Alternative Method to Estimate IDA Curves

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***Abstract*—The conventional Incremental Dynamic Analysis (IDA), which is a series of nonlinear dynamic analysis, has been developed to study structural performance under earthquakes. Based on the methodology, a structural model is subjected to an earthquake record which is scaled to several seismic levels. These analyses are presented through one or more curves, the Damage Measure (DM) of the structure against the Intensity Measure (IM) of the earthquake record, known as IDA curves. By considering the high volume of computational efforts in the conventional incremental dynamic analysis, this paper presents a methodology to estimate IDA curves using capacity curves. For this purpose, the accuracy of the suggested method was investigated for 3-story SAC SEATTLE model under 20 different earthquake records by OpenSees. The results have revealed a reasonable accordance between two methods. The run time of the new suggested approach proved that the method is fast and computationally beneficial to be applied for estimating IDA curves.**

***Index Terms*—capacity curve, incremental dynamic analysis, IDA curves, performance based design**

I. Introduction

Earthquakes are recognized worldwide as one of the costliest natural hazards. As a result, many researches are aimed at presenting more accurate and constructive approaches to alleviate the effect of damage and economic losses [1]-[2] Measurement of earthquakes effects on structures have been always challenging [3]. In the past, the concepts of strength and performance were supposed to be the same. However, in recent decades, the differences were recognized and it was an introduction to performance based earthquake engineering. Generally, to access the performance objectives, various analysis procedures such as linear static, nonlinear static, linear dynamic, and nonlinear dynamic analysis were proposed. Considering nonlinear static analysis, researchers suggested a new method known as Incremental Dynamic Analysis (IDA), which is a series of nonlinear dynamic analyses. Using this approach, a set of time history analyses is carried out for a structural model by applying various intensity levels of an earthquake [4]-[6]. The results are presented by a diagram known as IDA curve. In such diagram, Intensity Measure (IM) parameters of the earthquake are plotted against Damage Measure (DM) parameters of the structure. It is noteworthy that due to the IDA, yielding strength of supposed model must be constant during each time history analysis. In other words, an IDA curve is obtained for a structure with a specific yielding strength. This analysis is implemented in many dynamic tests which aim at improving the performance of the built environment through strengthen the structure itself by adding more active and passive earthquake resistant elements [7]-[11] and also by stabilizing the soil which plays an important role in interaction of soil and structure in earthquake events [12]-[13].

As a result of high time consumption and expenses of IDA for complicated models, different alternatives have been proposed. However, each method is accompanied with several advantages and shortcomings. Dolŝek and Fajfar [14] presented a new method known as Incremental N2 (IN2). This parametric approach is a collection of nonlinear N2 analyses which are based on pushover analysis and response spectrum method. To obtain the IDA curves, Dolŝek and Fajfar [15] also applied the IN2 approach for an infilled reinforced concrete frame. Nevertheless, IN2 is limited by the N2 method deficiencies. Vamvatsikos and Cornell [16]-[17] reached 16%, 50% and 84% summarized IDA curves for the first-mode-dominated of Multiple Degree of Freedom (MDOF) model. This was possible by utilizing connections between Static Pushover (SPO) and IDA curve. Mofid et al. [18] and Han and Chopra [19] suggested a Modal Incremental Dynamic Analysis (MIDA) in order to access the summarized IDA curves. As a result of utilizing this method, Modal Pushover Analysis [20]-[21] was applied to replace the MDOF model with equivalent SDOF models which both have the same structural behavior; subsequently, the IDA is performed on the substituted models. Finally, the responses are combined by mathematical combination rules, such as, SRSS and CQC. Zafarkhah et al. [22] also exerted the MIDA in a structural model with additional damping. As it can be seen, based on the MIDA, time history analysis is still applied to equivalent SDOF systems. Therefore, to

Manuscript received March 15, 2019; revised December 7, 2019.

doi: 10.18178/ijscer.9.1.64-71

reduce computational efforts more efficiently, Moon et al. [23] proposed another procedure, “by incorporating empirical equations of inelastic displacement (CR) and collapse strength ratio (Rc)”, instead of time history analysis, IDA curves can be calculated. Azarbakht and Dolŝek [24]-[25] introduced Progressive Incremental Dynamic Analysis (PIDA) method. Using this method, to assess the IDA curves, only limited numbers of accelerograms were selected by Genetic algorithm and Simple Procedure. Vamvatsikos [26] suggested another procedure to obtain the IDA curve by parallel processing for structural models.

In this paper, using a diagram known as the Capacity Curve, an alternative approach is introduced to obtain the IDA curves [27]-[29]. Based on the suggested method, an equivalent SDOF system is estimated by MPA which can be considered as a representative for a MDOF response. Moreover, a diagram is illustrated by using a series of nonlinear dynamic analyses under a specific record. This diagram plays a significant role to access the IDA curves. The outstanding advantage of this method is to obtain the IDA curves for a structural model while having different yielding strength. In other words, by drawing a capacity curve, the IDA curves are obtained for a model with a constant period and different yielding strengths. To sum up, this approach presents the following benefits:

- Quicker access to IDA curves.
- Decreasing the computational effort.
- Using the capacity curve to obtain IDA curves for various yielding strength.

II. Methodology

A. Modal Pushover Analysis (MPA)

In this paper, to simulate the MDOF model response, Modal Pushover Analysis is utilized. This method is one of the most powerful and accurate existing applications which can consider the higher modes effects in high-rise buildings. It is based on substituting an N degree of freedom system to an equivalent single degree of freedom system. The procedure of this analysis is given as follows:

- Determining the period and mode shape of n^{th} mode.
- Plotting pushover diagram (V_{bn}, U_m) under lateral high-rise load pattern equals to (1).

$$S_n^* = [m] \times \{\emptyset_n\} \tag{1}$$

  In which, $[m]$ stands for diagonal mass matrix and $\{\emptyset_n\}$ represents the vector of n^{th}-natural vibration mode.

- Converting the pushover diagram to equivalent SDOF response curve by using (2) and (3). This step is schematically shown in Fig. 1,

$$D_n = U_m/\Gamma_n \emptyset_{rn} \tag{2}$$

$$F_{sn} = V_{bn}/\Gamma_n \tag{3}$$

  where U_m and V_{bn} are roof displacement and base shear of MDOF model due to n^{th} mode, respectively. The transition factor is Γ_n which is defined by (4).

$$\Gamma_n = \sum_i m_i \emptyset_{in} / \sum_i m_i {\emptyset_{in}}^2 \tag{4}$$

- Repeating the above steps for the few first most effective modes and combining the results by SRSS or CQC rule.

Next, there is an equivalent SDOF system whose response approximately is the same as the initial MDOF model.

B. The Capacity Curve Method for SDOF Models

The basis of this method is to obtain the capacity curve, force-deformation curve, for the substituted SDOF model. By calculating such curve for a model with a constant period, the IDA curve can be plotted for different yielding strength.

C. The Capacity Curve

Let us consider a SDOF model with a displacement-strength response as shown in Fig. 2. In this figure, U_y and U_p are yield and maximum nonlinear displacements, respectively.

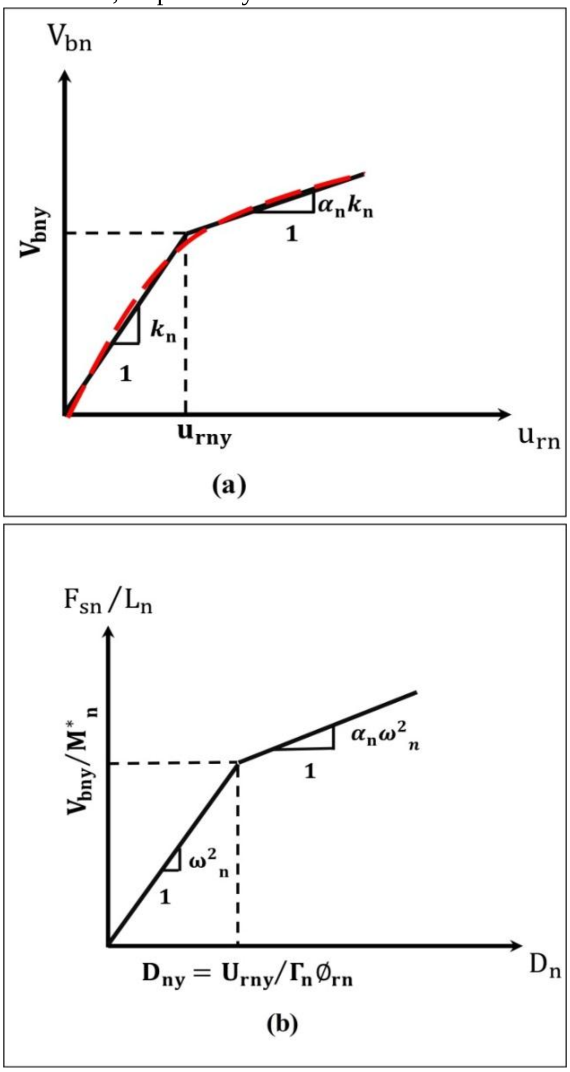

Figure 1. Determining the response diagram of equivalent SDOF system a) idealized pushover curve b) equivalent SDOF system.

The Capacity Curve for such model is demonstrated in Fig. 3, with a specific period under Trinidad earthquake acceleration record. In this figure, the vertical axis is the ratio of F_y/F_e, in which F_y stands for yielding strength of structure and F_e represents the minimum sufficient strength to cause elastic response of the structure under the aforementioned record. The horizontal axis represents maximum displacement.

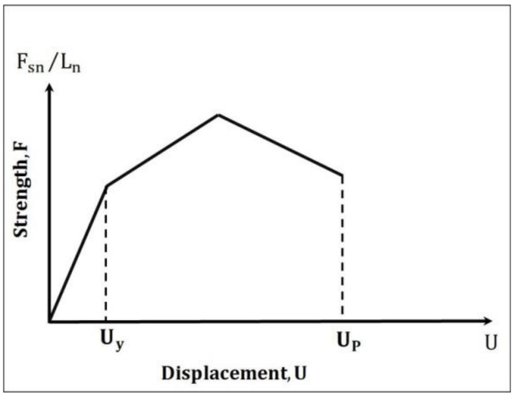

Figure 2. The backbone curve of the proposed model.

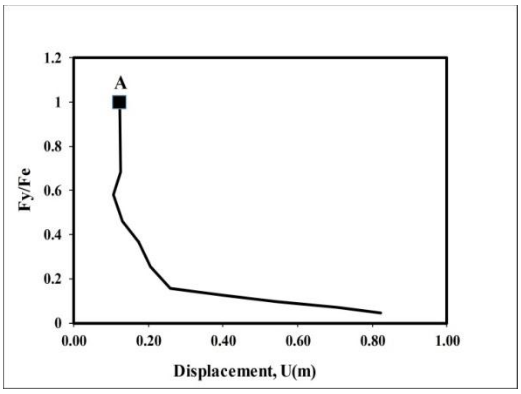

Figure 3. The capacity curve for the model under Trinidad earthquake record.

To draw the capacity curve, the following procedure is applied:

- First, to find the first point of the curve (the point A in Fig. 3), a linear analysis is performed where the maximum base shear of the SDOF model, is equal to F_e. It is important to note that during the linear analysis, F_e equals to F_y. ($F_y/F_e=1$)
- Next, to find other points, the yielding strength is decreased by the step of $0.05F_e$. A nonlinear dynamic analysis is performed and the corresponding maximum displacement is calculated in each step. This procedure was continued until F_y is reached zero. By calculating the coordinates and connecting them during each step, a capacity curve is illustrated.

D. Introducing the Suggested Method

Fig. 4 illustrates three capacity curves drawn for the SDOF model. In this diagram, the model is subjected to Trinidad earthquake acceleration record which is scaled to have PGAs of 0.5g, 1g and, 2g. As it can be seen in Fig. 4, the OC length is exactly twice the amount of OB length and OA is half the amount of OB. In fact, a capacity curve calculated for an earthquake record, which is scaled 2 times of Trinidad earthquake, is exactly twice the amount of capacity curve drawn for Trinidad earthquake. Therefore, the capacity curve of a SDOF structure under an earthquake, which is N times of the original earthquake, can be extracted from the capacity curve of a structure under original earthquake considering that N is the scale factor. In order to avoid any misunderstanding, this sentence should be presented in theoretical terms as (5) to (7).

$$X_c = N \times X_b \tag{5}$$

$$Y_c = N \times Y_b \tag{6}$$

$$OC = N \times OB \tag{7}$$

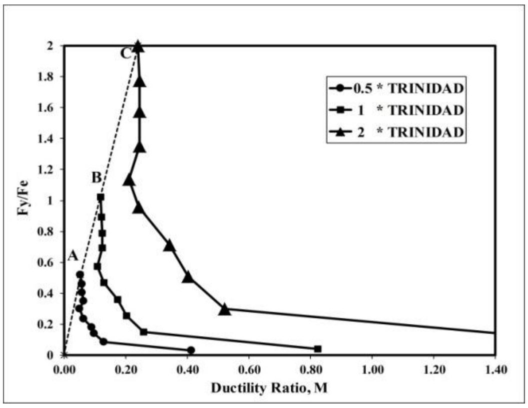

Figure 4. A SDOF structure with 0.1 seconds period under Trinidad earthquake.

To obtain an IDA curve from capacity curve, the following procedure is carried out: first, a horizontal line is drawn where the vertical component equals the ratio of yielding strength of the SDOF system to the weight of structure (W). This line virtually intersects a collection of hypothetical capacity curves which have linear relation with each other. As it can be observed in Fig. 5, point C is the intersection of the horizontal line with the virtual capacity curve drawn for the N times of Trinidad earthquake record. Drawing line OC, the original capacity curve is intersected at point B, next the OC/OB ratio illustrates the scale factor of original earthquake. On the other hand, horizontal component of point C (U_c) represents the corresponding maximum displacement.

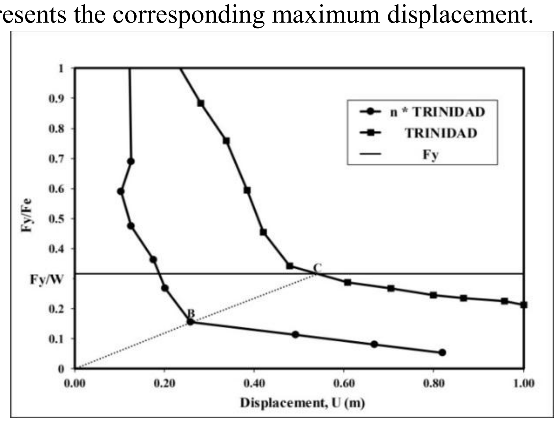

Figure 5. Diagram of presented theory for SDOF model.

Therefore, the maximum displacement of the SDOF structure subjected to any scaled earthquake can be extracted from the capacity curve which is constructed for the original earthquake.

Fig. 6 represents the IDA curves which are anticipated by conventional and proposed methods for the SDOF system. It is perceived that the suggested method has assessed the IDA curves with appropriate accuracy.

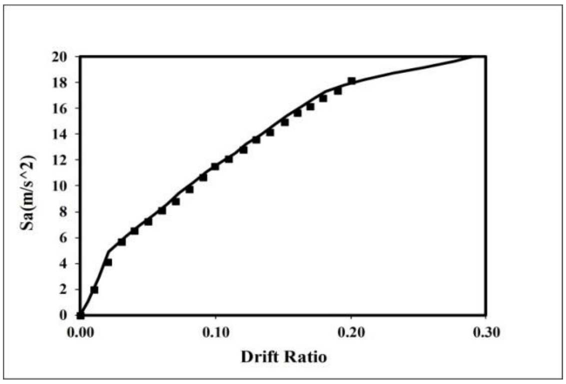

Figure 6. The verification of IDA curve for the capacity curve and conventional incremental dynamic analysis.

E. Theoretical Basis for the Capacity Curve Method

By considering the free body diagram of a SDOF model shown in Fig.7, the motion equation can be obtained based on (8), in which M and C represent mass and damping ratio of the system, respectively. Also, u is the system response under the subjected earthquake.

$$M\ddot{u} + C\dot{u} + f(u) = -M\ddot{u}_g \tag{8}$$

If the both sides of (8) are multiplied by a constant equals to$(1/\alpha)$, the equation can be rewritten based on (9) and z is response of the system for the new state:

$$M(\ddot{z}/\alpha) + C(\dot{z}/\alpha) + (1/\alpha)f(z) = -M(\ddot{u}_g/\alpha) \tag{9}$$

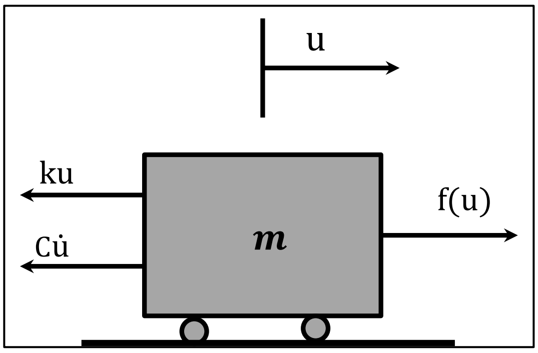

Figure 7. Free body diagram of a SDOF system.

Then (8) and (9) are equal if the following condition exists:

$$f(u) = (1/\alpha)f(z) \tag{10}$$

In this article, all of the studied models follow this relation which can be regarded a reasonable assumption. Therefore, the following relation can be concluded:

$$(z/\alpha) = u \;\rightarrow\; z = \alpha u \tag{11}$$

Considering (11) and Fig. 8, the reader can vividly conclude that in the elastic zone:

$$if\ U_2 = \alpha U_1\ then\ f(U_2) = \alpha f(U_1) \tag{12}$$

In the plastic zone, the same relation also exists because as it will be mentioned in section 4.1 when the yielding strength decreases, the backbone curve changes with constant overall shape. This claim schematically has been illustrated in Fig. 8.

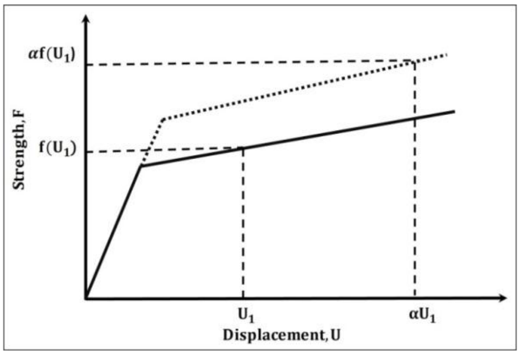

Figure 8. Decreasing backbone curve with constant overall shape.

F. Generalized Capacity Curve method for MDOF Systems

In MDOF systems, first the Modal Pushover Analysis (MPA) is exerted in order to convert a MDOF model to equivalent SDOF systems. Then, the suggested method is applied for the substituted models. It should be noted that, owing to negligence for the effect of higher modes in short-level buildings, this can be omitted. On the other hand, for high-rise buildings, the effect of higher modes is considered and the results are combined by a mathematical rule such as, SRSS and CQC.

III. Case Study

A. The Structural Model

To verify the suggested hypothesis, a 3-story SAC Seattle frame has been chosen which is designed by UBC code [30]. This building lateral load-resisting system is steel special moment-resisting frame. The configuration of this frame is illustrated in Fig. 9. As it can be seen, this frame is 9.15(m) in width with 4 bays. The frame story heights are 3.96(m). The seismic mass of 1st and 2nd floor is 478500 kg and for the roof this equals to 520000 kg. The yielding strength of steel is assumed to be 345 MPa. Here, the effect (second order) is also included. To simulate this model, the Opensees 2.4.0 [31] is utilized and the elements are defined by Steel 02 material with 0.03 hardening ratio. The dimensions of all element sections are available in Table I. To access more details about 3–story SAC frame, refer to FEMA-355c [32]. It should be noted that modal analysis of 3-story SAC model resulted in 3 different modes. In this study, the first mode considered as the dominant mode was which plays the most effective role in anticipating structural response. Therefore, only the first mode was regarded.

TABLE I. DETAILS OF ELEMENT SECTIONS

Story/Floor	Exterior Columns	Exterior Columns	Doubler Plates (m)	Girder
1/2	W 14 x 159	W 14 x 176	0, 0.00635	W 24 x 76
2/3	W 14 x 159	W 14 x 176	0, 0.0022	W 24 x 84
3/ Roof	W 14 x 159	W 14 x 176	0,0	W 18 x 40

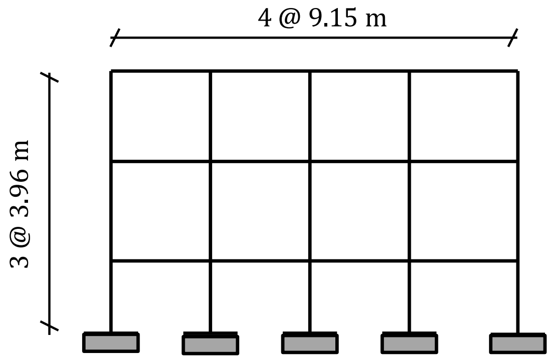

Figure 9. Configuration of two dimensional 3story (SE) frame.

B. Capacity Curve Method for SAC(SE)

As previously mentioned, the MPA method is initially utilized to create the equivalent SDOF systems. Properties of modal inelastic SDOF systems related to MPA procedure are summarized in Table II. Fig. 10 presents the pushover curve for the model which is modeled by a three-linear curve. Thereafter, by considering the MPA equations, the backbone curve of SDOF system is calculated. Moreover, for this equivalent system, the capacity curves are drawn for the earthquake records from Table III in the Appendix. For instance, the accordance of both, conventional method (scaling the records) and the capacity curve method are illustrated in Fig. 11.

C. Ground Motions

To verify this method, 20 ground motion acceleration records (far/near field) are considered. The characteristics of these earthquakes are presented in Table III in the Appendix.

TABLE II. MODAL PROPERTIES OF INELASTIC SDOF SYSTEMS IN MPA

Mode	M_n^* (kg)	Γ_n	F_{sny}/Ln (kg)	D_{ny} (kg)	ξ(%)
1	1266320	1.27	2.6374	0.0133	5%

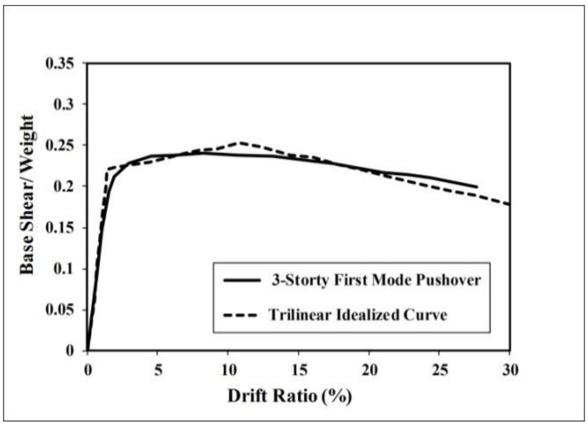

Figure 10. Pushover and trilinear idealization curve for 3-story SAC (SE).

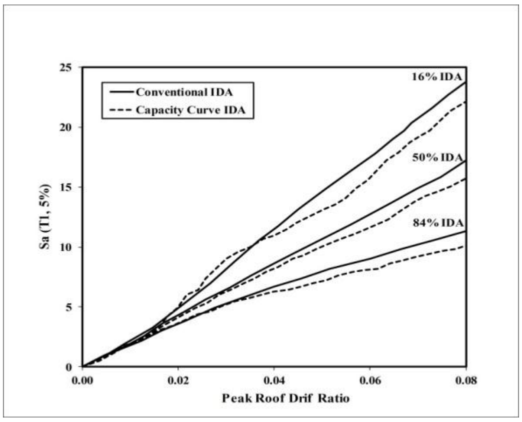

Figure 11. The accordance of both methods for SAC (SE) model with Fy=345 MPa

IV. THE COMPARISON OF CONVENTIONAL IDA AND CAPACITY CURVE METHOD

A. The Advantages

The utmost benefit of capacity curve method is to obtain the IDA curves for different yielding strength. In other words, if the yielding strength of elements changes somehow the period of the structure remains constant, subsequently, the capacity curve method can calculate the IDA curve for new values of F_y without implementing time history analyses. For instance, in a case which the steel material is substituted from St 37 to St 52, or investigating the effects of frictional dampers, the yielding strength of elements became different, while, the period of the model remains constant. In this case, without implementing the Incremental Dynamic Analysis, the IDA curve can be anticipated by using initial capacity curve.

Fig. 12 confirms this stated claim. In this figure, the pushover curves are demonstrated for SAC model, by considering yielding strength of elements to be equal to 345MPa in one state and 245MPa in another one. As it can be seen, the pushover curve shifts down with constant overall shape. This points emphasizes the new backbone and also transforms down so that the AB and BC are parallel to A'B' and B'C'. Hence, the IDA curve can be achieved for a new state without calculating the new capacity curve. For this purpose, by considering the yielding strength of elements, the vertical component of the horizontal line is decreased and this line is shifted down. The new values of the spectral acceleration and the maximum drift are calculated from Fig. 5 by using the new F_y.

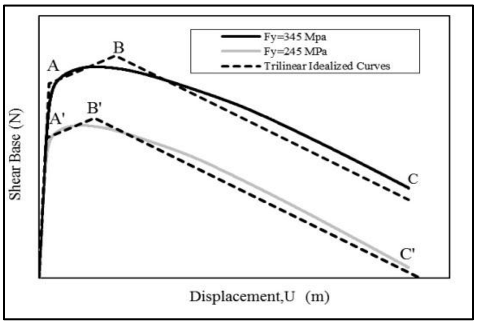

Figure 12. Pushover and tri-linear idealized curve for 3-story SAC (SE) with elements yielding strength 345 MPa and 245 MPa.

This claim is accentuated in Fig. 13 where the summarized IDA curves are calculated from the new F_y. As indicated in this figure, the IDA curves extracted from the proposed method are acceptable compared with conventional IDA curves. The proposed method, however, needs less computational efforts.

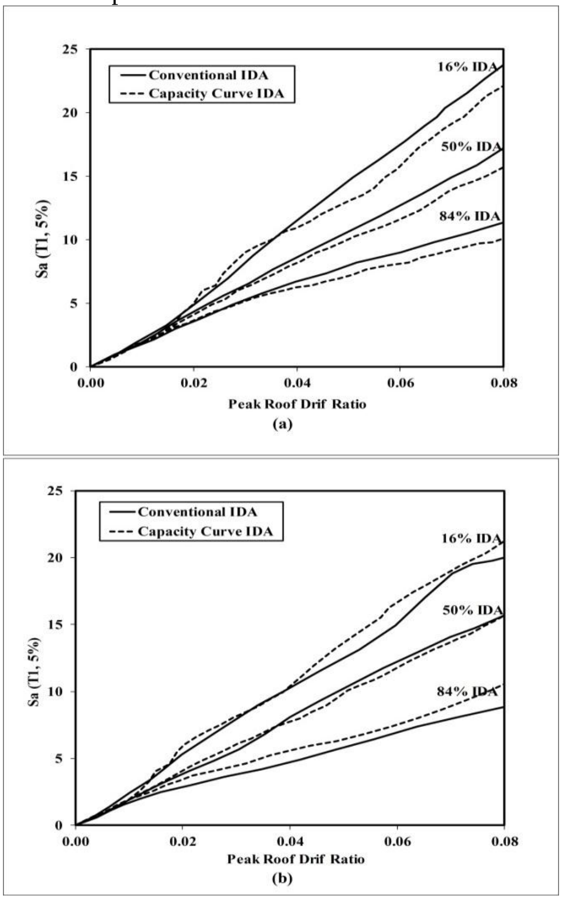

Figure 13. Comparison of the capacity curve and conventional IDA method for Fy=245 MPa: a) the equivalent SDOF system b) SAC(SE).

B. The Limitations

The capacity curve method is an approximate approach which is accompanied with several uncertainties. By considering Fig. 3, it can be perceived that if the F_y/F_e ratio is decreased nearby zero, the maximum displacement reaches the infinitive. Therefore, for small numerical values of the ratio (very weak structure), the curve will be parallel to the horizontal axis and; consequently, the value of N (OC/OB ratio) will be constant. Nevertheless, for very large value of displacements, the IDA curves are achieved by the capacity curve method which becomes linear. On the other hand, usage of the MPA inserts an error in order to estimate the modal SDOF systems.

V. Conclusion

In this article, an alternative approach, the Capacity Curve method, was introduced to drive IDA curves which play an effective role in accessing the performance based earthquake engineering objectives. Based on this suggested method, the IDA curves can be estimated by using capacity curve diagrams in which the strength is plotted against the maximum nonlinear displacement of the structure. This method can be applied for both the SDOF and MDOF systems with different structural behavior. It should be stated that for the MDOF systems, the Modal Pushover Analysis (MPA) was implemented to stimulate structural response of the model to an equivalent SDOF model. Then, the capacity curve method is applied for the substituted model and IDA curve is drawn.

The Capacity curve method was accompanied with the following advantages:

- Quicker access to IDA curves.
- Obtaining IDA curves for various yielding strength.
- Decreasing the computational effort.

As it was discussed in this article, the proposed method is not dependent on hardening ratio. It means that the theory is true for different behaviors such as hysteretic with various hardening ratios. In addition, it should be mentioned that the capacity curve method also works for different periods. In this regard, for short period models which equal energy rule governs, the suggested theory is accurate. Moreover, for long period models that follow the equal displacement rule, the capacity curve method is also true. The most important benefit of the suggested method is to extract the IDA curves for the model with the same period but different yielding strengths. In other words, if the yielding strength of elements changes, somehow the period of the structural model remains constant, IDA curve can be extracted from the same capacity curve. To verify the theory, a 3-story SAC SEATTLE frame under 20 different earthquake records was utilized. The results revealed reasonable coincidence between the proposed and conventional incremental dynamic analysis.

Appendix

TABLE III. The Characteristics of Studied Earthquake Records

No	Record Name	Station	Time	PGA (g)	Distance (km)	Magnitude	Soil (USGS)	Bracket Duration (s)
1	CAPE MENDOCINO	EUREKA - MYRTLE & WEST	25/04/1992	0.154	44.6	7.1	B	38.5
2	CAPE MENDOCINO	FORTUNA - FORTUNA BLVD	25/04/1992	0.116	23.6	7.1	B	40.38
3	CAPE MENDOCINO	RIO DELL OVERPASS FF	25/04/1992	0.385	18.5	7.1	B	31.34
4	CAPE MENDOCINO	PETROLIA	25/04/1992	0.662	9.5	7.1	C	35.98
5	IMPERIAL VALLEY	SUPERSTITION MTN CAMERA	15/10/1979	0.195	26	6.5	B	20.99
6	LOMA PRIETA	APEEL9 CRYSTAL SPR RES	18/10/1989	0.113	46.5	6.9	B	33.88

7	LOMA PRIETA	COYOTE LAKE DAM DOWNST	18/10/1989	0.179	22.3	6.9	B	28.25
8	LOMA PRIETA	GILORY - GAVILAN COLL	18/10/1989	0.357	11.6	6.9	B	39.95
9	NORTHRIDGE	CASTAIC OLD RIDGE RT	17/01/1994	0.568	23.6	6.7	B	23.01
10	NANAHI	SITE2	23/12/1985	0.323	8	6.8	B	19.94
11	MORGANHILL	COYOTE LAKE DAM DOWNST	24/04/1984	1.298	0.1	6.2	B	29.95
12	MORGANHILL	COYOTE LAKE DAM DOWNST	24/04/1984	0.711	0.1	6.2	B	29.95
13	KOBE	KAKOGAWA	16/01/1995	0.345	26.4	6.9	D	24.8
14	COYOTE LAKE	GILLORY ARRAY #4	06/08/1979	0.387	4.5	5.7	C	27.09
15	COYOTE LAKE	GILLORY ARRAY #6	06/08/1979	0.316	3.1	5.7	B	27.09
16	COALINGA	OIL CITY	22/07/1983	0.866	8.2	5.8	B	21.23
17	COALINGA	TREANSMITTER HILL	22/07/1983	0.84	9.2	5.8	B	32.04
18	SAN SALVADOR	GEOTECH INVESTING CENTER	10/10/1986	0.88	6.3	5.8	B	9.02
19	TRINIDAD	RIO DELL OVERPASS, E GROUND	08/11/1980	0.163	78.22	7.2	B	21.76
20	SAN FERNANDO	LAKE HUGHES #4	09/02/1971	0.324	24.2	6.6	B	26.07

Conflict of Interest

The authors do not have any conflict of interest.

Author Contributions

First Author's responsibilities for the paper were conceptualization the idea, leading the research and finalizing the paper for submission. Second author did the analysis and prepared the first draft of this paper. Third author assisted the second author with the analysis.

Acknowledgment

The authors would like to gratify the editor and all the reviewers for their constructive comments and valuable suggestions to improve the quality of the article.

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