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ON THE APPROXIMATE PUSHOVER CURVES BASED ON ERROR DISTRIBUTION, USING MULTI-MODAL INCREMENTAL DYNAMIC ANALYSIS

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ABSTRACT

In this paper, a new technique for the study of the nonlinear performance of structures in different levels of earthquake is developed. In this novel technique, the Incremental Dynamic Analysis (IDA) curves are not achieved from nonlinear dynamic analysis of multi degree of freedom structure. Rather, the procedure of calculating curves is based on the transformation of the total structure into the several single degree of freedom structures and finally analyzing them through modal pushover analysis method. Also a new idea for approximating pushover curves that is based on error distribution shall extensively be discussed.

It is important to note that the level of energy absorbency of structure can be a good criteria for the intensity of the earthquake. Therefore, in this study the input energy to the equivalent structural system is appropriately used as intensity measure, when applying the different levels of scaled earthquakes. This method possesses all the advantages of the IDA method in studying performance of structures in different levels of earthquake. It also benefits from easy usage, high solving speed and low computational volume.

In this research, several earthquake records have been applied over four steel structural frames of 4, 8, 12 and 16 stories. Structural responses derived by this method containing maximum displacement, maximum drift, maximum plastic hinge rotation and hysteretic energy at the end of quake, have been compared with IDA method; and the results are found from Multi-modal Incremental Dynamic Analysis to have an acceptable precision.

Introduction

Techniques for the design of structures in the most countries are rapidly changing. Extensive damage to the commercial as well as residential buildings during the high moderate and sever earthquakes showed that the existing codes should significantly be reconsidered. In the other words, existing design procedures are not strong enough to satisfy the economical design of resisting buildings against earthquakes. In most design cases, the nonlinear dynamic time history analysis of structures is lengthy, expensive, tedious, time consuming, uneconomical and also not easy to be practiced in all structures. In the other hand, additional techniques such as the nonlinear static pushover and/or capacity spectrum gets benefit of some kind of increasing static load in their technique, to show the proper passage from elastic region into the inelastic region and finally the complete yielding of the structure. The nonlinear static pushover analysis technique is mostly used in the ‘performance based design’ of structures. In this method, the final loading and/or displacement gradually get increased in different steps. In the each step

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strain/displacement of each member gets controlled. Until the final rupture of one and/or a few sections of the structure, considering reasonable margin of safety, the analysis will repeatedly be continued.

With this thinking, the approximate method of Incremental Dynamic Analysis (IDA) was a novel idea, which was initiated through a step by step changing of the loads. This concept was most likely introduced by Bertero (1977), who was followed by many other scientists and engineers such as Luco and Cornell (1998), Bazzurro and Cornell (1994), Yun and Foutch (2001), Mehanny and Deierien (2000), Dubina et al. (2000), De Matteis et al. (2000), Nassar and Krawinkler (1991), Psycharis et al. (2000) and Dimitrios and Cornell, who work extensively on this perception afterward. General speaking, this technique is based on the nonlinear behavior of the structure, headed for the calculation of the Damage Measure (DM) in the different level of a specific scaled earthquake record. Chopra and Goel in 2002 developed a method to include the effect of higher modes of vibration in estimating the seismic deformation demand of structures. The developed technique was based on the idea of multi-modal pushover analysis and by means of the concepts of spectral response analysis method. Paying no attention to the correlation between different modes, time history modal analysis can be carried out for a structure in the nonlinear region. This approximate method was suggested as the basis for Modal Pushover Analysis (MPA) in estimating seismic response of structures instead of using nonlinear time history dynamic analysis (Chopra and Goel 2001).

In this study, an original pertinent method of analysis named Modal Incremental Dynamic Analysis (MIDA) is presented which is practical for study of seismic behavior and realistic performance of structures under earthquake forces. This method is very handy, inexpensive and with acceptable precision. In fact, this method originates from the combination of 'incremental dynamic' and 'modal pushover' analysis methods where, it benefits from as many advantages of these two methods possible. This means that by equalizing structure to the number of equivalent single degrees of freedom systems and applying different levels of seismic loads, one can simply obtain an appropriate curve which accounts for the linear and nonlinear behavior of structure in different levels of earthquake. With the application of this method, Damage Indices (DM) at the end of earthquake shall easily be calculated and compared with other techniques. Essentially, these indices do include the maximum displacement, drift, hinge rotation and hysteretic energy at the end of the scaled earthquake.

By paying attention to the fact that input energy to the structure can also be a suitable criterion for the intensity of the earthquake, consequently it will be a great idea to investigate the damage criteria in accordance with the input energy applied to the structure. Therefore, in this study as well as introducing the original method "MIDA", the benefits from the use of energy as a criterion for intensity of earthquake has carefully been studied and compared with the criteria of Peak Ground Acceleration (PGA).

Remarks on Modal Incremental Dynamic Analysis (Mida)

The idea of using equivalent SDF system of multi-degree of freedom system has been extensively employed in this investigation. In this technique, one of the most important things is to correctly find the suitable and appropriate specification of this transformation. These measurements are such as period; damping, yielding loads, strain stiffness and finally the transformation factor of dynamic responses of SDF structure toward the actual multi-degree of freedom building. To transfer the MDF system into an equivalent SDF system and get its equivalent force – displacement curve for the n th mode of inelastic SDF system, as shown in the

Fig. (1), it is required to have: $(\xi_n, \omega_n)_{SDF} = (\xi_n, \omega_n)_{MDF}$

Consequently, the following relation-ships can be writhen:

$$(F_{yn})_{SDOF} = (F_{yn})_{MDOF} /(L/M)_n \quad (1)$$

$$(u_{rny})_{SDOF} = (u_{rny})_{MDOF} /(L/M)_n \, \phi_{rn} \quad (2)$$

$$(\alpha)_{SDOF} = (\alpha)_{MDOF} \quad (3)$$

$$L_n = \sum mi \, \phi_{im} \quad , \quad M_n = \sum mi \, \phi_{im}^2 \quad (4)$$

Where;
$F_{y\,n}$ = yielding strength of the n th mode of vibration,
$U_{r\,n\,y}$ = yielding displacement of the roof of the ith mode of vibration,
α = the strain hardening angle of the material,
$\Phi_{r\,n}$= the n th roof mode shape.

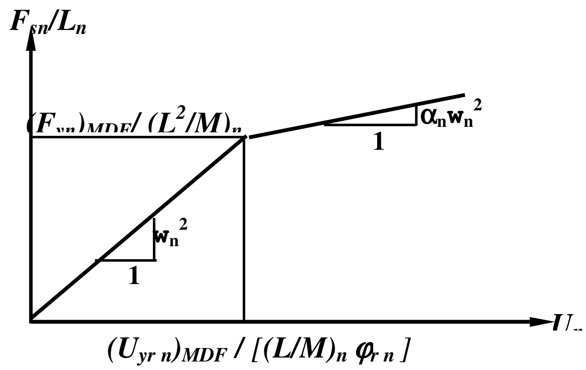


Figure 1. Load-displacement curve of the equivalent SDF oscillator, for the nth mode.

The maximum displacement on each mode of equivalent SDF system, according to different scaled level of an earthquake record will easily be calculated. And finally, the maximum displacement of the main multi-degree of freedom example problem for each level of the constructed scaled earthquake record can be obtained through out the proper conversion coefficient:

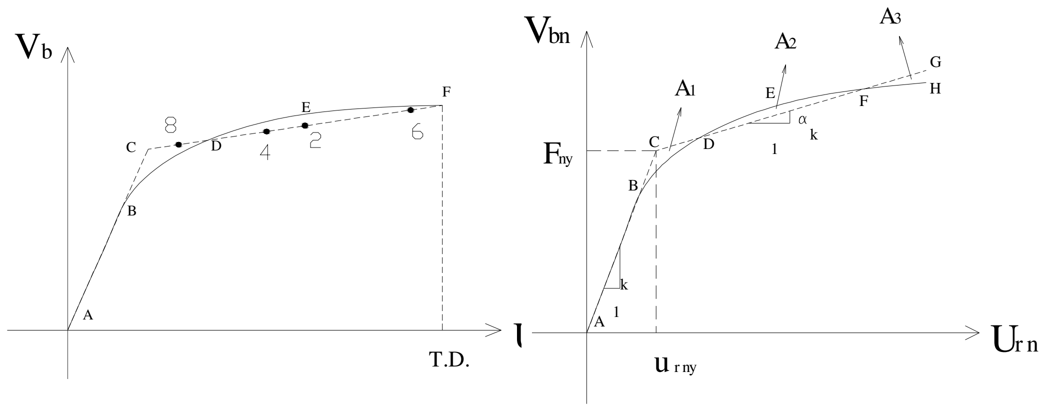
$$(\text{Max Dis})_{\text{MDOF}} = (\text{Max Dis})_{\text{SDOF}} \times \left(L/M \right)_n \times \phi_m \quad (5)$$

Load-displacement of a general single degree of freedom, which is constructed by means of conventional techniques, is shown in Fig.2.a, schematically. It should be noted that the line ABC will watchfully connect the endpoint of the first part which represent the linear region to the endpoint of the second part which represent the nonlinear region. It is also important to point that the endpoint of the second part is called ‘target displacement’ and can easily get founded through the conventional codes, trial and error computational processes and/or some other logical assumptions.

It is clear from the hysterics diagram of the SDF system under an imaginary earthquake record, the oscillator enters the nonlinear part several times; however, it just experiences the ‘target displacement’ only on one occasion. This fact expresses that the area below the bilinear model and the area below the capacity curve become equal once.

Although, dislocations less than the ‘target displacement’ slightly affect the maximum displacement of stories and the maximum drift, nevertheless they are pretty effectual toward the calculation of hysteretic energy. The large difference between the area below the capacity curve and the area below the bilinear model causes inaccuracy in the calculation of hysteretic energy. This problem shows more sever effect in records with greater duration, while the structure experiences more nonlinearities and also greater number of yielding cycles, within this type of earthquakes. Therefore, it seems that the way of estimating the capacity curve with bilinear model must get fairly re-evaluated. In this article, the estimation technique for the evaluation of ‘base shear’ versus ‘maximum displacement’ is obtained using a novel technique, founded on the error distribution.

With attention to the Fig. 2.b, the existing bilinear modeling gets corrected in a way that the slope of linear part ABC remains the same. However, the slope of second part CDFG shall be specified by trial and error, in such a way that the summation of bounded area between two lines becomes minimum. This condition dictates that the line CDFG intersects the curve in two places, where; $A_1+A_3=A_2$ .This approach of bilinear processing has two different advantages. The first one is that the new generated bilinear model in any possible position will remain closest to the capacity curve of the frame; and the bounded area under the bilinear model will be more realistic than before. Therefore, the error will tend to decrease in comparison with the previous condition. The other advantage is that besides the balance of the system between bilinear diagram and the main curve remains intact, this correction results a steadier and realistic distribution of error through out the resultant curve and also as shown in Fig. 2, the consequential error around C have a reasonable tendency to decrease.



(a) Bi-linear capacity curve model (b) New approximated bi-linear capacity curve

Figure 2. Schematic diagram of load-displacement for the SDF oscillator.

Example Structures and Applied Earthquake Records

In this investigation, steel moment resisting frames of 4, 8, 12 and 16 stories have been modeled and designed. The philosophy of weak beam-strong column has also been observed in design of these frames, therefore the primary failure mechanism is forcefully transferred to the beams. Furthermore, each frame consists of three spans of five meters and story height of three meters.

For the analysis and comparison of results, six records of Landers, Park Field, Northridge, Kern County, El-Centro and San Fernando are chosen. All these records are picked from California area, far from any possible effect of fault closure. Also, finite element procedure is used for all nonlinear static and dynamic analysis of the structures. Also, different damage indices according to different parameters such as maximum displacement, drift, plastic rotation and finally the hysteretic energy to the structure are extensively discussed. Furthermore, appropriate graphs for the PGA of the different scaled record and the total input energy versus the above parameters are produced and approximate results are compared with IDA technique. These graphs are shown as fallows in two cases: a) Comparison of MIDA and IDA methods for one earthquake record in Fig.3 to10. b) Comparison of MIDA and IDA methods for multi records by the means of average curves of several seismic records in Fig.11 to 18. Using definitions of “over-average” for average plus dispersion value and “under-average” for average minus dispersion value.

In all of the shown MIDA and Multi-MIDA curves, the new approximated bi-linear capacity curve is used. Also the results induce proper improvement of the new method to estimate pushover curve, in comparison with the outcomes from old technique. As an example the comparison between old and new method for Landers earthquake and 12 stories structure is shown in Fig 19.

a) Comparison of MIDA and IDA curves

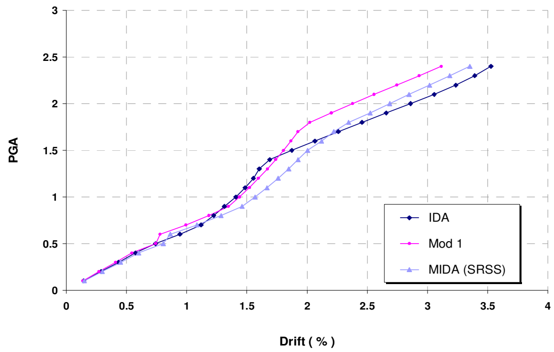


Figure 3. MIDA and IDA curves for 8 stories structure, Sanfernando,Max.Drift – PGA.

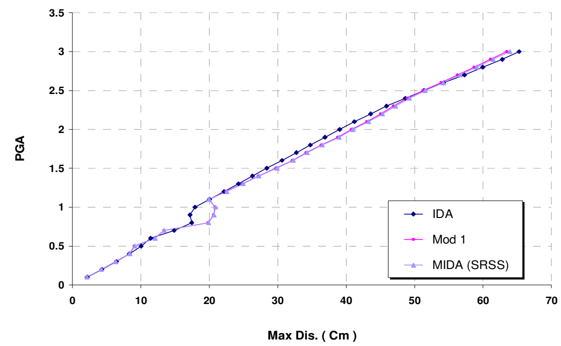


Figure 4. MIDA and IDA curves for 4 stories structure Landers, Max. Displacemant – PGA.

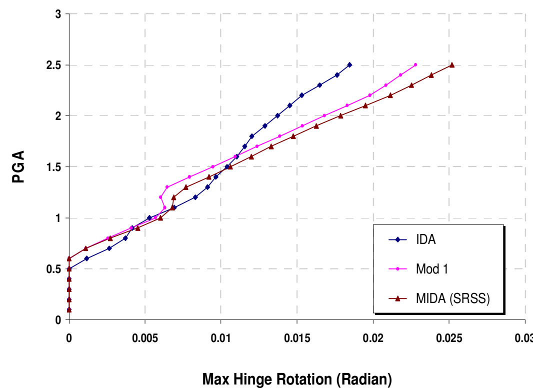


Figure 5. MIDA and IDA curves for 16 stories structure, Park Field, Hinge Rotation – PGA.

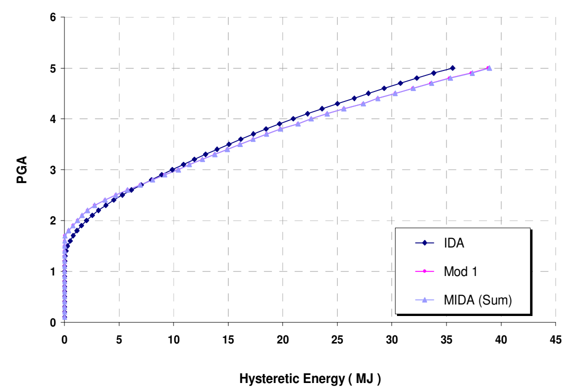


Figure 6. MIDA and IDA curves for 12 stories structure, Northridge, Hystertic Energy – PGA.

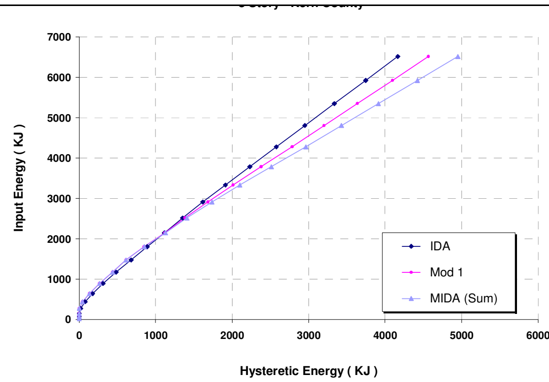


Figure 7. MIDA and IDA curves for 8 stories structure, Kern County, Hystertic Energy-Input Energy.

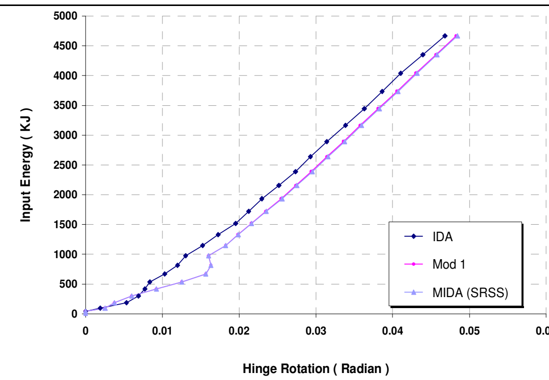


Figure 8. MIDA and IDA curves for 4 stories structure, El Centro , Hinge Rotation -Input Energy.

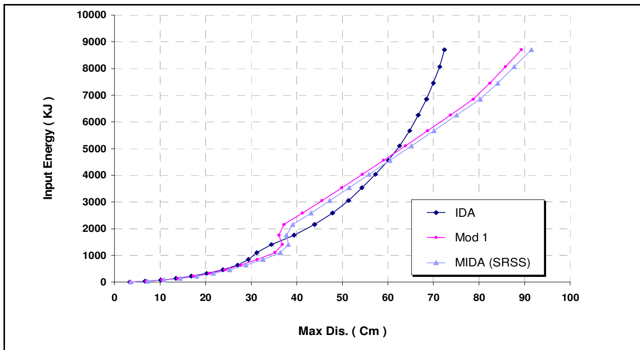


Figure 9. MIDA and IDA curves for 16 stories structure, Park Field, Max.Displ - Input Energy.

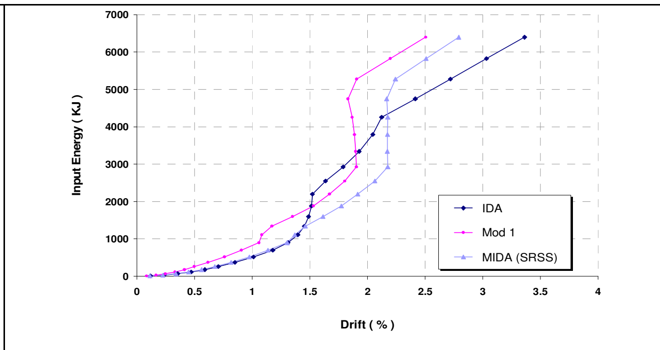


Figure 10. MIDA and IDA curves for 12 stories structure, Sanfernando, Max. Drift - Input Energy.

b) Comparison of Multi MIDA and IDA curves

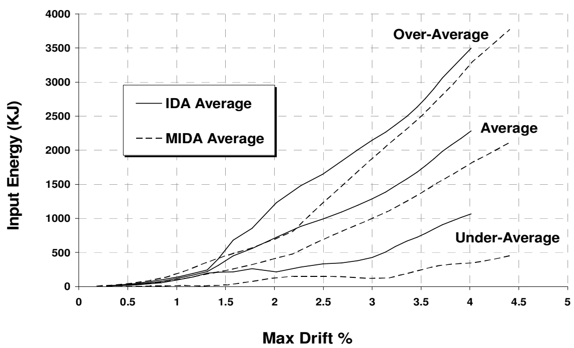


Figure 11. Multi-MIDA and IDA curves for 4 stories structure.

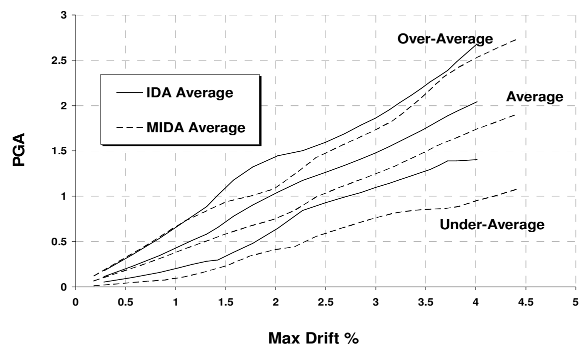


Figure 12. Multi-MIDA and IDA curves for 4 stories structure.

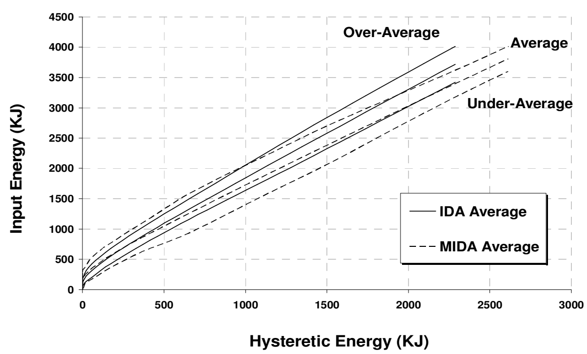


Figure 13. Multi-MIDA and IDA curves for 8 stories structure.

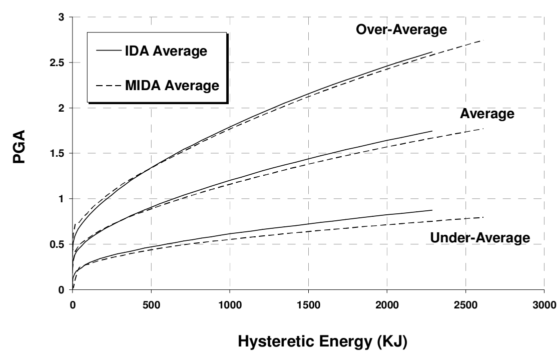


Figure 14. Multi-MIDA and IDA curves for 8 stories structure.

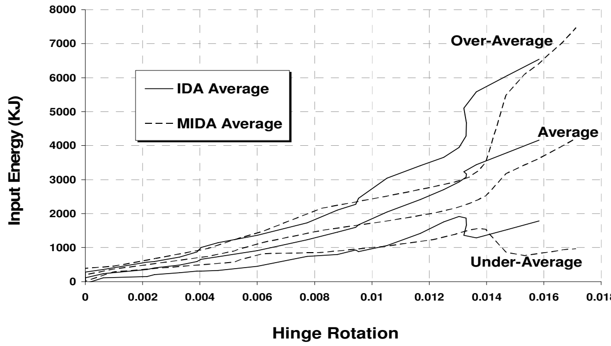


Figure 15. Multi-MIDA and IDA curves for 12 stories structure.

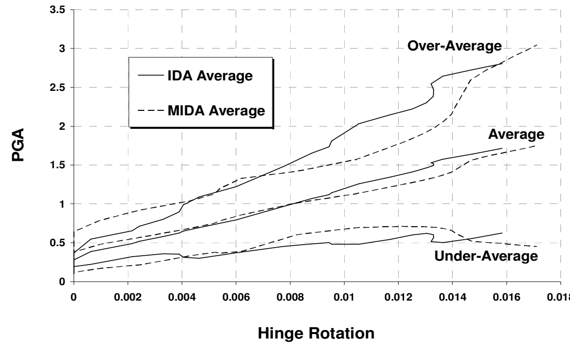


Figure 16. Multi-MIDA and IDA curves for 12 stories structure.

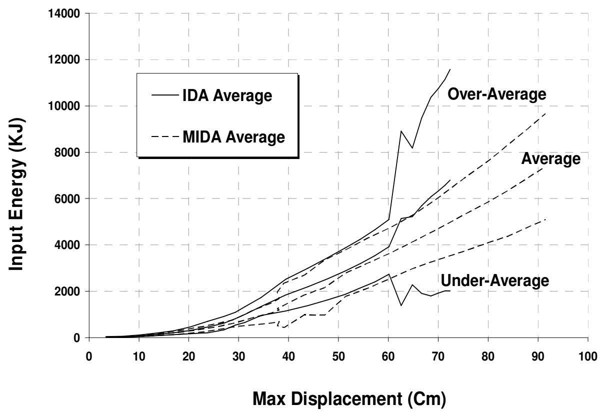


Figure 17. Multi-MIDA and IDA curves for 16 stories structure.

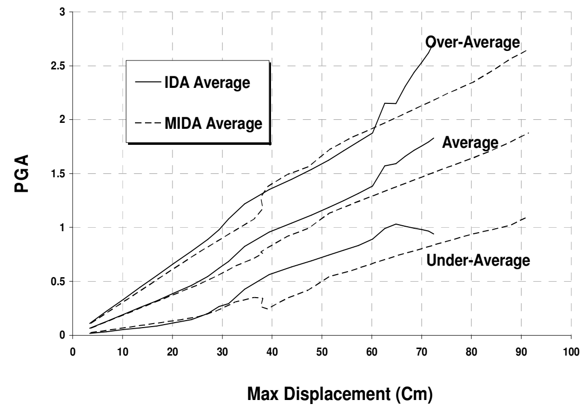


Figure 18. Multi-MIDA and IDA curves for 16 stories structure.

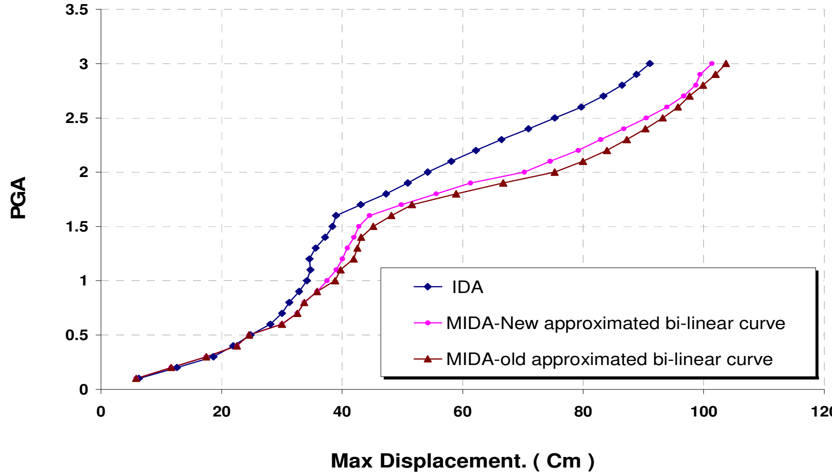


Figure 19. Comparison between old and new method to approximate pushover curve for Landers earthquake and 12 stories structure.

Conclusions

- The MIDA method reasonably estimates the average values of the exact solution of the problem with good accuracy. These approximated values can practically be used in appropriate design problems.
- Employment of the total input energy into the structure as the 'Intensity Measure (IM)' is much better and more effective than utilization of Peak Ground Acceleration (PGA) due to the decrease of results dispersion. Because the dispersion of responses for different seismic records, decreases through the use of the total input energy criterion. This particular fact is clearly observable in average curves.
- Approximation of base shear versus the maximum displacement with a bilinear curve induces some practical error. However, the new approximated bi-linear capacity curve shows proper improvement in the transformation error.
- The hysteretic energy of the structure, which is an important damage factor, has a close relation with the total input energy into the structure. Very low dispersion in the total input energy versus hysteretic energy diagrams and also the smoothness of these diagrams for different scaled records does strongly support this fact.
- In order to calculate the maximum displacement of conventional structures, only the first mode of vibration can be considered. However, calculation of the plastic hinge rotation and drift, especially in tall buildings, requires at least the first three modes of vibration.
- Most of the diagrams presented through utilization of the MIDA scheme, contrary to the IDA curves, are smooth and free of alteration due to input scaled records.

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