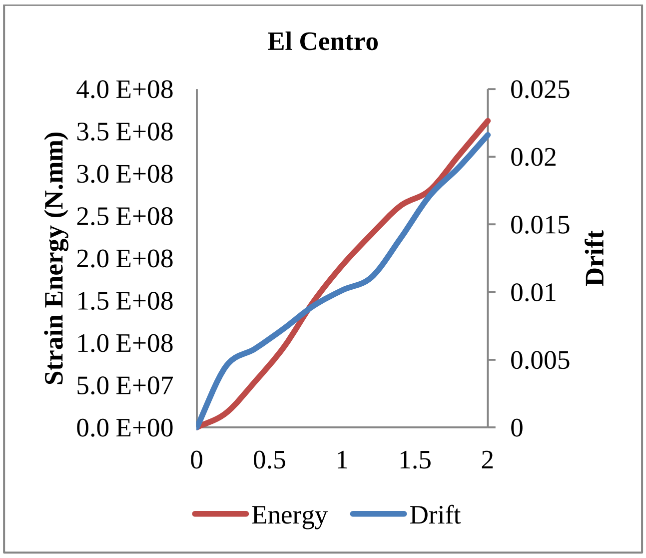

Fig 10a: IDA Curve for Drift & Strain Energy for El Centro

Table 6b: Drift & Strain Energy Values of NR Mulholland

Scale Factor (PGA)	Drift	Strain Energy (N.mm)
0	0	0
0.2	0.0045	26240000
0.4	0.00871	94740000
0.6	0.011	1.68E+08
0.8	0.01351	2.1E+08
1	0.01767	2.38E+08
1.2	0.02225	2.4E+08
1.4	0.02678	2.45E+08
1.6	0.03136	2.66E+08
1.8	0.03565	2.95E+08
2	0.04029	3.03E+08

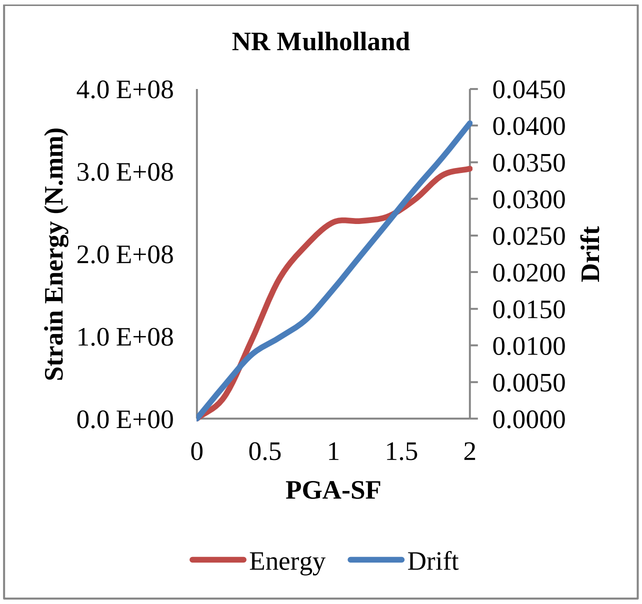

Fig 10b: IDA Curve for Drift & Strain Energy for NR Mulholland

Table 7a: Drift & Kinetic Energy Values of El Centro

Scale Factor (PGA)	Drift	Kinetic Energy (N.mm)
0	0	0
0.2	0.0045	22260000
0.4	0.0058	1.26E+08
0.6	0.00731	2.7E+08
0.8	0.00896	4.37E+08
1	0.01013	6.03E+08
1.2	0.01108	7.68E+08
1.4	0.01396	9.39E+08
1.6	0.0171	1.11E+09
1.8	0.0192	1.29E+09
2	0.02159	1.49E+09

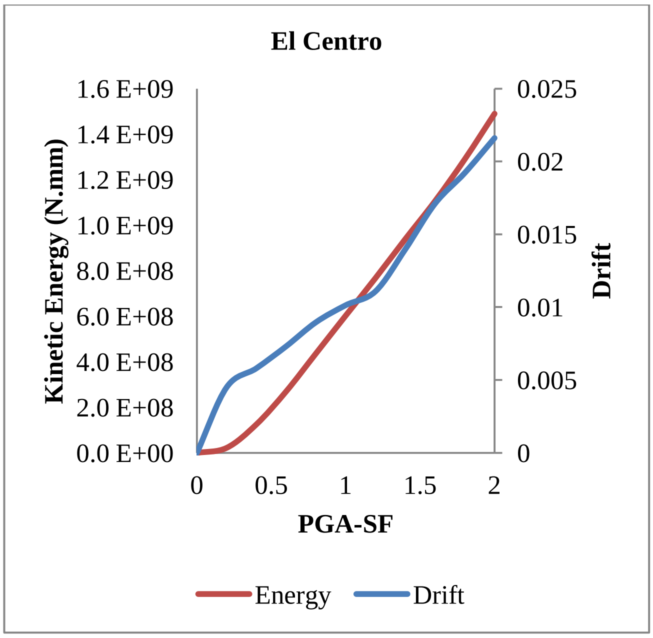

Fig 11a: IDA Curve for Drift & Kinetic Energy for El Centro

Table 7b: Drift & Kinetic Energy Values of NR Mulholland

Scale Factor (PGA)	Drift	Kinetic Energy (N.mm)
0	0	0
0.2	0.0045	45520000
0.4	0.00871	1.76E+08
0.6	0.011	3.26E+08
0.8	0.01351	4.28E+08
1	0.01767	5.07E+08
1.2	0.02225	6.23E+08
1.4	0.02678	7.88E+08
1.6	0.03136	9.8E+08
1.8	0.03565	1.19E+09
2	0.04029	1.4E+09

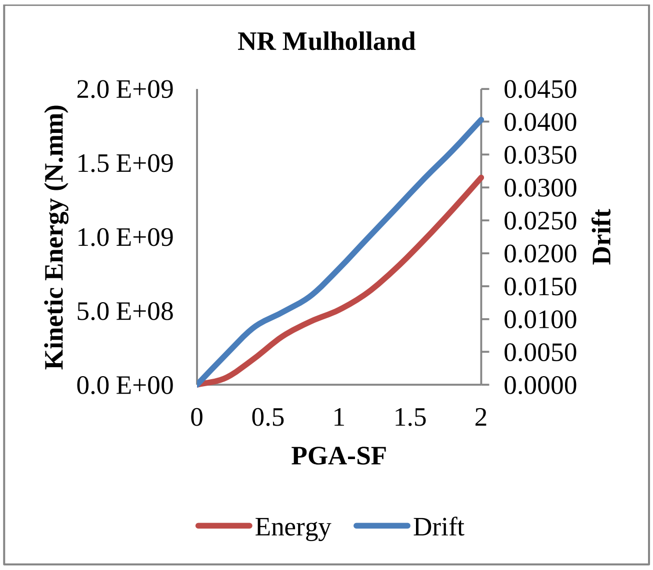

Fig 11b: IDA Curve for Drift & Kinetic Energy for NR Mulholland

Table 8a: Drift & Modal Damping Energy Values of El Centro

Scale Factor (PGA)	Drift	Modal Damping Energy (N.mm)
0	0	0
0.2	0.0045	2200000
0.4	0.0058	8000000
0.6	0.00731	17300000
0.8	0.00896	27500000
1	0.01013	37100000
1.2	0.01108	45900000
1.4	0.01396	54600000
1.6	0.0171	62500000
1.8	0.0192	71400000
2	0.02159	81700000

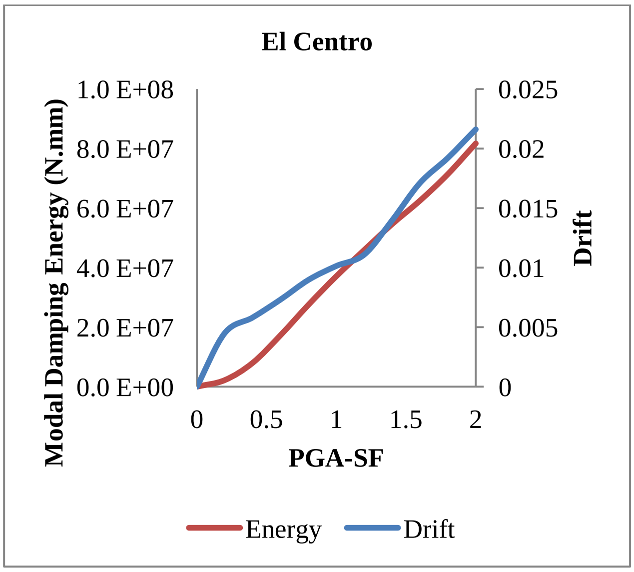

Fig 12a: IDA Curve for Drift & Modal Damping Energy for El Centro

Table 8b: Drift & Modal Damping Energy Values of NR Mulholland

Scale Factor (PGA)	Drift	Modal Damping Energy (N.mm)
0	0	0
0.2	0.0045	4000000
0.4	0.00871	15360000
0.6	0.011	28000000
0.8	0.01351	37100000
1	0.01767	44300000
1.2	0.02225	59200000
1.4	0.02678	76400000
1.6	0.03136	95400000
1.8	0.03565	1.16E+08
2	0.04029	1.39E+08

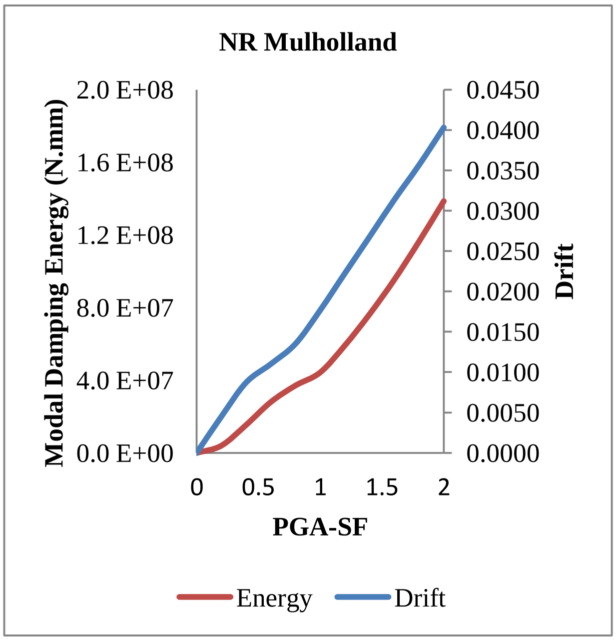

Fig 12b: IDA Curve for Drift & Modal Damping Energy for NR Mulholland

IV CONCLUSIONS

Based on the sufficient time history analysis i.e. incremental dynamic analysis on the regular and irregular structure, this paper studied the effect of the energy as design criterion and hence the designed structure was compared with the inter-story drift. From this evaluation the following conclusions are obtained

1. The use of energy balance concept as design criterion for the considered regular and irregular structures is effective.
2. Considering the limited results available the inelastic energy plays major role in the concept of energy based seismic design of structures.
3. Energy demand versus energy capacity may help for identification and quantification of areas of weakness and likely damage in the structures.
4. Fragility curve can be developed using this incremental dynamic analysis curve which are much important for assessing the global risk of the structure from probable large earthquakes and to estimate the economic impact can happen for the future ground motions.
5. They can be used for the development of seismic codes intended for the seismic design of structures based on energy based concept.

Furthermore, calibrations are required with more set of ground motions for the applicability and reliability of the energy-based design method.

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