

INTERACTIVE INTERFACE FOR INCREMENTAL DYNAMIC ANALYSIS PROCEDURE (IIIDAP) USING DETERIORATING SINGLE DEGREE OF FREEDOM SYSTEMS

Version 1.1.5



THEORY AND EXAMPLE APPLICATIONS MANUAL

By

Dimitrios G. Lignos, Ph.D.

March, 2010

TABLE OF CONTENTS

1. Introduction.....	4
2. Component Deterioration Models.....	4
2.1 Backbone Curve.....	5
2.2 Rules defining basic hysteretic characteristics	6
2.3 Rules for quantifying modes of deterioration	6
3 Ground Motion Sets.....	9
4 Incremental Dynamic Analysis Procedure.....	10
5 Fragility Curves	11
6 Description of Main Functions of IIIDAP Software.....	12
7 Example Using the IIIDAP Software	19
7.1 Median Collapse Spectrum.....	29
8 Example Using the SDOF Dynamic Analysis Menu.....	31
9 User Defined Ground Motions.....	34
10 References	36

LIST OF FIGURES

Figure 1. Basic options of stable hysteresis characteristics (Medina and Krawinkler, 2003)	4
Figure 2. Modified Ibarra-Medina Krawinkler deterioration model. Backbone curve and basic modes of cyclic deterioration (Lignos and Krawinkler, 2009, 2011)	5
Figure 3. Individual deterioration modes of the IMK model, illustrated on a peak-oriented model (Ibarra and Krawinkler, 2005)	7
Figure 4. Examples of calibrated moment rotation diagrams for steel and reinforced concrete components using the modified IMK model (Lignos et al. 2009)	8
Figure 5. Examples of calibrated load deformation and moment rotation diagrams for infill wall structures and high performance fiber reinforced concrete (HPFRC) panels using the modified IMK model	9
Figure 6. Incremental dynamic analysis curves for an SDOF wall structure	11
Figure 7. Example of collapse fragility curve for SDOF infill wall structure	12
Figure 8. Main groups of input fields of IIIDAP software	13
Figure 9. Menu to specify how to include P-Delta effects	15
Figure 10. Backbone curves for hysteretic models with and without P-Delta (Ibarra and Krawinkler, 2005)	16
Figure 11. Infill wall SDOF structure	19
Figure 12. Selection of hysteretic model	20
Figure 13. Additional input menu for pinching model	21
Figure 14. Unit convention specification menu	21
Figure 15. Specification of SDOF input parameters, backbone curve, cyclic deterioration and number of ground motions	22
Figure 16. Ground motion selection menu	23
Figure 17. LMSR-N Ground motion list menu	23
Figure 18. Menu for step size of incremental dynamic analysis	24
Figure 19. Menu for step size of incremental dynamic analysis	25
Figure 20. IDA curves for the full set of LMSR-N ground motions	25
Figure 21. Cumulative distribution functions given a hazard level and collapse fragility curve for SDOF infill panel system with $T_l = 0.30\text{sec}$	26
Figure 22. Inputting scaling period after selecting the FEMA P695 scaling process	27
Figure 23. IDA curves for the set of 44 far field ground motions using FEMA P695 scaling procedure	28
Figure 24. Cumulative distribution functions given a hazard level for SDOF infill panel system with $T_l = 0.30\text{sec}$ using FEMA P695	29
Figure 25. Cumulative distribution functions given a hazard level and collapse fragility curve for SDOF infill panel system with $T_l = 0.30\text{sec}$ using FEMA P695	29
Figure 26. Process to develop median collapse spectrum for SDOF system using LMSR-N set of ground motions	30
Figure 27. Example of median collapse spectrum for SDOF wall panel system using LMSR-N ground motion set	31
Figure 28. Summary table for SDOF with $T_1=0.03\text{sec}$	32
Figure 29. Relative displacement history for SDOF with $T_1=0.03\text{sec}$ for ground motion LP89agw	33
Figure 30. Hysteretic behavior of the SDOF with $T_1=0.03\text{sec}$ for ground motion LP89agw (SF=3.33)	34

INTERACTIVE INTERFACE FOR INCREMENTAL DYNAMIC ANALYSIS PROCEDURE (IIIDAP)

1. Introduction

The Interactive Interface for Incremental Dynamic Analysis Procedure (IIIDAP) is a generic single degree of freedom (SDOF) analysis software for seismic evaluation of deteriorating and non-deteriorating SDOF systems. The software uses advanced deteriorating hysteretic models that can adequately capture all the important deterioration modes of a component or system. The software is able to simulate dynamic collapse of SDOF systems subjected to seismic loading. This manual describes the background and basic functions of IIIDAP Version 1.1.5.

2. Component Deterioration Models

The component deterioration models that are available in IIIDAP software are based on a modified version of the Ibarra-Medina-Krawinkler model (Ibarra et al. 2005). All the modifications are described in Lignos and Krawinkler (2009, 2011). Three different hysteretic responses illustrated in Figure 1 (Bilinear, peak – oriented and pinching hysteretic response) are available. All hysteretic models include up to four deterioration modes (see Ibarra et al. 2005 and Lignos and Krawinkler, 2011).

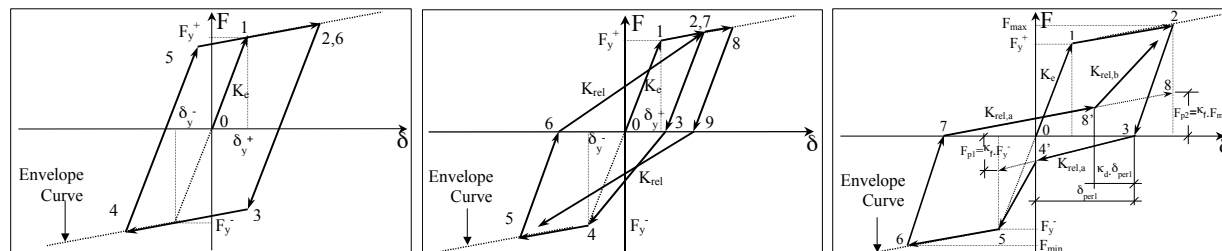


Figure 1. Basic options of stable hysteresis characteristics (Medina and Krawinkler, 2003)

2.1 Backbone Curve

The modified Ibarra–Medina-Krawinkler (IMK) deterioration model is defined by a backbone curve shown in Figure 2. The backbone curve defines the boundaries in which the hysteretic response of the component/structure is confined. The modified IMK model includes compromises that need to be made in order to describe the hysteretic response of a component or a single degree of freedom system. The primary compromise is that the analytical model does not account for cyclic hardening, i.e. the effect of cyclic hardening at early cycles of loading history should be averaged. For reinforced concrete (RC) components the effect of cyclic hardening is typically not significant compared to steel components. This is based on observations from recently developed RC and steel beam databases (Lignos and Krawinkler, 2009, 2011).

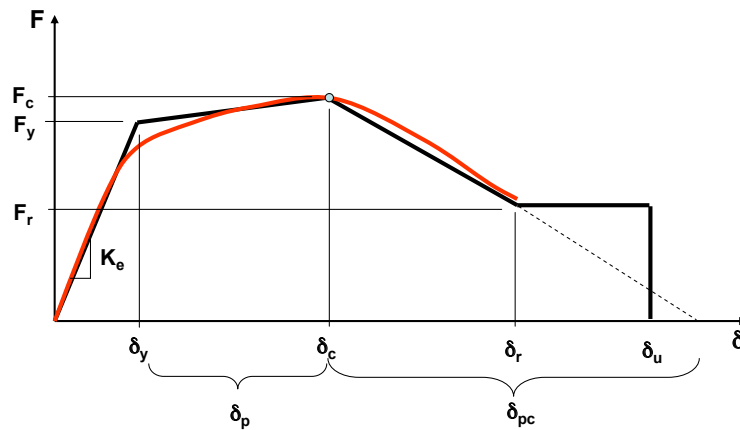


Figure 2. Modified Ibarra-Medina Krawinkler deterioration model. Backbone curve and basic modes of cyclic deterioration (Lignos and Krawinkler, 2009, 2011)

The quantities F and δ are generic force and deformation quantities. For plastic hinge regions $F = M$ and $\delta = \theta$. For SDOF configurations such as wall structures F is the story shear force and the deformation quantity δ is the story drift ratio δ/h , denoted θ from here on. The properties of the backbone curve may be different in the positive and negative loading direction. Residual strength $F_r = \kappa \cdot F_y$ may or may not be present. The ultimate deformation capacity δ_u is usually associated with a sudden failure mode or with behavior that can no longer be relied upon. The parameters needed to define the backbone curve comprehensively are shown in Figure 2. These are the effective yield strength and deformation (F_y and δ_y), the effective stiffness $K_e = F_y/\delta_y$, the capping strength and associated deformation for monotonic loading (F_c and δ_c), the

plastic deformation capacity for monotonic loading δ_p , the post-capping deformation capacity δ_{pc} , the residual strength $F_r = \kappa \cdot F_y$ and the ultimate deformation capacity δ_u .

2.2 Rules defining basic hysteretic characteristics

The modified IMK deterioration model can be employed together with any of the basic linearized hysteretic models used widely in the literature (i.e. bilinear model, peak-oriented model and pinching model). These models are shown in Figure 1.

2.3 Rules for quantifying modes of deterioration

The cyclic deterioration rates are controlled by a rule developed by Rahnama and Krawinkler (1993). This rule is based on the hysteretic energy dissipated when the component is subjected to cyclic loading. The main assumption of this rule is that regardless of the loading history that a component is subjected to, this component possesses an inherent reference hysteretic energy dissipation capacity, E_t . Lignos and Krawinkler (2009, 2011) modified the same rule in order to incorporate asymmetric rates of cyclic deterioration to the analytical model. The cyclic deterioration in excursion i is defined by the parameter β_i , which is given by the following expression,

$$\beta_{s,c,a,k,i}^{+/-} = \left(\frac{E_i}{E_t - \sum_{j=1}^{i-1} E_j} \right)^c \cdot D^{+/-} \quad (1)$$

Where $\beta_{s,c,a,k,i}^{+/-}$ = parameter defining the deterioration in excursion i , strength $\beta_{s,i}^{+/-}$, post-capping strength $\beta_{c,i}^{+/-}$, accelerated reloading stiffness deterioration $\beta_{a,i}^{+/-}$ and unloading stiffness deterioration $\beta_{k,i}^{+/-}$, E_i =hysteretic energy dissipated in excursion i and $D^{+/-}$ = parameter defining the decrease in rate of cyclic deterioration in the positive or negative loading direction (e.g. in the case of a composite beam the slab decelerates the deterioration in the positive direction). The parameter D can only be $0 < D^{+/-} \leq 1$. When the rate of cyclic deterioration is the same in both

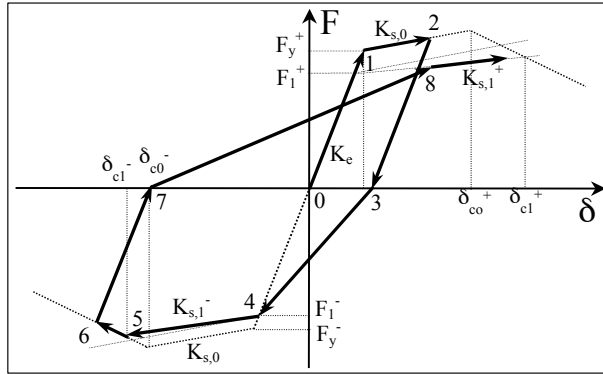
loading directions then $D^{+/-} = 1$ and the cyclic deterioration rule is essentially the same as the one included in the original IMK model (Ibarra et al. 2005). The deteriorated yield strength $F_i^{+/-}$, deteriorated post-capping strength $F_{ref,i}^{+/-}$, deteriorated accelerated reloading stiffness deterioration strength $F_{a,i}^{+/-}$ and unloading stiffness $K_{u,i}$ per excursion i are given by the set of the following equations,

$$F_i^+ = (1 - \beta_{s,i}^{+/-}) F_{i-1}^{+/-} \quad (2)$$

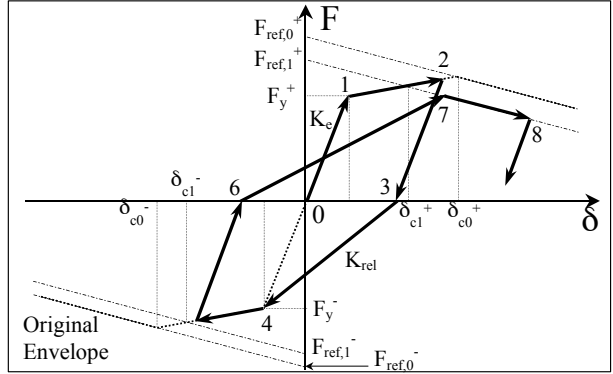
$$F_{ref,i}^{+/-} = (1 - \beta_{c,i}^{+/-}) \cdot F_{ref,i-1}^{+/-} \quad (3)$$

$$F_{a,i}^{+/-} = (1 + \beta_{a,i}^{+/-}) \cdot F_{a,i-1}^{+/-} \quad (4)$$

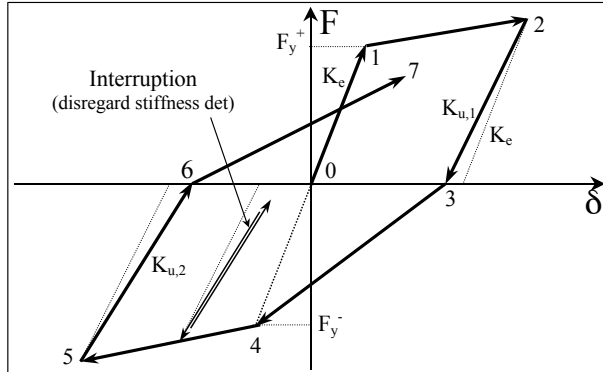
$$K_{u,i}^{+/-} = (1 - \beta_{k,i}^{+/-}) K_{u,i-1}^{+/-} \quad (5)$$



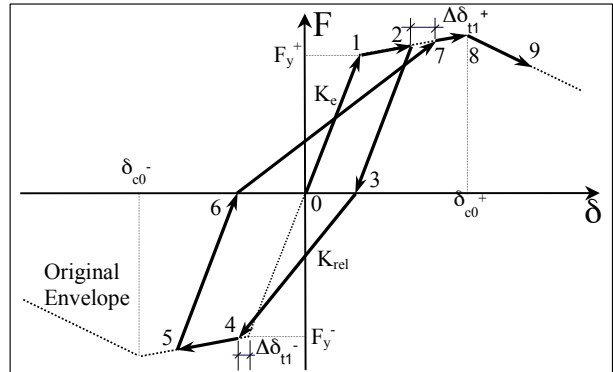
(a) Basic strength deterioration



(b) Post-capping strength deterioration



(c) Unloading stiffness deterioration



(d) Accelerated reloading stiffness deterioration

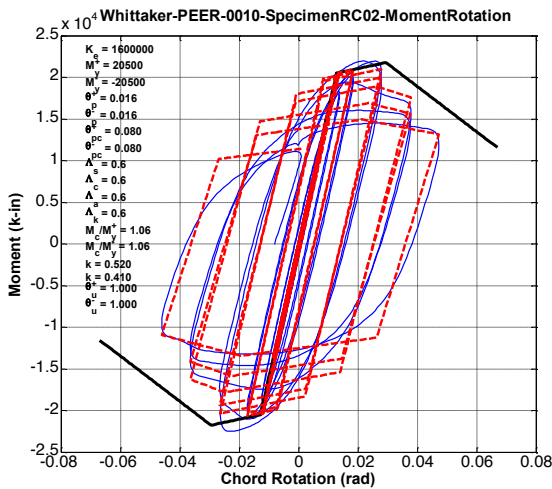
Figure 3. Individual deterioration modes of the IMK model, illustrated on a peak-oriented model (Ibarra and Krawinkler, 2005)

The reference hysteretic energy dissipation capacity of the component or SDOF system is expressed as a multiple of $F_y \cdot \delta_p$,

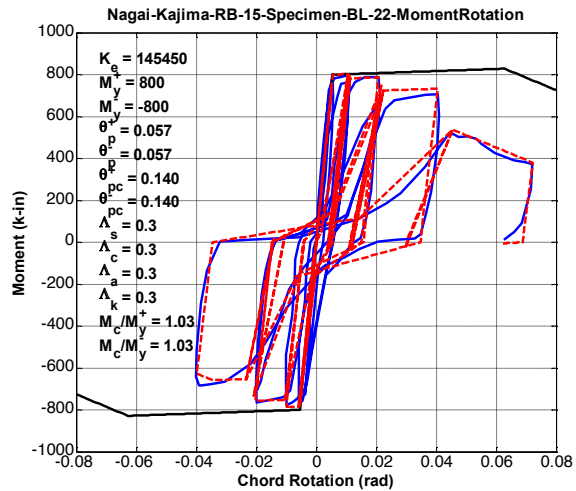
$$E_t = \lambda \cdot \delta_p \cdot F_y \text{ or } E_t = \Lambda \cdot F_y \quad (6)$$

where $\Lambda = \lambda \cdot \delta_p$ is the reference cumulative deformation capacity, and δ_p , and F_y are the plastic deformation capacity and effective yield strength of the component, respectively. Few applications of these rules for the four modes of deterioration is illustrated in Figure 3 using the peak-oriented deterioration model. The parameter λ or Λ is obtained after calibration of the hysteretic response of the deterioration model as described in the next paragraph.

The modified IMK model has been used extensively to calibrate more than 600 tests of steel and reinforced concrete (RC) components (see Figure 4) that have been collected as part of two databases for deterioration modeling of structural components (Lignos and Krawinkler (2007, 2009, 2011)). The same analytical model has been used for calibration of SDOF systems such as walls and panels as shown in Figure 5. The calibration process is presented in detail in Lignos and Krawinkler (2009, 2011).

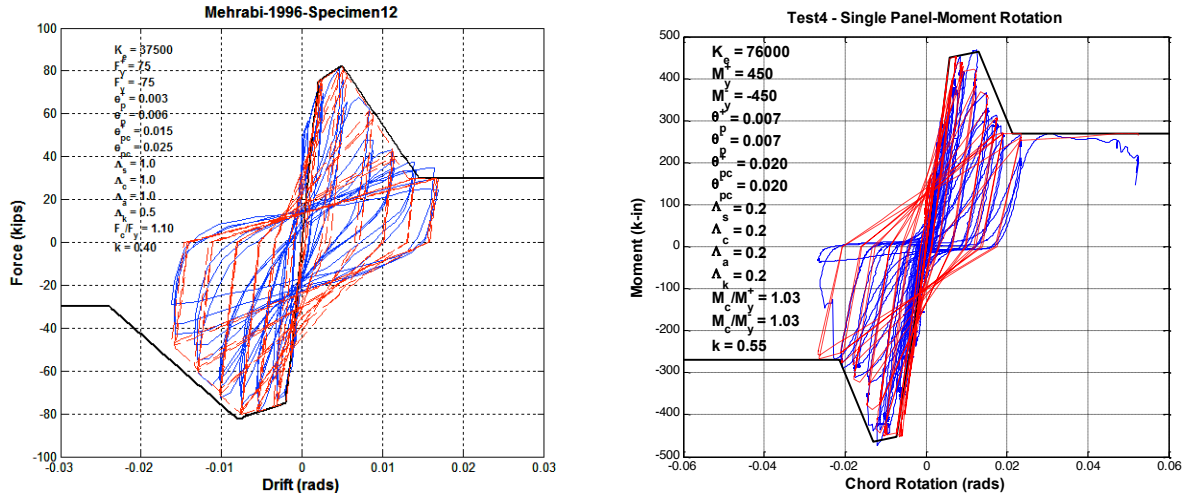


(a) steel component (Tajim et al. 2000)



(b) reinforced concrete component

Figure 4. Examples of calibrated moment rotation diagrams for steel and reinforced concrete components using the modified IMK model (Lignos et al. 2009)



(a) Wall structure (see Mehrabi et al. 1996)

(b) Infill panel system made of HPFRC

(see Lignos et al. 2009)

Figure 5. Examples of calibrated load deformation and moment rotation diagrams for infill wall structures and high performance fiber reinforced concrete (HPFRC) panels using the modified IMK model

3 Ground Motion Sets

The Interactive Interface for Incremental Dynamic Analysis procedure has a library of ground motion sets available for seismic performance evaluation of SDOF systems. The two existing ground motion sets are described as follows,

- A set of 40 ground motions noted as LMSR-N with certain magnitude $6.5 \leq M_w \leq 7.5$ and rapture distance $13.0 \text{ km} \leq R$. Detailed information of this ground motion set is presented in Medina and Krawinkler (2003).
- A set of 44 ground motions noted as FEMA P695 set that represents far field ground motions normalized using the FEMA P695 appendix A methodology. All ground motions have been scaled to represent a scale factor of 1.0. Detailed information about the ground motion records can be found in FEMA P695 and Haselton and Deierlein, (2007).
- A user-defined set of ground motions can also be selected (see Section 9).

4 Incremental Dynamic Analysis Procedure

Incremental dynamic analysis (IDA) is a parametric analysis method that is utilized to estimate the seismic performance of structural systems. The procedure involves subjecting the structural model to a set of ground motions, each scaled to multiple levels of ground motion intensity in order to produce response curves (IDA curves) parameterized versus intensity level (see Vamvatsikos and Cornell, 2002). The IDA curve relates a selected intensity measure (IM) of the selected ground motion set with an engineering demand parameter (EDP) of the structural system such as relative displacement, story drift ratio or absolute acceleration. The IDA also known as “dynamic pushover” involves a series of dynamic non-linear response history analysis performed under scaled acceleration histories whose IMs are ideally selected to cover the whole range from elastic to nonlinear and finally dynamic collapse of a building.

In an IDA the intensity of the ground motion is incremented and applied to the structural model up to the point at which dynamic lateral instability occurs. There are various ways to scale a ground motion. A “traditional” IM that may be used is the spectral acceleration at the fundamental period of the building $S_a(T_1, \xi\%)$. IDAs are performed for a number of representative ground motions that are likely to occur at the location of the building. Figure 6 illustrates a set of 40 IDA curves (i.e. 40 ground motion records) for an SDOF wall structure with a period of 0.30sec. When each curve becomes flat the structural system loses its lateral resistance, i.e. collapse occurs. This IM has the advantage that seismic hazard data for S_a is readily available; however, there are drawbacks to the use of a single scalar IM, and alternatives are investigated (Cordova et al. 2000; Luco, 2002; FEMA P695). The main disadvantages for the selected IM are (1) that is based on the elastic behaviour of the structural system and (2) for a selected S_a higher mode effects are not considered. The frequency content of the ground motion cannot be considered explicitly. The large dispersion in spectral accelerations due to the different frequency content of the selected ground motions is illustrated in Figure 6, in which the records of set LSMR-N are scaled to have the same spectral acceleration at $T = 0.30s$. Ibarra and Krawinkler (2005) showed that the dispersion increases with period, and response predictions may exhibit significant scatter depending on the extent of inelasticity, which leads to period elongation.

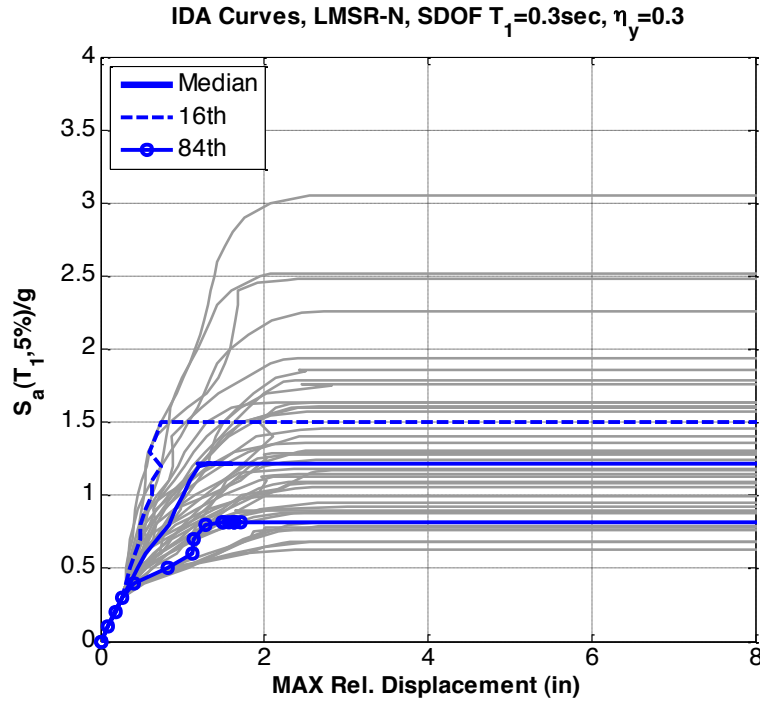


Figure 6. Incremental dynamic analysis curves for an SDOF wall structure

5 Fragility Curves

In performing a seismic risk analysis of a structural system, seismic vulnerability of structural systems associated with various damage states should be identified. A widely practiced approach to express seismic vulnerability at various damage states is in the form of fragility curves. Typically the development of fragility curves will require synergistic use of the following methods: (1) Professional judgment; (2) quasi-static and design code consistent analysis; (3) utilization of damage data associated with past earthquakes; and (4) numerical simulation of the seismic response of structures based on dynamic analysis (Shinozuka et al. 2000). Analytical fragility curves are typically developed based on the assumption that the random sample is lognormally distributed. This assumption can be confirmed by conducting a standard Kolmogorov – Smirnov (K-S) test (Benjamin and Cornell, 1970).

Collapse safety can be evaluated by using fragility curves that describe probability of failure as function of (S_a/g) . Since the collapse capacity of a structural system is a function of the ground motion frequency content, the hysteretic characteristics of the system and gravity load effects (Ibarra et al. 2002) it is typical to use as an IM parameter the $[(S_a/g)/n_y]$, in which n_y is the base

shear coefficient defined as the yield base shear V_y over the total seismic weight W of the structural system. The advantage of using the parameter $(S_a/g) / \eta$ to express the capacity of the system is that the probability of failure is neither a function of the ground motion intensity nor the strength of the system, η .

Figure 7 illustrates the empirical and analytical collapse fragility curve for an infill wall structural system with predominant period of 0.30sec. The median collapse capacity of the system is 1.18g (corresponds to 50% probability of collapse) and the standard deviation is $\beta_c = 0.41$. The dispersion β_c expresses the record-to-record variability (R-T-R) to collapse and a typical value based on numerous studies (Ibarra et al. 2002; Ibarra and Krawinkler, 2005; Zareian, 2006; FEMA P695; Lignos and Krawinkler, 2009; Zareian et al. 2010) is 0.40.

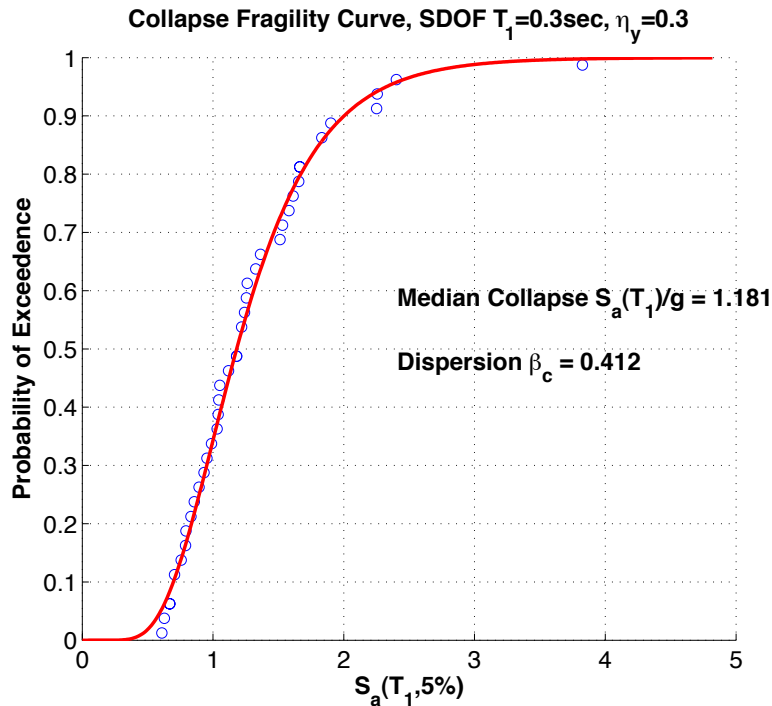


Figure 7. Example of collapse fragility curve for SDOF infill wall structure

6 Description of Main Functions of IIDAP Software

The Interactive Interface for Incremental Dynamic Analysis Procedure consists of seven main function groups. A user should specify a number of parameters in these groups in order to conduct incremental dynamic analysis for an SDOF system. Figure 8 illustrates the main groups

of input fields that need to be specified in order to conduct an incremental dynamic analysis with IIIDAP.

Interactive Interface for Incremental Dynamic Analysis Procedure Version 1.1.5

File Options Ground Motion List SDOF Dynamic Analysis Collapse Spectra Help

Definition of Single Degree of Freedom System

Group 1: T, m, ξ ; T, K, ξ ; m, K, ξ

Backbone Curve Parameters

Group 2: Base Shear Coefficient $n=F_y/W$; Strain Hardening a_s ; Normalized dp/dy ; Normalized dpc/dy ; Residual Strength Ratio k ; Normalized du/dy

Loading Direction: Positive Negative

Group 3: λ $D+$ $D-$

Group 4: Strength Degradation λ s ; Post Cap. Strength Degradation λ c ; Accelerated Stiffness Degradation λ a ; Unloading Stiffness Degradation λ k

Cyclic Deterioration Parameters

P-Delta Effects

☐ Include P-Delta

Control Buttons

Group 5: Scaling Process of Gr. Motion: ☐ Scale at $S_a(T, 5\%)$; ☐ FEMA P695

Group 6: Run IDA ; Plot IDA Curves ; Reset ; Collapse Fr. Curves ; STOP ; P [EDP/IMNC]

Developed by Dimitrios G. Lignos and Professor Helmut Krawinkler, Stanford University CA, October 2009

Figure 8. Main groups of input fields of IIIDAP software

Group 1 “Definition of Single Degree of Freedom System”: Specifies the single degree of freedom system characteristics. The user has three different options to specify the SDOF system by inputting any combination of the two quantities specifying an SDOF system, i.e. period T , seismic mass m and lateral stiffness K . In any of the three options the user needs to specify the damping ratio ξ (noted as ξ_i).

Group 2 “Backbone Curve Parameters”: This group of fields specifies the backbone curve of the modified IMK deterioration model described earlier in this manual. The software gives the option to provide different backbone characteristics in the two loading directions in case of asymmetric hysteretic response. The fields specified by the user are summarized as follows for positive and negative loading directions:

- Base shear coefficient $n_y = V_y/W$,
- strain hardening as ,
- normalized pre-capping deformation capacity δ_p/δ_y with respect to yield deformation δ_y of the SDOF system,
- normalized post capping deformation capacity δ_{pc}/δ_y with respect to yield deformation δ_y of the SDOF system,
- residual strength ratio $\kappa = F_r/F_y$, in which F_r and F_y are the residual and yield strength of the SDOF system and
- normalized ultimate deformation capacity δ_u/δ_y with respect to the yield deformation δ_y of the SDOF system. The program assumes by default that the δ_u/δ_y ratio is “infinite” (999).

Given the SDOF system characteristics from *Group 1* the user can determine δ_y . For an SDOF structure the period is given by,

$$T = 2 \cdot \pi \cdot \sqrt{\frac{m}{k}} \quad (6)$$

hence,

$$T = 2 \cdot \pi \cdot \sqrt{\frac{W/g}{F_y/\delta_y}} \quad (7)$$

hence,

$$\delta_y = \frac{F_y \cdot g}{W} \cdot \left(\frac{T}{2 \cdot \pi} \right)^2 \quad (8)$$

and,

$$\delta_y = n_y \cdot g \cdot \left(\frac{T}{2 \cdot \pi} \right)^2 \quad (9)$$

Group 3 “Cyclic Deterioration Parameters”: This group of fields specifies the cyclic deterioration parameters λ needed to simulate up to four deterioration modes of the modified IMK model. The program by default sets all the λ values equal to zero, i.e. no cyclic deterioration is assumed. From *Group 3* the user may specify the $D^{+/-}$ -rate of cyclic deterioration in case that a asymmetric hysteretic response is simulated. For symmetric hysteretic behavior the default values for $D^{+/-}$ are equal to 1.0.

Group 4 “P-Delta Effects”: This group specifies if P-Delta effects are included in the dynamic analysis. When P-Delta effects are considered in the analysis the user has two options in order to include P- Δ (see Figure 9) by either specifying the stability coefficient θ of the SDOF system, i.e. the height of the SDOF system is then uniquely defined, or by specifying the height of the SDOF system, i.e. the stability coefficient is then uniquely defined if P-Delta is considered in the analysis.

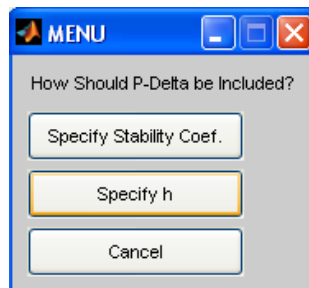


Figure 9. Menu to specify how to include P-Delta effects

If h is the total height of the SDOF system then the stability coefficient θ is defined based on the following expression,

$$\theta = \frac{W \cdot \delta}{h \cdot V} \quad (10)$$

Where $W=mg$ is the total weight of the SDOF system, δ is the displacement at which the base shear V is measured. The IIIDAP software by default assumes $\theta = 0.0$ (no P-Delta effects). Figure 10 shows the effect of P-Delta on the backbone curve of an SDOF system. This figure is based on Equation (10). Based on the same equation when $\theta \geq 1.0$ the SDOF system is statically unstable.

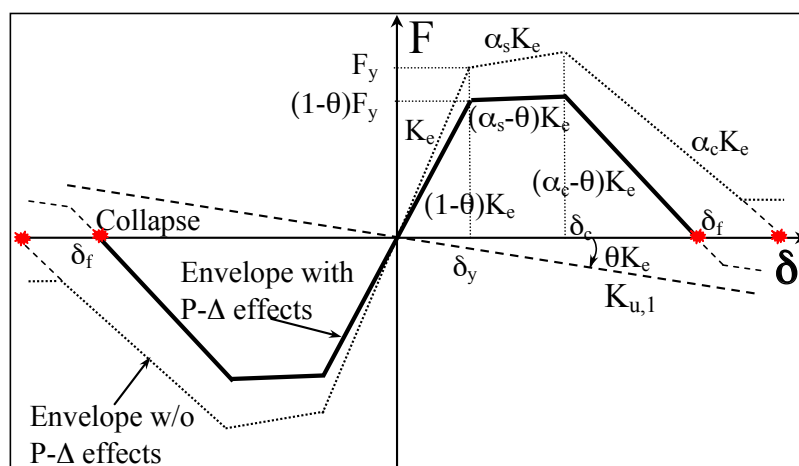


Figure 10. Backbone curves for hysteretic models with and without P-Delta (Ibarra and Krawinkler, 2005)

Group 5 “Scaling Process of Ground Motion”: This group of fields specifies the scaling process of the ground motion set that is used in order to conduct incremental dynamic analysis. Two scaling processes are currently implemented in IIIDAP Version 1.1.5. The first one is based on scaling at the same spectral acceleration of the first mode period of the SDOF system $S_a(T_1, 5\%)$ for the set of the selected ground motions used. The second scaling process is summarized in FEMA P695.

Group 6 “Control Buttons”: This group of IIIDAP software includes a set of 6 buttons:

- “RunIDA”: This button is used to execute an IDA analysis given all the input parameters that have been specified based on Groups 1 to 5. If there is a field that has not been specified by the user a “warning” message pops-up. Before the IDA analysis is executed IIIDAP software asks the user which directory should be used in order to store the analysis data. The default directory is “IDA-1”. Multiple directories should be used in case that a new analysis is conducted else the information is overwritten if the same folder is used.
- “Reset”: This button clears all the variables after/before each IDA run. It is recommended that this button be used to clear all the variables from previous analysis cases.
- “STOP”: This button is used to stop the analysis that is being conducted. The program will also be shut down and any information that is currently available will be lost.
- “Plot IDA Curves”: This button plots the IDA curves (see Figure 6 for illustration) for the analyzed cases. Three different plots are generated. In the vertical axis for all three plots the Intensity Measure (IM) is used ($S_a(T_i, 5\%)$ or Scale Factor in case that the FEMA P695 methodology is employed). In the horizontal axis three different sets of EDPs are used. These are the peak relative displacements, the peak story drift ratios (SDR) and the peak absolute accelerations of the SDOF system subjected to the selected ground motions. Note that this button can be used without having to execute a new IDA analysis using previously analyzed set of data.
- “Collapse Fr. Curves”: This button plots the collapse fragility curve of an SDOF system *for a complete set of 40 ground motions*. In case that there the SDOF system does not collapse when subjected to at least one ground motion of the predefined ground motion set then the collapse fragility curve of the SDOF system is not generated.
- “P[EDP|IM|NC]”: This button plots the cumulative distribution function given a specified hazard level(IM) from the user and given no collapse.

Group 7 “Menus”: This group contains six different menus of the IIIDAP software. These menus are summarized as follows:

- *File*: Contains a “Save SDOF information” option that stores in a txt file the information of the current analysis run in case that the user chooses this option. This menu also contains the “exit” option if the user would like to shut down the IIIDAP software.
- *Options*: Contains a “Hysteretic model” option with three different alternatives (bilinear, peak-oriented and pinching model) as shown in Figure 1. The “Options” menu also contains the “Units” option that allows to the user to choose between SI and English unit system.
- *Ground Motion List*: Contains the “LMSR-N set” and the “FEMA P695” ground motion sets. These two options represent two sets of ground motions described in detail in Medina and Krawinkler (2003) and FEMA P695, respectively. Any ground motion data set may be added as an external library to the “Ground Motion List” option.
- *SDOF Dynamic Analysis*: Contains the “run...” option in which a user can conduct nonlinear response history analysis of the specified SDOF system from the main interface using a single ground motion selected from the two sets of the available Ground Motion List.
- *Collapse Spectra*: This option provides the user the flexibility to conduct a parametric Incremental Dynamic Analysis through collapse of a SDOF system that its characteristics are specified from the main interface. The period of the SDOF system is varied over a certain range periods, which is specified from the “Period Variation” option. The Collapse Spectrum is generated after the user clicks on the “Execute...” option from the “Collapse Spectra” menu. The median collapse spectrum is plotted when the “Plot Collapse Spectrum” option is selected from the “Collapse Spectra” menu. It should be noted that IIIDAP will not conduct IDA for a combination of parameters that result to a statically unstable ($\theta \geq 1.0$) SDOF system. The software will inform the user that the last period that will be used is the one that leads to a system with $\theta < 1.0$.
- *Help*: Contains the “Manual” and “About...” that both include background information regarding the IIIDAP software.

7 Example Using the IIDAP Software

The capabilities of the IIDAP software for seismic performance evaluation of deteriorating SDOF systems are illustrated through a comprehensive step-by-step example that involves the seismic performance evaluation of an infill wall structure (see Figure 11). The structural system has a period $T_I = 0.30\text{sec}$ and is idealized as a single degree of freedom system with height $h = 120''$ with unit mass (m). The base shear coefficient of the system n_y is 0.30.

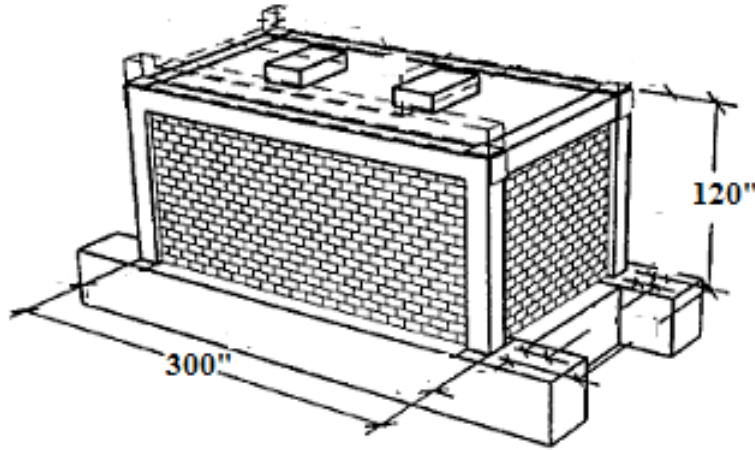


Figure 11. Infill wall SDOF structure

A typical hysteretic behavior of the system is similar to Figure 5a, i.e. the parameters used to specify the modified IMK model are summarized as follows:

- Strain hardening in both loading directions is assumed to be $\alpha_s = 5\%$
- Damping coefficient is assumed to be $\zeta = 5\%$
- Plastic deformation capacity is assumed to be $\theta_p = 0.01\text{rad}$
- Post capping deformation capacity is assumed to be $\theta_{pc} = 0.01\text{rad}$
- Residual strength factor $\kappa = 0.0$

- Ultimate deformation capacity $\theta_u = \infty$ (assume infinite, i.e. 999)
- Cyclic deterioration parameter $\lambda = 50$
- Set of ground motion records: LMSR-N set (see Section 4 of this manual)

The single degree of freedom system (SDOF) is initially defined by using the first option (T,m,xi) from *Group 1*. Regarding the hysteretic model, from the menu $\rightarrow$ Options we select the peak oriented model based on the experimental data (see Figure 12)

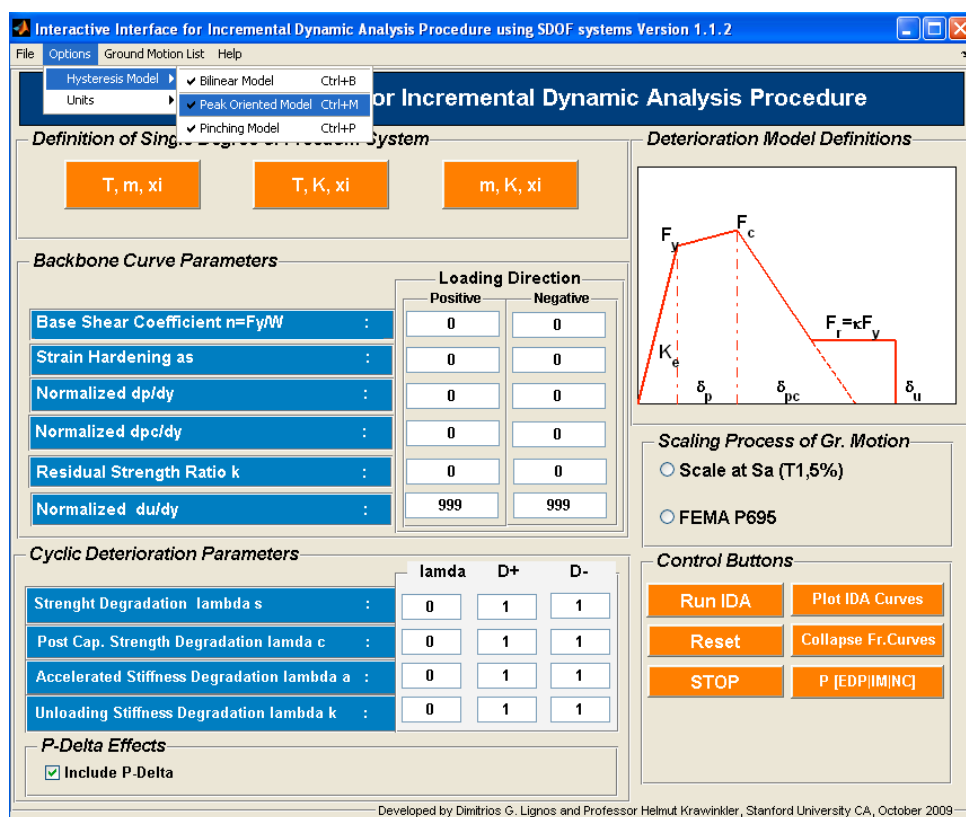


Figure 12. Selection of hysteretic model

In case that the pinching model is selected then the user should specify three additional parameters related to the pinching model for positive/negative loading direction and deviation point (see Figure 13). A default value of 0.5 is used for all three pinching parameters.

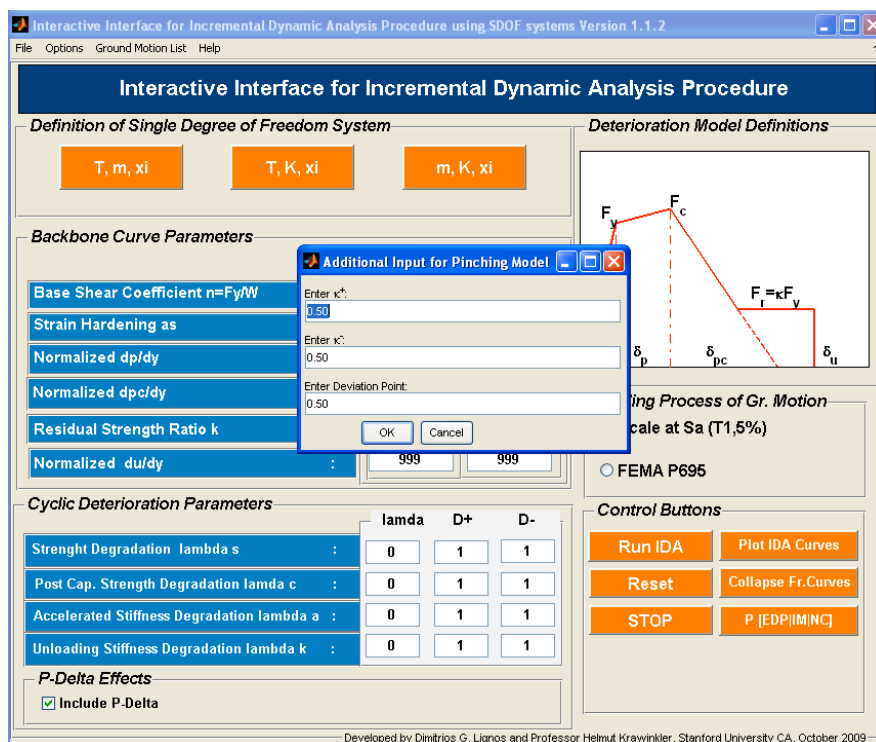


Figure 13. Additional input menu for pinching model

Unit Convention: Menu $\rightarrow$ Options $\rightarrow$ Units $\rightarrow$ Kips-in (see Figure 14).

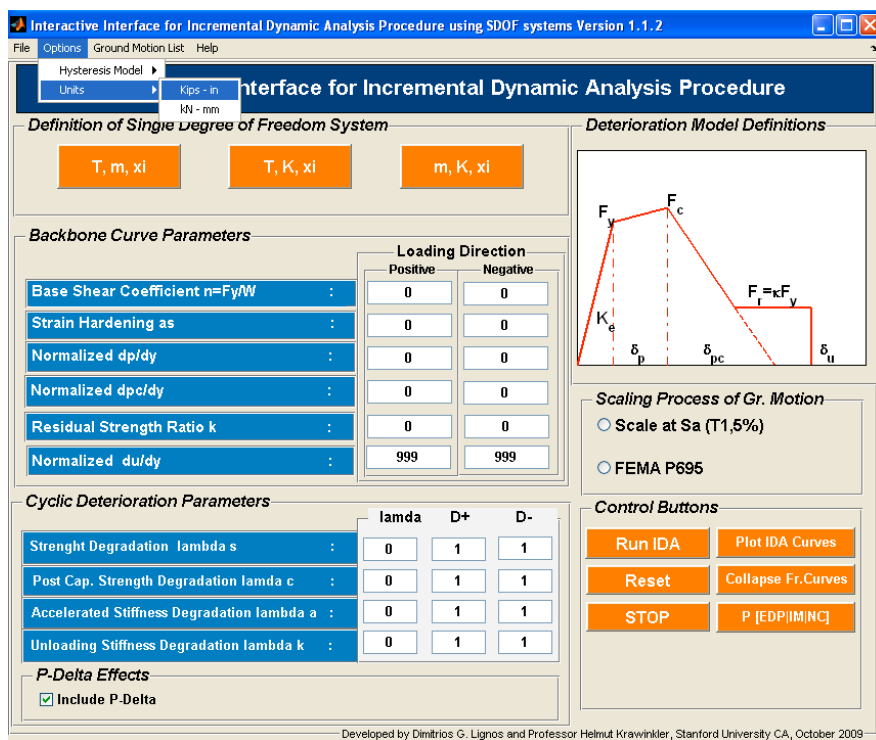


Figure 14. Unit convention specification menu

The backbone and cyclic deterioration parameters are inputted in Groups 2 and 3, respectively, as shown in Figure 15. Since we are concerned with symmetric hysteretic response $D^{+/-} = 1.0$. P-Delta effects are considered by specifying the height of the SDOF system ($h=120''$) and Equation (10).

Interactive Interface for Incremental Dynamic Analysis Procedure

File Options Ground Motion List Help

Definition of Single Degree of Freedom System

T, m, xi T, K, xi m, K, xi

Backbone Curve Parameters

	Positive	Negative
Base Shear Coefficient $n=F_y/W$	0.30	0.30
Strain Hardening as	0.05	0.05
Normalized dp/dy	5	5
Normalized dpc/dy	6	6
Residual Strength Ratio k	0	0
Normalized du/dy	999	999

Cyclic Deterioration Parameters

	lambda	D+	D-
Strenght Degradation λs	50	1	1
Post Cap. Strength Degradation λc	50	1	1
Accelerated Stiffness Degradation λa	50	1	1
Unloading Stiffness Degradation λk	50	1	1

P-Delta Effects

☒ Include P-Delta

Deterioration Model Definitions

Graph showing Force (F) vs. Displacement (δ) with points F_y , F_c , and F_k . The graph illustrates the backbone curve and the hysteretic response.

Scaling Process of Gr. Motion

☒ Scale at $S_a(T1,5\%)$

☐ FEMA P695

Control Buttons

Run IDA Plot IDA Curves

Reset Collapse Fr. Curves

STOP P [EDP|IM|NC]

Developed by Dimitrios G. Lignos and Professor Helmut Krawinkler, Stanford University CA, October 2009

Figure 15. Specification of SDOF input parameters, backbone curve, cyclic deterioration and number of ground motions

Ground Motion Selection: Click on Ground Motion List $\rightarrow$ LMSR-N (see Figure 16). The LMSR-N ground motion set (Medina and Krawinkler, 2003) is selected. Figure 17 shows the ground motion list of the 40 earthquake records. For this example we use all the records. By clicking the “Update Motions” button the user (a) updates the ground motion list to be used for analysis and (b) is able to see a comparison of the acceleration spectrum of all the selected motions from the ground motion list (see Figure 17). If the ground motion list is modified by the user the “Update Motions” button should be used again to update the ground motion selection for the next IDA analysis. In case that all motions should be used then the select all option should be ticked and the “Update Motions” button should be used.

Interactive Interface for Incremental Dynamic Analysis Procedure using SDOF systems Version 1.1.2

File Options Ground Motion List Help

LMSSR-N set
FEMA P695

Definition of Single Degree of Freedom System

T, m, xi T, K, xi m, K, xi

Backbone Curve Parameters

	Loading Direction	
	Positive	Negative
Base Shear Coefficient $n=F_y/W$	0.30	0.30
Strain Hardening as	0.05	0.05
Normalized dp/dy	5	5
Normalized dp/dy	6	6
Residual Strength Ratio k	0	0
Normalized du/dy	999	999

Cyclic Deterioration Parameters

	lambda	D+	D-
Strenght Degradation lambda s	50	1	1
Post Cap. Strength Degradation lambda c	50	1	1
Accelerated Stiffness Degradation lambda a	50	1	1
Unloading Stiffness Degradation lambda k	50	1	1

P-Delta Effects

☒ Include P-Delta

Deterioration Model Definitions

Scaling Process of Gr. Motion

☒ Scale at Sa (T1,5%)

☐ FEMA P695

Control Buttons

Run IDA Plot IDA Curves

Reset Collapse Fr.Curves

STOP P [EDP/IM/NC]

Developed by Dimitrios G. Lignos and Professor Helmut Krawinkler, Stanford University CA, October 2009

Figure 16. Ground motion selection menu

LMSRGroundMotion

Ground Motion List

☒ Select All Motions

Imperial Valley, 1979, Mw=6.5

- ☐ ID: IV79cal, R=23.8km Station: Calopatria Fire Station
- ☐ ID: IV79chi, R=26.7km Station: Chihuahua
- ☐ ID: IV79cmp, R=32.6km Station: Compuertas
- ☐ ID: IV79e01, R=15.5km Station: El Centro Array #1
- ☐ ID: IV79e12, R=18.2km Station: El Centro Array #12
- ☐ ID: IV79e13, R=21.9km Station: El Centro Array #13
- ☐ ID: IV79nil, R=35.9km Station: Niland Fire Station
- ☐ ID: IV79pls, R=31.7km Station: Plaster City
- ☐ ID: IV79wkp, R=23.6km Station: Cucapah
- ☐ ID: IV79wsm, R=15.1km Station: Westmorland Fire Station

Long Hills, 1989, Mw=6.9

- ☐ ID: LP89agw, R=28.2km Station: Agnews State Hospital
- ☐ ID: LP89cap, R=14.5km Station: Capitola
- ☐ ID: LP89g03, R=14.4km Station: Gilroy Array #3
- ☐ ID: LP89g04, R=16.1km Station: Gilroy Array #4
- ☐ ID: LP89gmr, R=24.2km Station: Gilroy Array #7
- ☐ ID: LP89hch, R=26.2km Station: Hollister City Hall
- ☐ ID: LP89hda, R=25.8km Station: Hollister Differential ...
- ☐ ID: LP89svr, R=31.6km Station: Halls Valley
- ☐ ID: LP89spw, R=32.6km Station: Salinas - John & Work
- ☐ ID: LP89slc, R=36.3km Station: Palo Alto - SLAC Lab.
- ☐ ID: LP89svl, R=29.8km Station: Sunnyvale - Colton ...

Northridge, 1994, Mw=6.7

- ☐ ID: NR94cen, R=30.9km Station: LA - Centinela St.
- ☐ ID: NR94cnp, R=15.8km Station: Canoga Park - Topanga Can.
- ☐ ID: NR94far, R=23.9km Station: LA - N Faring Rd.
- ☐ ID: NR94fle, R=29.5km Station: LA - Fletcher Dr.
- ☐ ID: NR94olo, R=25.4km Station: Glendale - Las Palmas
- ☐ ID: NR94hol, R=25.5km Station: LA - Hollywood Stor FF
- ☐ ID: NR94lh1, R=36.3km Station: Lake Hughes #1
- ☐ ID: NR94lh2, R=37.7km Station: Leona Valley #2
- ☐ ID: NR94lh6, R=30.5km Station: Leona Valley #6
- ☐ ID: NR94nya, R=22.3km Station: LA Crescenta - New York
- ☐ ID: NR94pic, R=32.7km Station: LA - Pico & Sentous
- ☐ ID: NR94etc, R=13.3km Station: Northridge - 17645 ...
- ☐ ID: NR94stn, R=30.0km Station: LA - Saturn St.
- ☐ ID: NR94ver, R=39.3km Station: LA - E Vernon Ave

San Fernando, 1971, Mw=6.6

- ☐ ID: SF71pel, R=21.2km Station: LA - Hollywood Sto...

Superstition Hills, 1987, Mw=6.7

- ☐ ID: SH87bra, R=18.2km Station: Brawley
- ☐ ID: SH87icc, R=13.2km Station: El Centro Imp. Co. ...
- ☐ ID: SH87pls, R=21.0km Station: Plaster City
- ☐ ID: SH87wsm, R=13.3km Station: Westmorland Fire Station

Absolute Acceleration Spectrum

Ground Motion Information

Update Motions

Figure 17. LMSR-N Ground motion list menu

Perform Incremental Dynamic Analysis: After inputting all the parameters to IIIDAP software the next step is to conduct IDAs for the selected set of ground motions. A scaling process of the ground motions should be selected. By clicking on “Scale at $S_a(T_l, 5\%)$ ” (see Figure 18) the program asks for the IDA step size in multiples of acceleration gravity g . the default setting is 0.10. A different step can be used depending on the case that is analyzed. The scaling step is selected depending on the simulated case (if low or high collapse capacity is expected).

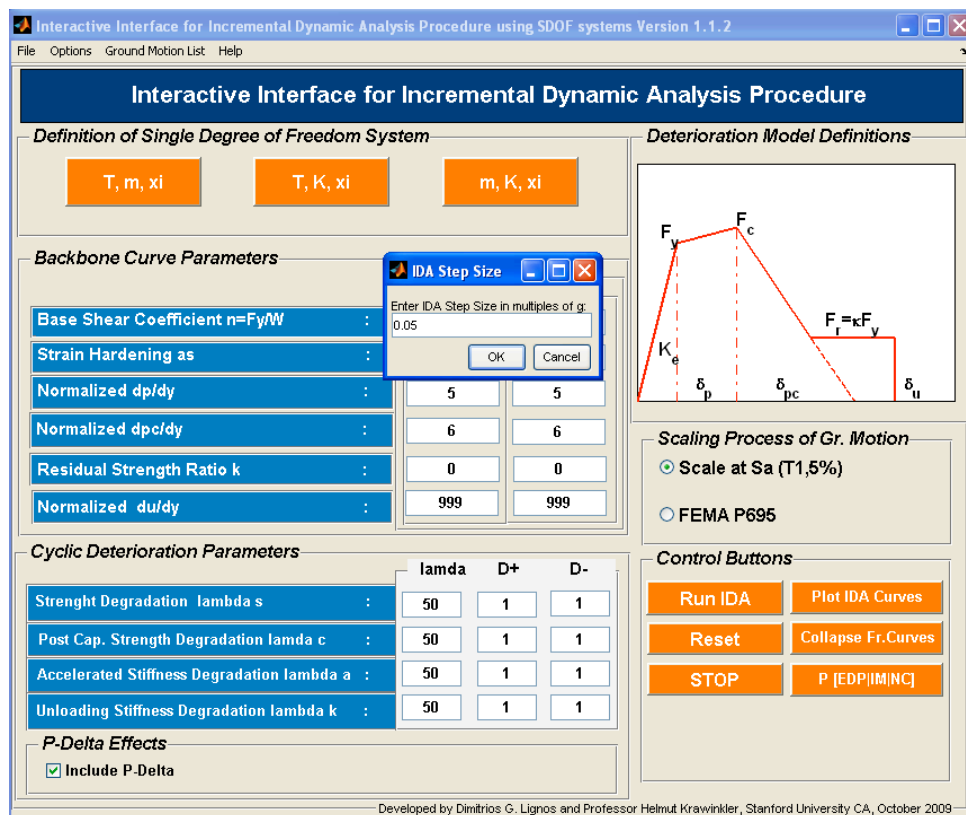


Figure 18. Menu for step size of incremental dynamic analysis

After clicking on the “Run IDA” button, the user needs to specify if an upper bound of spectral acceleration should be considered in order to stop the analysis for each ground motion as shown in Figure 19. This option is important in case that the user is analyzing a non-deteriorating SDOF system without P-Delta effects or a non-deteriorating SDOF system with a stability coefficient, which is smaller or equal than its strain hardening. In these two cases there is no collapse, i.e. the analysis would never stop if an upper bound of spectral acceleration is not considered. For the example described herein the “No” option is selected since the system degrades and the SDOF will sooner or later collapse for each one of the selected ground motions.

Interactive Interface for Incremental Dynamic Analysis Procedure

Definition of Single Degree of Freedom System

T, m, xi T, K, xi m, K, xi

Deterioration Model Definitions

Backbone Curve Parameters

Base Shear: Input Upper Bound of Spectral Acceleration

Strain Hardening: Yes/No

Normalized: Yes/No

Residual Strength Ratio k: 0

Normalized du/dy: 999

Loading Direction

Positive	Negative
0.30	0.30
0.05	0.05
5	5
6	6
0	0
999	999

Cyclic Deterioration Parameters

	lambda	D+	D-
Strength Degradation lambda s	50	1	1
Post Cap. Strength Degradation lambda c	50	1	1
Accelerated Stiffness Degradation lambda a	50	1	1
Unloading Stiffness Degradation lambda k	50	1	1

P-Delta Effects

☒ Include P-Delta

Scaling Process of Gr. Motion

☒ Scale at Sa (T1,5%)

☐ FEMA P695

Control Buttons

Run IDA Plot IDA Curves

Reset Collapse Fr. Curves

STOP P [EDP/IMIN]

Developed by Dimitrios G. Lignos and Professor Helmut Krawinkler, Stanford University CA, October 2009

Figure 19. Menu for step size of incremental dynamic analysis

While the incremental dynamic analysis process is in progress a dynamic information DOS window summarizes the information related to the SDOF system and the ground motion that is currently analyzed. For a set of 40 ground motions and an IDA step of 0.10g the simulation time takes about 15min. This time varies depending on the computer processor. By clicking on the “Plot IDA Curves” button the user can plot the IM-EDP curves that are illustrated in Figure 20.

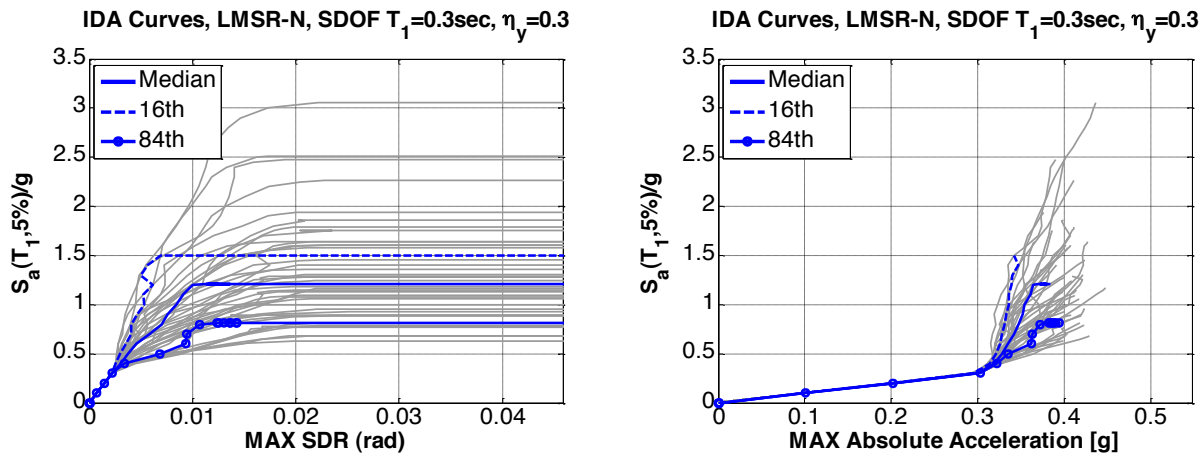


Figure 20. IDA curves for the full set of LMSR-N ground motions

The IIIDAP software is able to develop collapse and drift-based fragility curves given a hazard level. Figures 21a to 21c illustrate the drift-based cumulative distribution curves given no collapse for 50% probability of exceedence in 50 years (service level event), 10% probability of exceedence in 50 years (design level event) and 2% probability of exceedence in 50 years (maximum considered event) together with median and standard deviation of the fitted lognormal distributions. Figure 21d illustrates the collapse fragility curve of the infill wall system for the selected set of 40 ground motions.

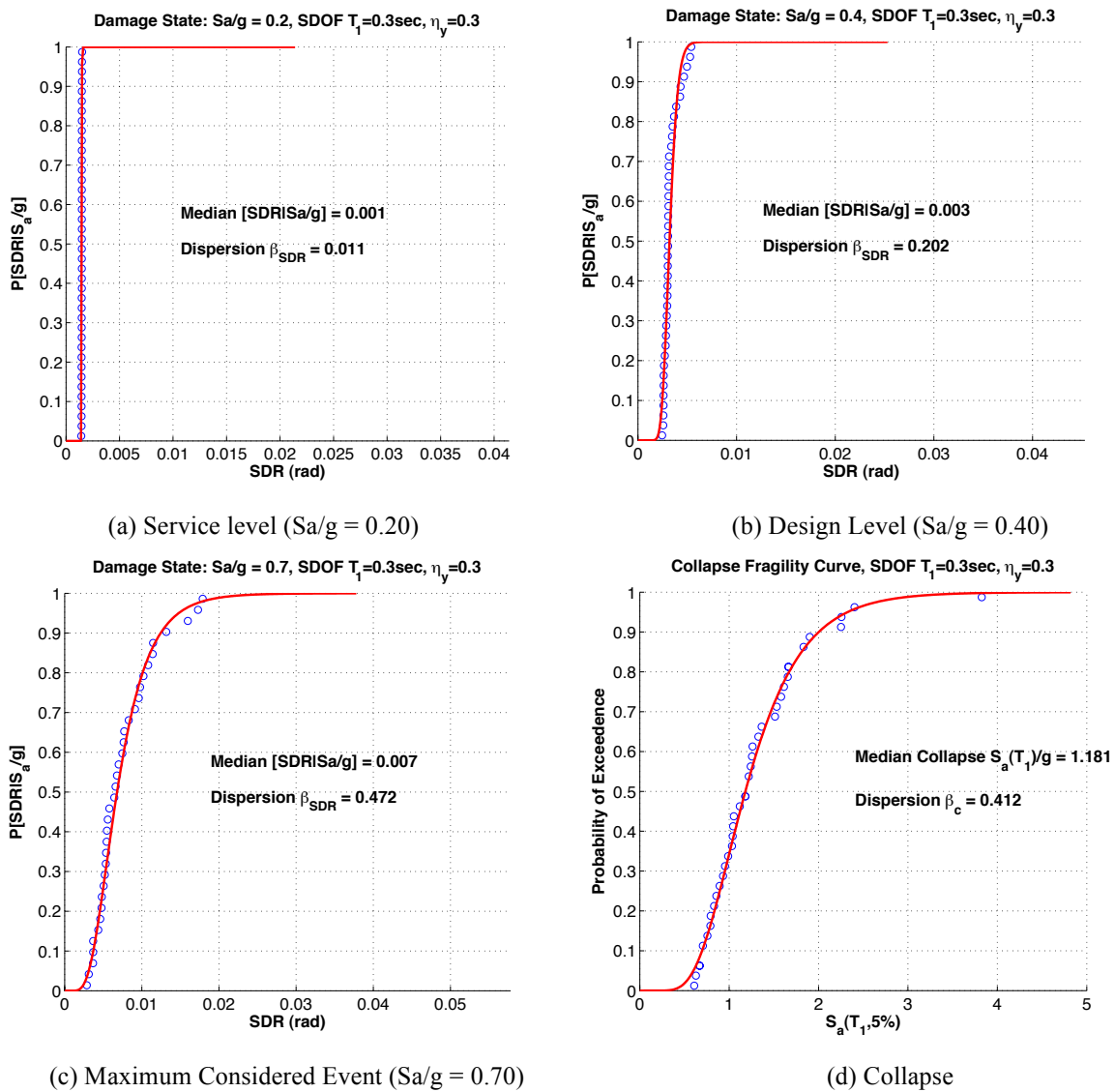


Figure 21. Cumulative distribution functions given a hazard level and collapse fragility curve for SDOF infill panel system with $T_1 = 0.30\text{sec}$

The process to obtain the seismic performance of the infill wall is repeated using the FEMA P695 scaling process for the set of 44 FEMA P695 ground motions. These earthquake motions are selected from the “Ground Motion List” menu. This time the FEMA P695 set is selected. In order to scale these ground motions based on FEMA P695 procedure, the “FEMA P695” option is selected from the “Scaling Process of Gr. Motion” group. A pop up window asks the user to specify the period T of scaling (see Figure 22). For this example the motions are scaled at 0.30sec. Based on the classical FEMA P695 procedure the $C_u T_a$ period of the structural system should be selected. An IDA scale factor step of 0.10 is selected for this case.

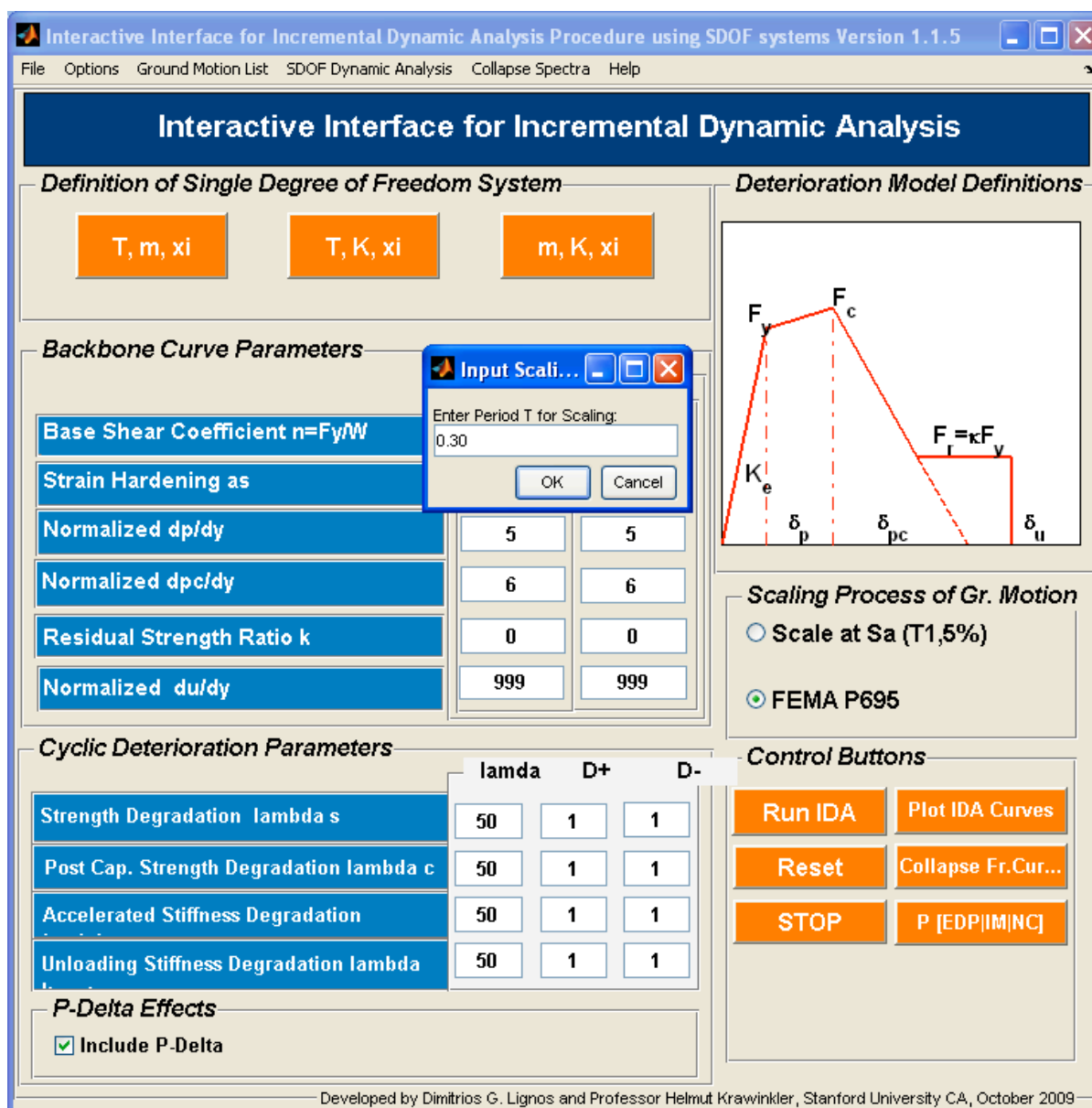


Figure 22. Inputting scaling period after selecting the FEMA P695 scaling process

After the completion of the IDA analysis based on the FEMA P695 procedure, the IM -peak SDR plot is shown in Figure 23. Note that due to the different scaling process the dispersion for each intensity level is different compared to the scaling technique at the first mode period of the SDOF system.

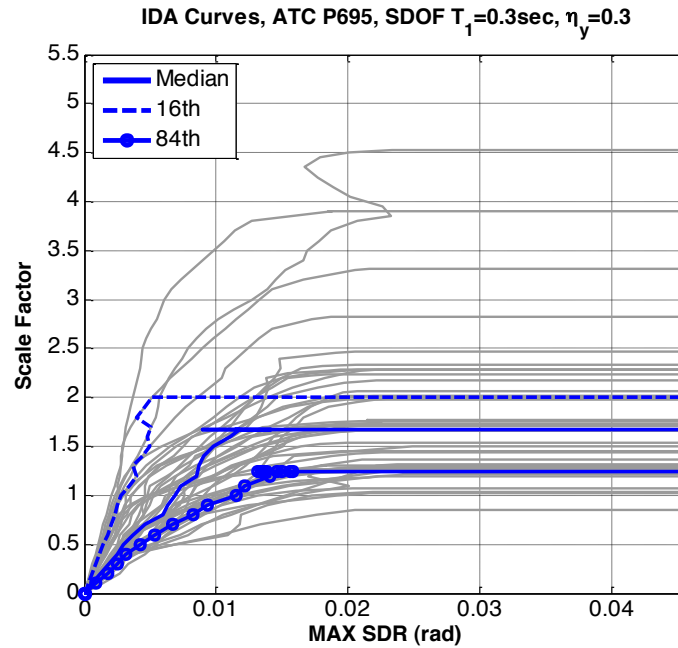


Figure 23. IDA curves for the set of 44 far field ground motions using FEMA P695 scaling procedure

The cumulative distribution functions for different hazard levels given no collapse are shown in Figures 24 and 25a. These hazard levels are specified by selected scale factors (0.2, 0.6 and 0.90) to represent a service level, design level and maximum considered earthquake event. The collapse fragility curve for the complete set of data is shown in Figure 25b. In this figure the median collapse capacity is expressed as the median of the scale factors that lead the SDOF system to collapse for 22 of the 44 selected ground motions.

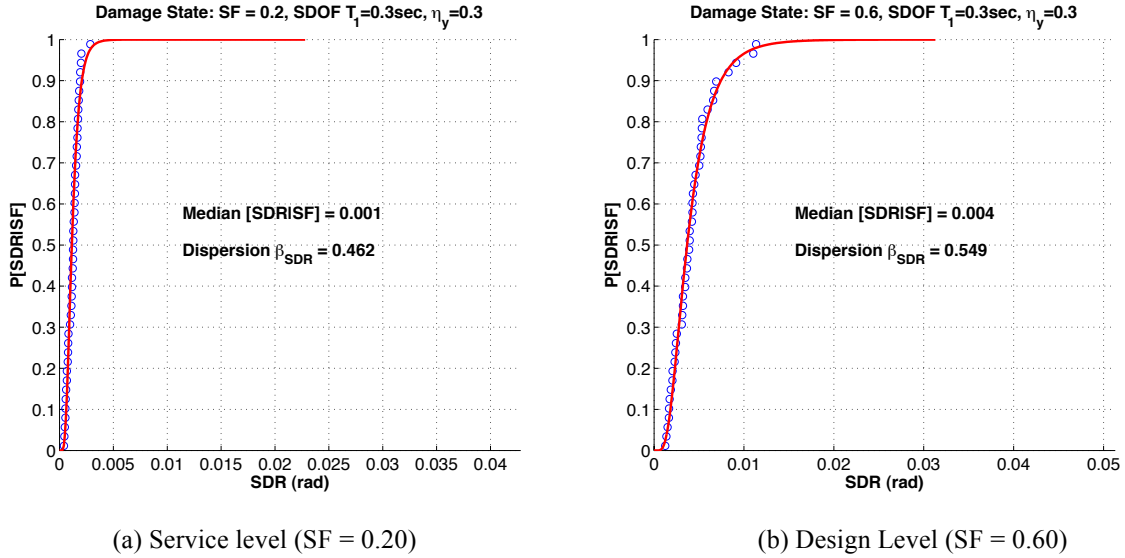


Figure 24. Cumulative distribution functions given a hazard level for SDOF infill panel system with $T_I = 0.30\text{sec}$ using FEMA P695

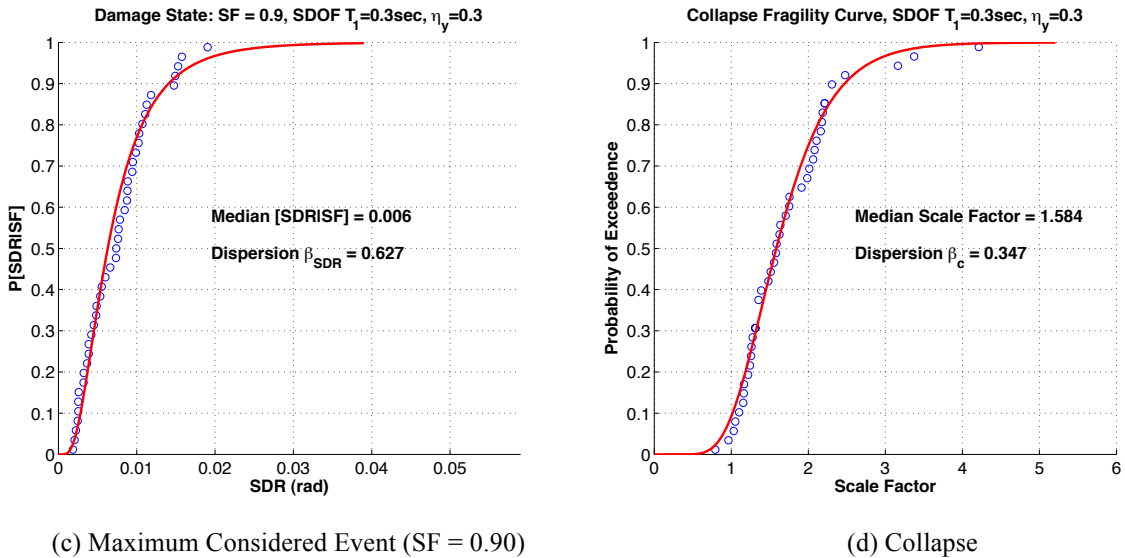


Figure 25. Cumulative distribution functions given a hazard level and collapse fragility curve for SDOF infill panel system with $T_I = 0.30\text{sec}$ using FEMA P695

7.1 Median Collapse Spectrum

In order to create a median collapse spectrum for a deteriorating SDOF system the parameters that define the system should be specified first in the main interface of the IIIDAP program. In the example discussed in this section the SDOF wall structure is used. From the menu “Collapse Spectra” the “Period Variation” option is selected (see Figure 26). The minimum period that is selected is $T^{\min}=0.05\text{sec}$, the maximum period is $T^{\max}=4.05\text{sec}$ and the period increment is

selected to be 0.50sec. In order to develop the median collapse spectrum for the range of selected periods, IIIDAP calculates the stability coefficient (if height is inputted) for each period based on equations (9) and (10) shown in Section 6. For each one of the individual periods of the SDOF system IIIDAP will conduct IDA for the selected set of ground motions (LMSR-N in the case summarized herein). If the stability coefficient of the system for a given period exceeds 1.0 (statically unstable system) then IIIDAP informs the user that the collapse spectrum will be computed up to the period that the stability coefficient is less than 1.0.

Interactive Interface for Incremental Dynamic Analysis Procedure using SDOF systems Version 1.1.5

File Options Ground Motion List SDOF Dynamic Analysis Collapse Spectra Help

Interactive Interface

Period Variation
Execute...
Plot Collapse Spectrum

Dynamic Analysis

Definition of Single Degree of Freedom System

T, m, xi T, K, xi m, K, xi

Backbone Curve Parameters

	Positive	Negative
Base Shear Coefficient $n=F_y/W$	0.3	0.3
Strain Hardening as	0.05	0.05
Normalized dp/dy	5	5
Normalized dp/dy	6	6
Residual Strength Ratio k	0	0
Normalized du/dy	999	999

Cyclic Deterioration Parameters

	lamda	D+	D-
Strength Degradation lamda s	50	1	1
Post Cap. Strength Degradation lamda c	50	1	1
Accelerated Stiffness Degradation	50	1	1
Unloading Stiffness Degradation lamda	50	1	1

P-Delta Effects

☒ Include P-Delta

Deterioration Model Definitions

Graph showing Force (F) vs. Displacement (δ). Key points: F_y , F_c , K_e , δ_p , δ_{pc} , δ_u . The graph illustrates a bilinear hysteretic model with a peak force F_c and a yield force F_y . The displacement at peak force is δ_p , and the ultimate displacement is δ_u . The residual strength is $F = \kappa F_y$.

Scaling Process of Gr. Motion

☐ Scale at $S_a(T1, 5\%)$

☒ FEMA P695

Control Buttons

Run IDA Plot IDA Curves
Reset Collapse Fr.Cur...
STOP P [EDP|IM|NC]

Developed by Dimitrios G. Lignos and Professor Helmut Krawinkler, Stanford University CA, October 2009

Figure 26. Process to develop median collapse spectrum for SDOF system using LMSR-N set of ground motions

After clicking on the “Execute...” option from the “Collapse Spectra” menu, the software asks the user in which folder the analysis output files should be saved. In this example the Collapse Spectra (Default option) is selected. The IDA output results for each vibration period are kept in individual folders. After the completion of the analysis, a summary file called “CollapseSpectrumInfo.out” is created. This file contains the output information of the SDOF system for each period that was analyzed. In order to plot the median collapse spectrum, the option “Plot Median Collapse Spectrum” from the “Collapse Spectra” menu is selected. The software will request the user to specify the folder that the information will be kept (Collapse Spectra for this case). Figure 27 shows the median collapse spectrum for the analyzed system from 0.05sec period to 3.05sec since for 3.55sec and 4.05sec the stability coefficient of the same system is 1.02 and 1.34, respectively (i.e., the SDOF system is not stable).

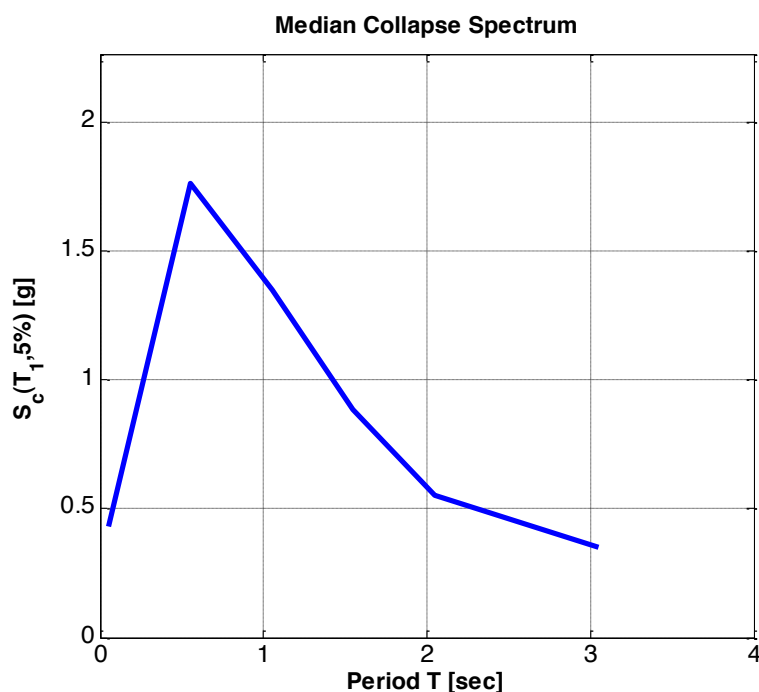


Figure 27. Example of median collapse spectrum for SDOF wall panel system using LMSR-N ground motion set

8 Example Using the SDOF Dynamic Analysis Menu

This section describes the process to conduct a single nonlinear response history analysis using a deteriorating SDOF system with IIDAP. The user still needs to specify the basic properties of

the single degree of freedom system through the main interface of IIIDAP. The example of Section 7 (see Figure 15) is used for illustration purposes. After specifying the input parameters of the SDOF system to be analyzed the basic information of the SDOF system needs to be saved from “File” menu after clicking the “Save SDOF Information” option. If this step is done correctly a summary table will pop-up that will summarize the input parameters of the SDOF system (see Figure 28). Each time that a different SDOF system is analyzed the steps summarized in this section must be repeated.

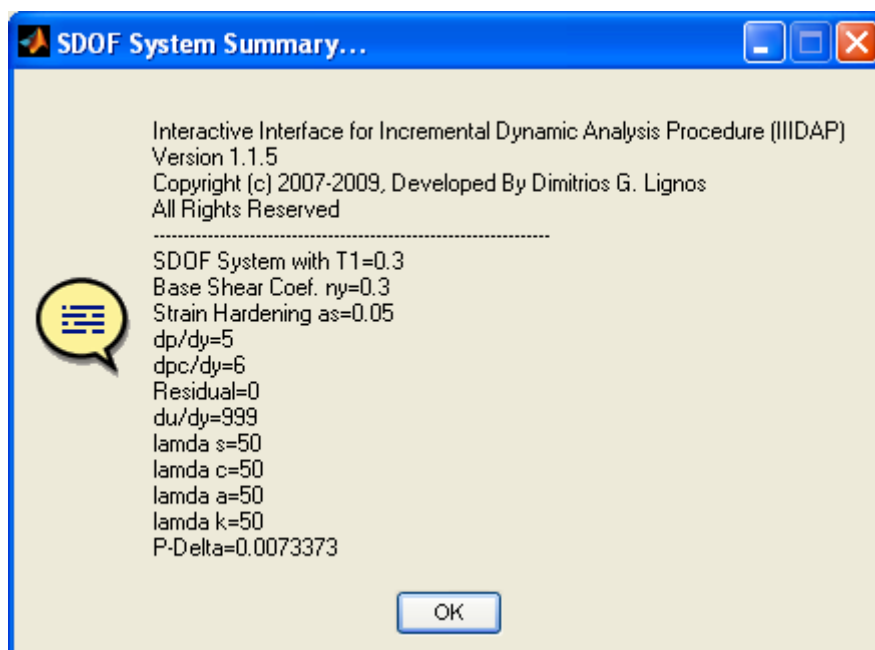


Figure 28. Summary table for SDOF with $T_1=0.03\text{sec}$

A single ground motion is selected from the Ground Motion List menu of IIIDAP. After selecting the motion the “Update” button should be clicked. To execute a single dynamic analysis from the main Menu of the IIIDAP click “SDOF Dynamic Analysis” and then select “Run...”. An interface similar to the one shown in Figure 29 should pop up. Since the SDOF system characteristics and ground motion have already been defined, by selecting the Ground Motion Scale Factor (by default set to be 1, i.e. unscaled motion) and by clicking on the “Run Dyn. Analysis” button a user can execute the single dynamic analysis of the specified SDOF system with the selected ground motion. When the analysis is completed the relative displacement history of the SDOF system is shown in the center figure of the SDOF Dynamic

Analysis Interface (see Figure 29). A number of response history options are available by selecting various options on the Y- and X- axis. The user should click on the plot button from the SDOF single dynamic analysis menu (see Figure 29).

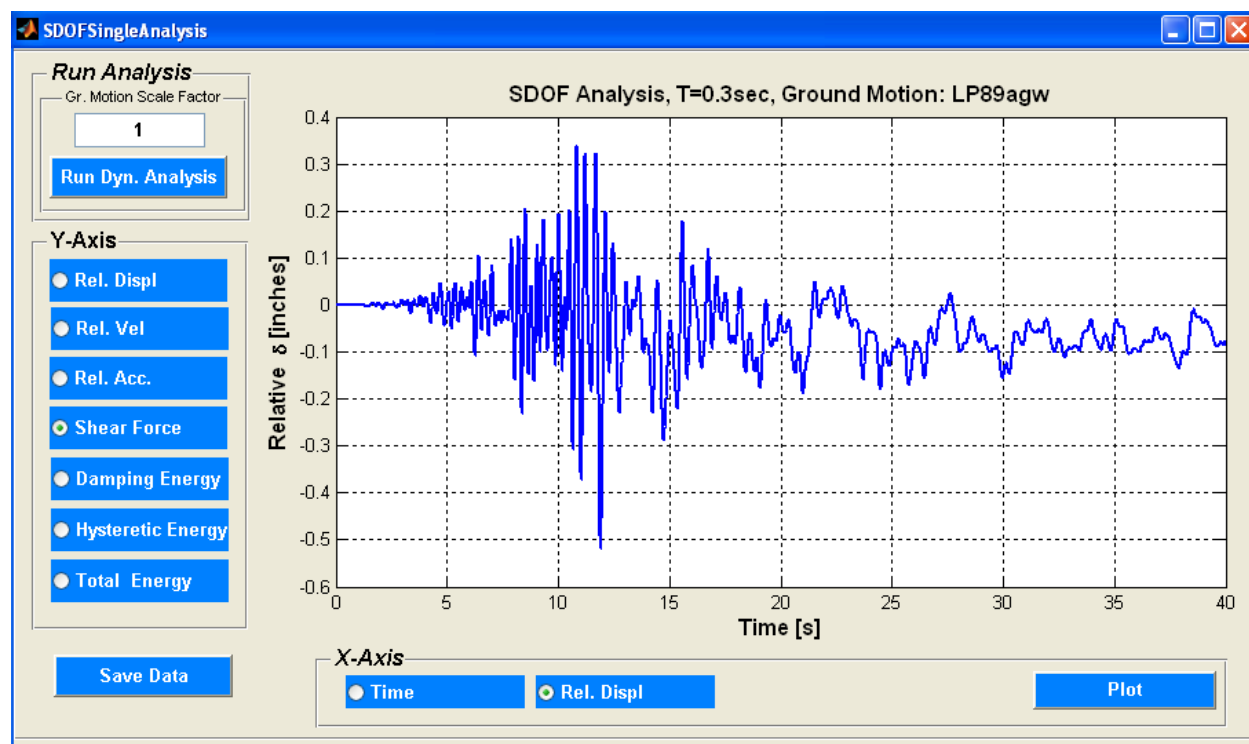


Figure 29. Relative displacement history for SDOF with $T_1=0.03\text{sec}$ for ground motion LP89agw

Saving the analyzed data: The current plot, which is shown in the main plot area of the SDOF single dynamic analysis menu is may be stored by clicking on the “Save Data” button. The digitized data of this plot is saved in a folder that the user may specify.

An example of the hysteretic response of the SDOF system with period of 0.3sec and a scale factor $SF = 3.33$ (collapse point) is shown in Figure 30.

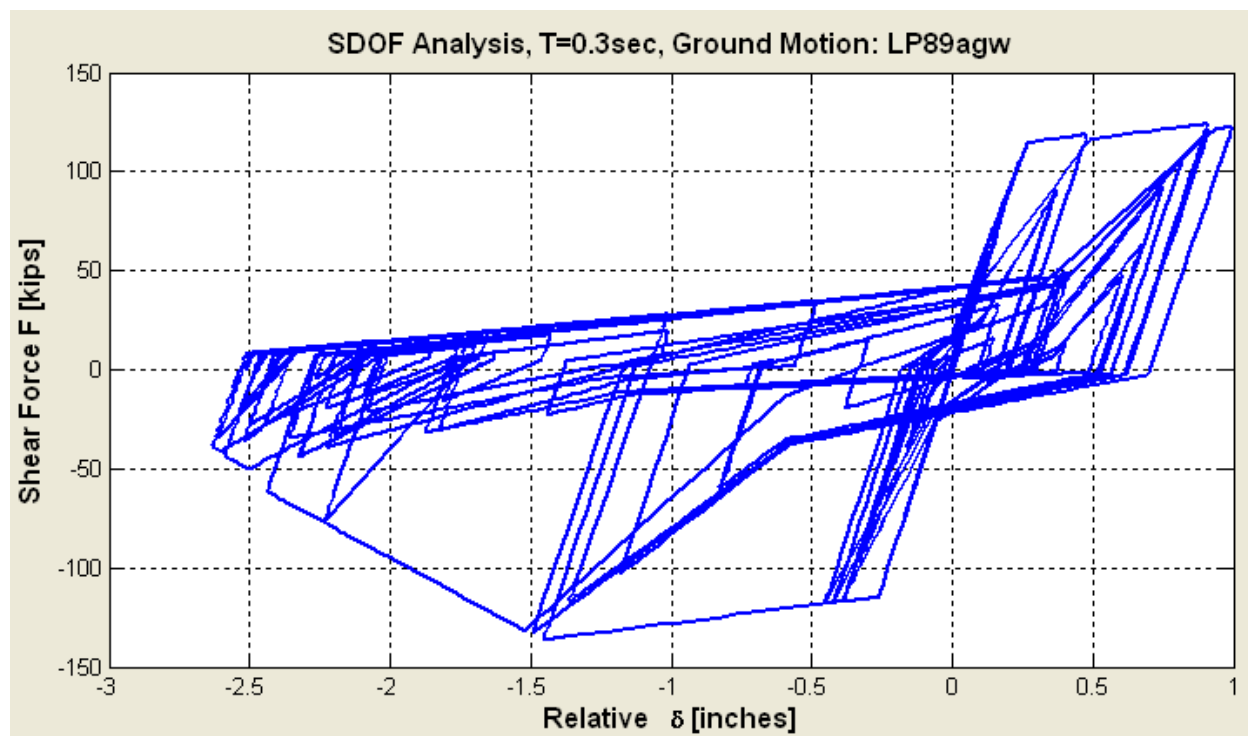


Figure 30. Hysteretic behavior of the SDOF with $T_1=0.03\text{sec}$ for ground motion LP89agw (SF=3.33)

9 User Defined Ground Motions

This section describes the process to create a user defined ground motion to be used in IIIDAP.

- The discrete acceleration values of each one of the user-defined ground motions should be normalized with respect to the acceleration of gravity (g). Each ground motion file must be saved with a 10-character name (letters and/or numbers must be selected). A “.th” extension should be used for each one of these files. Files with this extension can be processed with a regular text editor.
- The GroundMotions folder contains a folder called “UserDefined”. All the user-defined ground motion files that were developed in the previous step must be inserted in the “UserDefined” folder.
- The “UserDefined” folder contains four files that need to be modified from the WordPad editor is recommended. Each file including the necessary modifications are summarized as follows:
 - “GMnames.out”: Starting from the 7th line in this file (below the dashed line), the 10-character filename of the ground motion (without the file extension) must be written. One line per ground motion should be used. The total number of ground motions that this file should include is 40. Therefore, the file must finish in line 47. In case that more than 40 ground motions need to be used, then a separate set

of 40 ground motions should to be specified by the user. In case that less than 40 ground motions need to be used, the user should follow the same procedure discussed herein and just keep the rest file names contained in the “GMnames.out” file so that in total the ground motions should appear to be 40 even if less ground motions will be used.

- “GroundMotionTotalPoints.out”: Starting from top to bottom, the user must specify the total number of the discrete acceleration values of each ground motion. The total number of points per ground motion must be inserted in the same order that the ground motion names were inserted in the “GMnames.out” file.
- “GroundMotionTimeStep.out”: Starting from top to bottom, the user must specify the recorded ground motion time step for each ground motion. The ground motion time step must be inserted in the same order that the ground motion names were inserted in the “GMnames.out” file.
- “GroundMotionSpectra.out”: The user needs to specify the 5% absolute acceleration spectra for the set of 40 user-defined ground motions. The first row of this file should include the 10-character filename of each ground motion that was inserted in the “GMnames.out” file (without the filename extension). The first column of the “GroundMotionSpectra.out” file represents the periods of the ground motion acceleration spectra. It is recommended that a period range T from 0.01sec to 5.00sec with a period step of 0.01sec is used. Each other column represents the normalized absolute acceleration spectrum for each ground motion of the user-defined ground motion set. Each spectrum value must be normalized with respect to the acceleration of gravity (g).

The “GroundMotionSpectra.out” file is necessary if the user-defined ground motions need to be scaled based on the FEMA-P695 scaling procedure.

10 References

- [1] Benjamin, J.R., and Cornell, C.A. (1970). "Probability, statistics, and decision for civil engineers," New York, McGraw-Hill Book Company, 684p.
- [2] Cordova, P.P., Deierlein, G.G., Mehanny, S.S.F., Cornell, C.A. (2000). "Development of a two-parameter seismic intensity measure and probabilistic assessment procedure," *Proceedings, The Second U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*, 11-13 September, Japan, Berkeley, pp. 195-214.
- [3] FEMA P695 (2009). "Quantification of building seismic performance factors", *Report FEMA P695*, Federal Emergency Management Agency, Washington, D.C.
- [4] Haselton, C.B., and Deierlein, G.G. (2007). "Assessing seismic collapse safety of modern reinforced concrete moment frame buildings," *Report No. TR 156*, The John A. Blume Earthquake Engineering Research Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA.
- [5] Ibarra, L.F., Medina, R., Krawinkler, H. (2002). "Collapse assessment of deteriorating SDOF systems," *Proceedings of the 12th European Conference on Earthquake Engineering*, London, UK, Paper 665, Elsevier Science Ltd., September 9-13, 2002.
- [6] Ibarra L.F., Medina R.A., Krawinkler H. (2005). "Hysteretic models that incorporate strength and stiffness deterioration," *Earthquake Engineering and Structural Dynamics*, **34**(12), pp. 1489-1511.
- [7] Ibarra, L.F., and Krawinkler, H. (2005). "Global collapse of frame structures under seismic excitations," *Report No. PEER 2005/06*, Pacific Earthquake Engineering Research Center (PEER), University of California at Berkeley, Berkeley, CA.
- [8] Lignos, D.G., and Krawinkler, H. (2007). "A database in support of modeling of component deterioration for collapse prediction of steel frame structures," *Proceedings ASCE Structures Congress*, Long Beach CA, SEI institute.
- [9] Lignos D.G., and Krawinkler, H. (2009). "Sidesway collapse of deteriorating structural systems under seismic excitations," *Report No. TR 172*, The John A. Blume Earthquake Engineering Research Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA.
- [10] Lignos, D.G., Hunt, C. M., Krebs, A., and Billington, S.L. (2009). "Comparison of retrofitting techniques for existing steel moment resisting frames," *Proceedings ATC&SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures*, December 9-11, San Francisco, CA, 2009.
- [11] Lignos, D.G., Zareian, F., and Krawinkler, H. (2010). "A steel component database for deterioration modeling of steel beams with RBS under cyclic loading," *Proceedings Structures Congress*, ASCE, May 12-14, Orlando, Florida.

- [12] Lignos, D.G., Krawinkler, H. (2011). "Deterioration Modeling of Steel Components in Support of Collapse Prediction of Steel Moment Frames under Earthquake Loading," *Journal of structural Engineering*, ASCE, **137**(11), pp. 1291-1302.
- [13] Luco, N. (2002). "Probabilistic seismic demand analysis SMRF connection fractures and near-source effects," *PhD. Dissertation* submitted to the Department of Civil Engineering, Stanford University
- [14] Medina, R., and Krawinkler, H. (2003). "Seismic demands for non-deteriorating frame structures and their dependence on ground motions," *Report No. 144*, The John A. Blume Earthquake Engineering Research Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA.
- [15] Mehrabi, A.B., Shing, P.B., Schuller, M.P., and Noland, J.L. (1996). "Experimental evaluation of masonry-infilled RC frames," *Journal of Structural Engineering*, ASCE, **122**(3), pp.228-237.
- [16] Rahnama, M., and Krawinkler, H. (1993). "Effect of soft soils and hysteresis models on seismic design spectra," *Report No. 108*, The John A. Blume Earthquake Engineering Research Center, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA.
- [17] Shinozuka, M., Feng, M.Q., Lee, J., and Naganuma, T. (2000). "Statistical analysis of fragility curves", *Journal of Engineering Mechanics*, **126**(12), pp. 1224-1231.
- [18] Taejin K., Whittaker, A.S., Gilani, A.S., Bertero, V., and Takhirov, S. (2000). "Cover-plate and flange-plate steel moment-resisting connections." *Journal of Structural Engineering*, ASCE, **128**(4), pp. 474-482.
- [19] Vamvatsikos, D. and Cornell, C. A. (2002). "Incremental Dynamic Analysis," *Earthquake Engineering and Structural Dynamics*, **31**(3), pp. 491-514.
- [20] Zareian, F. (2006). "Simplified performance-based earthquake engineering," *Ph.D. Dissertation*, Department of Civil and Environmental Engineering, Stanford University.
- [21] Zareian, F., Lignos, D.G., and Krawinkler, H. (2010). "Evaluation of seismic collapse performance of steel special moment resisting frames using ATC-63 methodology", *Proceedings Structures Congress*, ASCE, May 12-14, Orlando, Florida.