User manual for SLAT: Seismic Loss Assessment Tool version 1.14

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Abstract

SLAT is a computer program for performing seismic loss assessment of structures subjected to earthquake risk. SLAT is written in FORTRAN and compatible with Microsoft operating systems.

The tool uses the uncoupled modelling approach advocated by the Pacific Earthquake Engineering Research (PEER) Centre, where the loss is computed through the use of interim variables.

This user manual is intended as a reference for users of SLAT to aid in: (i) the preparation of the primary input file; (ii) the preparation of external data files; (iii) the theory behind the numerical algorithm of the SLAT program; (iv) example problems for beginning users; and (v) the database of component fragility and loss functions built into the SLAT library.

While every effort has been made to ensure that the subroutines comprising SLAT are bug-free, users should always use simple checks and engineering judgment to ensure that the results are appropriate. Should any suspected errors be found please contact the author.

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1. Running the program

The program is run in interactive mode with a primary input file, and if necessary, additional external data files, all of which are prepared using a text editor (e.g. notepad, wordpad). Avoid using Microsoft Word to generate input files as it can embed tabs into the input file which will cause errors when running SLAT.

To run the program double click on the executable file SLAT.exe. The program will prompt the user for the output file name and the location of the input file. The program then executes the analysis and will return either a 'Program completed' message, or some form of error message(s).

The output of the program is a formatted output file (no file extension) which contains details on reading of the input data and the recording of any errors, as well as a binary output file (with extension .bin) which contains all of the results of the analysis.

The post-processor program postSLAT.exe can then be used to extract the desired information from the binary output file for plotting etc.

2. Overview of the data for SLAT

The analysis data for the structure is described by the following sequences of input lines. Each data set consists of the following items of data. Square boxes are used to indicate lines which need to be written for the input file. Following each square box are the descriptions/definitions of the input variables as well as the input format.

1. **Title for the analysis**
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15. **Ranges for output data**

2.1 Title for the analysis

Title for the analysis (up to 79 alphanumeric characters)

2.2 Principal analysis options

Two lines are required for defining the principal analysis options

N_IM N_EDP N_USERFRAG N_PG N_PARA N_EXTDATA nDS_Mob N_RG

N_IM	The number of Intensity Measures (IM)	**I5**
N_EDP	The number of Engineering Demand Parameters (EDP)	**I5**
N_USERFRAG	The number of user-defined damage functions	**I5**
N_PG	The number of performance groups	**I5**
N_PARA	The number of parameteric relationships	**I5**
N_EXTDATA	The number of external data files	**I5**
nDS_Mob[1]	The number of different states for the mobilization delay computation	**I5**
N_RG[1]	The number of different repair groups for downtime computations	**I5**

COLL EPI_UNC DEAGG DWNTIME

COLL	Consideration of collapse of the structure = 0 : Do not consider in the analysis = 1 : Consider in analysis	**I5**
EPI_UNC	Consideration of epistemic uncertainties = 0 : Do not consider in the analysis = 1 : Consider in analysis	**I5**
DEAGG	Computation of deaggregated losses = 0 : Do not consider in the analysis = 1 : Consider in analysis	**I5**
DWNTIME	Consideration of downtime in analysis = 0 : Do not consider in the analysis = 1 : Consider in analysis	**I5**

Notes:

[1] If **DWNTIME**=0 then can simply supply zero here also

2.3 Correlation options

One line is required giving details on correlations for aleatoric and epistemic uncertainties

COR_LDS   COR_DSEDP   COR_EDPIM   CORE_LDS   CORE_DSEDP

COR_LDS Aleatoric correlation for Loss|DS relationship between different components (i.e. $\rho_{L_{i'}|DS_i, L_{j'}|DS_j}$) **I5**

= 0 : Uncorrelated (i.e. $\rho = 0$)
= 1 : Perfectly correlated (i.e. $\rho = 1$)
= 2 : Partially correlated (i.e. $0 < \rho < 1$)

COR_DSEDP Aleatoric correlation for DS-EDP relationship between different components (i.e. $\rho_{DS_{i'}|EDP_i, DS_{j'}|EDP_j}$) **I5**

= 0 : Uncorrelated (i.e. $\rho = 0$)
= 1 : Perfectly correlated (i.e. $\rho = 1$)
= 2 : Partially correlated (i.e. $0 < \rho < 1$)

COR_EDPIM Aleatoric correlation for EDP|IM relationship between different demand parameters (i.e. $\rho_{EDP_{i'}, EDP_{j'}|IM}$) **I5**

= 0 : Uncorrelated (i.e. $\rho = 0$)
= 1 : Perfectly correlated (i.e. $\rho = 1$)
= 2 : Partially correlated (i.e. $0 < \rho < 1$)

CORE_LDS[1] Epistemic correlation for L|DS relationship within components (e.g. $\rho_{\mu_{L|DS}, \mu_{L|DS}}$) **I5**

= 0 : Uncorrelated (i.e. $\rho = 0$)
= 1 : Perfectly correlated (i.e. $\rho = 1$)
= 2 : Partially correlated (i.e. $|\rho| \leq 1$)

CORE_DSEDP[1] Epistemic correlation for DS|EDP parameters within components (e.g. $\rho_{\mu_{LD|EDP}, \mu_{DS|EDP}}$) **I5**

= 0 : Uncorrelated (i.e. $\rho = 0$)
= 1 : Perfectly correlated (i.e. $\rho = 1$)
= 2 : Partially correlated (i.e. $|\rho| \leq 1$)

Notes:

1. If **EPI_UNC**=0 then **CORE_LDS** and **CORE_DSEDP** are not considered

2.4 Integration Methods

One line is required defining the integration methods for solving the integral equations

INT_A INT_E REL_ERRA REL_ERRE AMAXITS EMAXITS

INT_A	The type of integration performed for aleatoric integrations = 0 : First-order second moment method (FOSM) = 1 : Direct numerical Integration utilising the Magnitude Oriented Adaptive Quadrature (MAQ) algorithm = 2 : Direct numerical Integration utilising MAQ but with FOSM method for computations of correlations	**I5**
INT_E	The type of integration performed for aleatoric integrations = 0 : Direct monte-carlo simulation	**I5**
REL_ERRA	The allowable relative error in aleatory uncertainty numerical integration (maximum allowable error is 0.1%)	**F10.4**
REL_ERRE	The allowable relative error in epistemic uncertainty consideration (currently not considered – simply supply 0.0)	**F10.4**
AMAXITS	The maximum function evaluations to perform when carrying out aleatoric integrations (if **INT_A**=0 simply supply ‘0’ here)	**I5**
EMAXITS	The number of simulations to perform when carrying out epistemic monte-carlo integrations (if **INT_E** =0 simply supply ‘0’ here)	**I5**

2.5 Output plotting parameters

Two lines are required defining the computation of various relationships

First line is for output of relationships which were input directly

OUT_IMR	**OUT_EDPIM**	**OUT_LEDP**	**OUT_CIM**

For all of the 4 input variables below, 1 = store in output file; 0 = do not store in output file

OUT_IMR	Output IM hazard relationships	**I5**
OUT_EDPIM	Output EDP|IM relationships	**I5**
OUT_LEDP	Output Loss|EDP relationships	**I5**
OUT_CIM	Output Collapse-IM relationships	**I5**

Second line is for output of relationships which require calculations to obtain

OUT_EDPR	**OUT_CR**	**OUT_LIM**	**OUT_EAL**	**OUT_LR**	**OUT_CORR**

For all of the 6 input variables below, 1 = store in output file; 0 = do not calculate.

OUT_EDPR	Output EDP hazard relationships	**I5**
OUT_CR	Output collapse hazard relationships	**I5**
OUT_LIM	Output Loss|IM relationships	**I5**
OUT_EAL	Output Expected loss and Expected annual relationships	**I5**
OUT_LR	Output Loss- hazard relationships	**I5**
OUT_CORR	Output Loss|EDP, EDP|IM, and Loss|IM aleatory correlation relationships (not currently avaliable = supply 0 here)	**I5**

2.6 Intensity measures

INTENSITY

First a line is required which indicates the form of the IM hazard relationship given

IM_DAT IMR_FIT

IM_DAT[1]	The type of IM-rate of exceedance relationship data provided = 0 : No IM-rate of exceedance data provided = 1 : IM-rate data provided only (i.e 2 column array of IM for different rates of exceedance values)[2]	**I5**
IMR_FIT[3]	The type of parametric fit if no data given for the IM hazard relationship = 0 : no parametric fitting. Uses logarithmic interpolation between the values provided[2] = 1 : use power-law parametric curve (McGuire, 1991)[2,4] = 2 : use non-linear hyperbolic law (Bradley, 2007)[2,4]	**I5**

Then one line is then required to be input for <u>each</u> IM value

IM_NUM IMR_LAB

IM_NUM	The Intensity Measure (IM) identifier	**I5**
IMR_LAB[4]	A data/fit label. If **IM_DAT≠0** then it is used to indicate the external data file for the IM hazard relationship in '**DATA**'. If **IM_DAT=0** it is used to indicate the parameters used for the IM hazard relationship in '**PARAMETERS**'.	**I5**

Notes:

[1] When IM raw data is given it must be provided for ascending values of IM

[2] See theory for details

[3] **IMR_FIT** cannot be 0 if **IM_DAT** =0, and also that no extrapolation of rate values will be carried out in the analysis

[4] In the current version it is not possible to perform parametric fits to raw data

2.7 Engineering demand parameters

DEMAND

First a line is required which indicates the form of the EDP|IM relationship given

EDP_DAT μEDP_FIT βEDP_FIT

EDP_DAT[1]	The form of the EDP|IM relationship data provided = 0 : No data is provided = 1 : moments of EDP|IM relationship data provided (i.e 3 column array of mean and dispersion of EDP (i.e. $\mu_{EDP \mid IM}, \sigma_{\ln EDP \mid IM}$) for different IM values. [2, 5] =2 : Multiple ground motion data provided for the EDP|IM relationship (i.e. an array of EDP values for each IM from time history/ modified modal analysis)[3]	**I5**
μEDP_FIT	The type of parametric form for the (conditional) mean EDP|IM relationship = 0 : No parametric fit performed(uses linear interpolation between the standard deviation values)[4] = 1 : Use power-law parametric curve, (Cornell *et al.* 2002)[5] = 2 : Use non-linear law (Aslani and Miranda 2005b)[5]	**I5**
βEDP_FIT	The type of parametric fit to perform for the (conditional) dispersion EDP|IM relationship = 0 : No parametric fit (uses linear interpolation between the dispersion values)[3] = 1 : use power-law parametric curve (Mackie and Stojadinovic 2007)[5] = 2 : use parabolic law (Aslani and Miranda 2005b)[5]	**I5**

One line is then required to be input for each EDP value

EDP_NUM IM_NUM EDP_LAB βFITL EFITL

EDP_NUM	The EDP number	**I5**
IM_NUM	The Intensity Measure (IM) that the EDP is related to, as defined in '**INTENSITY**'.	**I5**
EDP_LAB	A data/fit label. If **EDP_DAT ≠0** then it is used to indicate the external data file for the IM-rate relationship in '**DATA**'. If **EDP_DAT =0** it is used to indicate the parameters used for the IM-rate relationship in '**PARAMETERS**'.	**I5**
βFITL	A parameter label used to indicate the parameters used for the dispersion EDP|IM relationship in '**PARAMETERS**'. If **βEDP_FIT=0** then simply supply '0' here.	**I5**

Notes:

[1] The EDP|IM data provided must be in ascending values of IM down the external file.

[2] Consideration of epistemic uncertainties are not possible using the simplified moment-based EDP|IM representation

[3] See layout of external data files for further details

[4] **μEDP_FIT** ≠ 0 or **βEDP_FIT** ≠ 0 if **EDP_DAT** =0, and also that no extrapolation of IM values will be carried out in the analysis

[5] See Theory for further details of parametric equations

2.8 User defined fragility functions

This section is only required if **N_USERFRAG** >0

FRAGILITY

Then for each user-defined damage function, the following lines are required:

FRAG_NUM N_DS

FRAG_NUM[1]	The fragility identifier (<0) which is referred to in '**PGROUP**'	**I5**
N_DS	The number of discrete Damage States (DS) the **component** has	**I5**

For each of the DS (for a given fragility number) the following lines are required defining fragility:

μEDP_DS βEDP_DS EμEDP_DS EβEDP_DS

μEDP_DS	The mean EDP value for the onset of DSi	**G10.3**
βEDP_DS	The dispersion (in EDP) of the onset of DSi	**G10.3**
EμL_DS[3]	Epistemic uncertainty in mean lnEDP for the onset of DSi	**G10.3**
EβL_DS[3]	Epistemic uncertainty in variance lnEDP for the onset of DSi	**G10.3**

For each of the DS of the component the following lines are required defining direct loss:

μUL_DS μLL_DS NC_UL NC_LL βL_DS EμL_DS EβL_DS

μUL_DS[2]	The upper limit on the mean loss due to the onset DSi	**G10.3**
μLL_DS[2]	The lower limit on the mean loss due to the onset DSi	**G10.3**
NC_UL[2]	The number of components up to which the unit cost is the upper limit **μUL_DS**	**I5**
NC_LL[2]	The number of components after which the unit cost is the lower limit **μLL_DS**	**I5**
βL_DS	The (normalised) dispersion (in the loss) due to the onset of DSi	**G10.3**
EμL_DS[3]	Epistemic uncertainty in mean lnloss for the onset of DSi	**G10.3**
EβL_DS[3]	Epistemic uncertainty in variance lnloss for the onset of DSi	**G10.3**

If **DWNTIME**=1, then for each of the DS of the component the following lines are required defining time to repair the component:

μULDT_DS μLLDT_DS NC_UL NC_LL βLDT_DS EμLDT_DS EβLDT_DS

μULDT_DS[2]	The upper limit on the mean loss (time) due to the onset DSi	**G10.3**

μLLDT_DS[2]	The lower limit on the mean loss (time) due to the onset DSi	**G10.3**
NC_UL[3]	The number of components up to which the unit cost is the upper limit **μUL_DS**	**I5**
NC_LL[2]	The number of components after which the unit cost is the lower limit **μLL_DS**	**I5**
βLDT_DS	The (normalised) dispersion (in the loss (time)) due to the onset of DSi	**G10.3**
EμLDT_DS[3]	Epistemic uncertainty in mean lnloss (time) for the onset of DSi	**G10.3**
EβLDT_DS[3]	Epistemic uncertainty in variance lnloss (time) for the onset of DSi	**G10.3**

Notes:

[1] User defined fragility functions have fragility numbers less then zero, as all library functions have values greater than zero.

[2] See theory on the loss consequence function dependent on the number of components

[3] See theory on epistemic uncertainties for details

[4] Epistemic uncertainty in the user-defined fragility functions (both damage and loss) is perfectly correlated (for library fragility functions: none, perfect and partial correlations are permitted).

2.9 Performance group

PGROUP

For each component, the following lines are required:

PG_NUM FRAG_TYPE COM_EDP Q_PG PGPARA

PG_NUM	The component number	**I5**
FRAG_TYPE	The fragility function of the performance group (>1 for library damage functions; <1 for user-defined functions specified in '**FRAGILITY**')	**I5**
PG_EDP	The EDP that the performance group is related to as defined in **'DEMAND'**	**I5**
Q_PG	The number (quantity) of components that comprise the performance group	**I5**
PGPARA[1]	Additional parameter required for determining fragility functions	**G10.3**

Notes:

[1] Additional parameters are only required for some fragility functions

2.10 Global collapse

COLLAPSE

First, one line is required outlining the way in which the collapse-IM relationship is input

PC_DAT FIT_TYP

PC_DAT	Data type of the primary Collapse-IM relationship = 0 : moments of distribution provided = 1 : Fragility curve data is provided (i.e 1 column array of different IM values which caused collapse.) (not currently available)	**I5**
FIT_TYP	The type of parametric fit to perform for the Collapse-IM relationship = 0 : No parametric fit performed (not currently avaliable) = 1 : Use lognormal approximation[1].	**I5**

For each IM the following is required:
One line is first required which gives details on the collapse of the structure

IM_NUM PC_FITL

IM_NUM	The IM identifier (as defined in "INTENSITY") which collapse is related	**I5**
PC_FITL	A data label used to indicate the external data file for the Collapse-IM relationship in '**DATA**'.	**I5**

CollLossType RDDcost RDDdwntime

CollLossType	How is the total closs due to collapse determined: = 0 : As defined in the following line = 1 : Computed from the loss given failure of each of the performance groups defined in **PGROUP** plus additional loss due to re-design and demolition etc.	**I5**
RDDcost	Additional costs due to re-design and demolition etc. (as a fraction of the total cost). This is only required if **CollCostType**=1. If **CollCostType** =0 simply supply 0.0.	**G10.3**
RDDdwntime	Additional downtime due to re-design and demolition etc. (as a fraction of the total downtime). This is only required if **CollLossType**=1. If **CollLossType** =0 simply supply 0.0.	**G10.3**

If **CollLossType**=0 then the following line is also required

μCOL_CST βCOL_CST Eμ_COL_CST Eβ_COL_CST

μCOL_CST	Mean cost to replace the structure	**G10.3**
βCOL_CST	Dispersion of the cost of replacement (assumed to be lognormally distributed)	**G10.3**
Eμ_COL_CST[2]	Epistemic uncertainty in the mean of the logarithm of the collapse cost	**G10.3**
Eβ_COL_CST[2]	Epistemic uncertainty in the variance of the logarithm of the collapse cost	**G10.3**

If **DWNTIME**=1 then the following line is also required

μCOL_TIME βCOL_ TIME Eμ_COL_ TIME Eβ_COL_ TIME

μCOL_TIME	Mean time to replace the structure	**G10.3**
βCOL_ TIME	Dispersion of the time of replacement (assumed to be lognormally distributed)	**G10.3**
Eμ_COL_ TIME[2]	Epistemic uncertainty in the mean of the logarithm of the collapse repair time	**G10.3**
Eβ_COL_ TIME[2]	Epistemic uncertainty in the variance of the logarithm of the collapse repair time	**G10.3**

Notes:

[1] The collapse distribution is given as an external file. The moments are the mean (not median) and the lognormal standard deviation.

[2] See theory for details of epistemic uncertianties

2.11 Parametric equations

[only required if mean_EDP_IM_fit, std_EDP_IM_fit, mean_IM_fit, or std_IM_fit is non-zero for any EDP's in **DEMAND** or IM's in **INTENSITY**]

PARAMETER

For each different set of parameters the following lines are required

PARA_LAB NPAR PAR1 PAR2 PAR3 …

PARA_LAB	The label identifier of the parameters for a parametric relationship	**I5**
NPAR	The number of parameters for parameter_label	**I5**
PAR1	The first parameter value	**G10.3**
PAR2, PAR3	The second and third parameter values (etc.)	**G10.3**

2.12 Epistemic uncertainties

[only required if **EPI_UNC** is non-zero]

EPISTEMIC

nE_IMv nE_EDPIM E_DSEDP E_LDS nE_PCIM E_LC E_corr

nE_IMv	The number of different IM-rate relationships in the logic tree. If epistemic uncertainties are not considered in the IM-rate relationship enter zero.	**I5**
nE_EDPIM	The number of different EDP|IM relationships in the logic tree. If epistemic uncertainties are to not considered in the EDP|IM relationship enter zero.	**I5**
E_DSEDP[1]	Consider epistemic uncertainties in the DS|EDP relationship?[2]	**I5**
E_LDS[1]	Consider epistemic uncertainties in the Loss|DS relationship?[2]	**I5**
nE_PCIM	The number of different PC|IM relationships in the logic tree. If epistemic uncertainties are to not considered in the PC|IM relationship enter zero.	**I5**
E_LC[1]	Consider epistemic uncertainties in the L|C relationship?[2]	**I5**
E_Corr[1]	Consider epistemic uncertainties in the L|DS and DS|EDP correlations?[3]	**I5**

Notes:

[1] Epistemic uncertainties in the DS|EDP, L|DS and L|C relationships are considered in continuous variable form and hence only a [0,1] indicator is required for these two fields (0=No, 1=Yes).

[2] Although the numerical algorithms have been developed, currently epistemic uncertainties in the library fragility functions are set to zero (lack of empirical data)

[3] Although the numerical algorithms have been developed, currently the correlation matrices for library fragility function epistemic uncertainties are set to the identity matrix (i.e. uncorrelated).

2.13 Repair Downtime

[only required if **DWNTIME** is non-zero]

The first lines relate to the mobilization time computation. That is, the time taken before repair work commences. [If **nDS_Mob**=0 then this is not required]

Note: Computation of the mobilization time in SLATv1.14 is not currently implemented

The second lines relate to the computation of repair group times. Repair groups are comprised of various performance groups and also have precursor repair groups which must be completed before the specific repair group can be repaired. [If **N_RG**=0 then this is not required]

RGROUP

For each of the **N_RG** repair groups the following lines are required:

RGi N_RGiprecurssor N_PG_RGi

RGi	The repair group number	**I5**
N_RGiprecurssor	The number of precursor repair groups for which repair must be completed before repair is commended for repair group **RGi**	**I5**
N_PG_RGi	The number of performance groups in repair group **RGi**	**I5**

The numbers of the precursor repair groups must be provided. Up to 10 repair group numbers may be provided per line. If there are more than 10 precurssor repair groups then use a second and subsequent lines as necessary. If **N_RGiprecurssor**=0 then do not supply line

RGpre_1 RGpre_2 ….. RGpre_10

RGpre_1, RGpre_2	The number of the repair group which must be completed before the particular repair group of concern can be commenced	**10I5**

The numbers of the performance groups which comprise the particular repair groups must be provided. Up to 10 performance group numbers may be provided per line. If there are more than 10 performance groups in a single repair group then use a second and subsequent lines as necessary. If **N_PG_RGi**=0 then do not supply line

RGpg_1 RGpg_2 ….. RGpg_10

RGpg_1, RGpg_2	The numbers of the performance groups which comprise the repair group	**10I5**

2.14 External data files

[only required if EDP_IM_data or IM_data is non-zero for any EDP's in **DEMAND** of IM's in **INTENSITY**]

DATA

For each external data file required for the analysis, the following lines are required:

DAT_LAB DAT_STR

DAT_LAB	The external data label identifier	**I5**
DAT_STR	The string name of the external file (including directory, if necessary) (maximum of 79 alphanumeric characters. Leave 3 spaces between the end of **DAT_LAB** and **DAT_STR**.	**a79**

2.15 Ranges for output data

OUTPUT

One line is required to state the number of IM and EDP ranges provided

N_IM_RNGE   N_EDP_RNGE   N_L_RNGE

N_IM_RNGE	Number of IMs to compute output for	**I5**
N_EDP_RNGE	Number of EDPs to compute output for	**I5**
N_L_RNGE	Set to one (“1”) if considering loss-hazard output, otherwise ‘0’	**I5**
N_RG_RNGE	Number of RGs to compute downtime output for	**I5**

OUTPUTIM

For each IM (from 1 to **N_IM_RNGE)** in ‘**INTENSITY**’ requires one line to specify what range of IM values to compute output with

IM_NUM   NIM   IM_MIN   IM_MAX

IM_NUM	The Intensity Measure (IM) identifier	**I5**
NIM[1]	Number of IM points between **IM_MIN** and **IM_MAX**	**G10.3**
IM_MIN	Minimum IM to calculate data for	**G10.3**
IM_MAX	Maximum IM to calculate data for	**I5**

OUTPUTEDP

For each EDP (from 1 to **N_EDP_RNGE)** in ‘**DEMAND**’ requires one line to specify what range of EDP values to compute output with

EDP_NUM   NEDP   EDP_MIN   EDP_MAX

EDP_NUM	The Engineering Demand Parameter (EDP) identifier	**I5**
NEDP[1]	Number of EDP points between **EDP_MIN** and **EDP_MAX**	**G10.3**
EDP_MIN	Minimum EDP to calculate data for	**G10.3**
EDP_MAX	Maximum EDP to calculate data for	**I5**

OUTPUTLOSS

For output of the global DIRECT loss hazard curve, one line is required to specify what range of direct loss values to compute the hazard curve with are to be used.

IM_NUM NL L_MIN L_MAX

IM_NUM	The Intensity Measure (IM) identifier	**I5**
NL[1]	Number of Loss points between **L_MIN** and **L_MAX**	**I5**
L_MIN	Minimum loss to calculate data for	**G10.3**
L_MAX	Maximum loss to calculate data for	**G10.3**

OUTPUTRGTIME

If downtime is also considered (i.e. **DWNTIME**=1) then each Repair group (RG) requires a line defining the range of down time values to compute the loss hazard for:

RG_NUM NL L_MIN L_MAX

RG_NUM	The repair group (RG) identifier	**I5**
NL[1]	Number of Loss points (in days) between **L_MIN** and **L_MAX**	**I5**
L_MIN	Minimum loss (in days) to calculate data for	**G10.3**
L_MAX	Maximum loss (in days) to calculate data for	**G10.3**

Notes:

[1] The interpolation of the values used between the maximum and minimum values specified for all cases are linear with one exception. The exception is when the end result will be some form of hazard curve (either ground motion - (i.e. IM), demand - (i.e. EDP), or loss-hazard) in which case the interpolation of the points is in logarithmic space.

3. External file data preparation

This section describes how to format any external data files which are required for the λ_{IM} or EDP|IM relationships.

External data files are prepared in a notepad or wordpad format. Make sure that if a commercial wordprocessor is used that data **do not contain tabs**. If a tab is present within the data file then when the program reads the file an error will occur. Finding this problem can be aided by inspecting the output file which will show how much of the external file was read before the error occurred.

3.1 Ground motion hazard (λ_{IM}) relationship

Line 1: title

Line 2: [**N_IMpoints form weight**]

N_IMpoints*:	number of IM points that data is given for	(i5)
form	format of data	(a20)
weight	epistemic uncertainty weight	(g10.3)

Line 3-(end): [**IM λ(IM)**]

IM:	a given IM value	(format as given by **form** above)
λ(IM):	**(**Annual) frequency of exceedance of **IM**	(")

***N_IMpoints:** must be 100 or less (storage limitation)

see the example below where there is an array of 16 IM values. The format label (2g9.3) states that there are 2 columns of data each with the format g9.3. Note that the brackets are required.

When multiple hypotheses are available (i.e. epistemic uncertainties), simply leave a space and then follow the same format as for the first set of data.

012345678901234567890123456789012345678901234567890 - this line is for reference and does not appear in the file

```
IM-Rate data for Wellington Sa=0.6seconds – epistemic 1
   16             (2G9.3)     0.500
      0.01  0.972943
      0.02  0.556384
      0.04  0.246854
      0.08  0.086953
      0.10  0.059516
      0.20  0.016204
      0.40    0.0041
      0.60  0.001688
      0.80  0.000751
      1.00  0.000342
      1.20  0.000155
      1.40  0.000073
      1.60  0.000035
```

```
         1.80  0.000017
         2.00  0.000009
         2.20  0.000004

IM-Rate data for Wellington Sa=0.6seconds – epistemic 2
   16             (2G9.3)       0.500
         0.01  0.972943
         0.02  0.556384
         0.04  0.246854
         0.08  0.086953
         0.10  0.059516
         0.20  0.016204
         0.40    0.0041
         0.60  0.001688
         0.80  0.000751
         1.00  0.000342
         1.20  0.000155
         1.40  0.000073
         1.60  0.000035
         1.80  0.000017
         2.00  0.000009
         2.20  0.000004
```

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3.2 Engineering demand parameter-intensity (EDP|IM) relationship

There are two types of external file for the EDP|IM relationship.

Type 1: 4 column format

Line 1: title
Line 2: [**N_IMpoints** **nDatRow** **form**]

N_IMpoints:	number of IM points that data is given for	(i5)
nDatRow	number of data in each row	(i5)
form	format of data	(a20)

Line 3-(end): [**IM** $\mu_{EDP|IM}$ $\sigma_{lnEDP|IM(A)}$ $\sigma_{lnEDP|IM(E)}$]

IM:	a given IM value	(format as given by **form** above)
$\mu_{EDP|IM}$:	Mean EDP for the given **IM** level	(")
$\sigma_{lnEDP|IM(A)}$:	(Aleatoric) lognormal standard deviation in **EDP|IM**	(")
$\sigma_{lnEDP|IM(E)}$:	(Epistemic) lognormal standard deviation in **EDP|IM**	(")

see the example below where there is an array of 18 IM values for which the mean and dispersion is defined. For 4 column format **nDatRow** always equals 4. The format label (4g9.4) states that there are 4 columns of data each with the format g9.4. Note that the brackets are required.

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```
CSMdata used for model development
   18     4              (4g9.4)
  1.00E-03  5.01E-07     0.4      0.3
  2.62E-02  1.82E-05     0.4      0.3
  5.15E-02  3.83E-05     0.4      0.3
  7.67E-02  5.94E-05     0.4      0.3
  0.102     8.12E-05     0.4      0.3
  0.1272    1.04E-04     0.4      0.3
  0.1525    1.26E-04     0.4      0.3
  0.1777    1.50E-04     0.4      0.3
  0.2029    1.73E-04     0.4      0.3
  0.2282    1.97E-04     0.4      0.3
  0.2534    2.21E-04     0.4      0.3
  0.2787    2.45E-04     0.4      0.3
  0.3039    2.70E-04     0.4      0.3
  0.3292    2.95E-04     0.4      0.3
  0.3544    3.19E-04     0.4      0.3
  0.3796    3.45E-04     0.4      0.3
  0.4049    3.70E-04     0.4      0.3
  0.4301    3.95E-04     0.4      0.3
```

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Type 2: Individual ground motion format

Line 1: title
Line 2: [**N_IMpoints nEDP|IM form weight**]

N_IMpoints*:	number of IM points that data is given for	(i5)
nEDP|IM	number of EDP points for each IM	(i5)
form	format of data	(a20)
weight	logic tree weight for EDPIM	(g10.3)

***N_IMpoints** must be less than 20 (storage requirement)

Line 3-(end): [**IM EDP|IM*(nEDP|IM)**]

IM:	a given IM value	(format as given by **form** above)
EDP|IM:	A single realization of an **EDP|IM** value	(")

see the example below where there is an array of 10 IM values for which the mean and dispersion is defined. For IDA format **nDatRow** is equal to the number of ground motions used per IM level (6 in this case). The format label (7g9.4) states that there are 7 columns of data (the IM value and 6 response values) each with the format g9.4.

0123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123 - this line is for reference and does not appear in the file

```
NZpierEDPdata. for NZ bridge pier – epistemic 1
   10     6              (7g9.4)     0.500
      0.1  1.52E-03  1.50E-03  1.50E-03  1.48E-03  1.46E-03  1.50E-03
      0.2  3.03E-03  3.00E-03  3.00E-03  2.95E-03  2.92E-03  2.99E-03
      0.3  4.55E-03  4.50E-03  4.49E-03  4.43E-03  4.38E-03  4.49E-03
```

```
        0.4  6.07E-03  6.00E-03  5.99E-03   5.90E-03  5.84E-03  5.98E-03
        0.5  7.94E-03  7.37E-03  7.38E-03   7.00E-03  7.40E-03  7.62E-03
        0.6  1.06E-02  8.32E-03  9.26E-03   7.89E-03  1.02E-02  8.74E-03
        0.7  1.38E-02  9.81E-03  1.07E-02   8.42E-03  1.11E-02  9.67E-03
        0.8  1.74E-02  1.30E-02  1.16E-02   9.06E-03  1.21E-02  1.06E-02
        0.9  2.02E-02  1.46E-02  1.24E-02   9.69E-03  1.35E-02  1.15E-02
        1.0  2.26E-02  1.71E-02  1.30E-02   1.03E-02  1.60E-02  1.24E-02
```

```
NZpierEDPdata. for NZ bridge pier – epistemic 2
    10      6                  (7g9.4)        0.500
        0.1  1.52E-03  1.50E-03  1.50E-03   1.48E-03  1.46E-03  1.50E-03
        0.2  3.03E-03  3.00E-03  3.00E-03   2.95E-03  2.92E-03  2.99E-03
        0.3  4.55E-03  4.50E-03  4.49E-03   4.43E-03  4.38E-03  4.49E-03
        0.4  6.07E-03  6.00E-03  5.99E-03   5.90E-03  5.84E-03  5.98E-03
        0.5  7.94E-03  7.37E-03  7.38E-03   7.00E-03  7.40E-03  7.62E-03
        0.6  1.06E-02  8.32E-03  9.26E-03   7.89E-03  1.02E-02  8.74E-03
        0.7  1.38E-02  9.81E-03  1.07E-02   8.42E-03  1.11E-02  9.67E-03
        0.8  1.74E-02  1.30E-02  1.16E-02   9.06E-03  1.21E-02  1.06E-02
        0.9  2.02E-02  1.46E-02  1.24E-02   9.69E-03  1.35E-02  1.15E-02
        1.0  2.26E-02  1.71E-02  1.30E-02   1.03E-02  1.60E-02  1.24E-02
```

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3.3 Probability of global collapse ($P_{C|IM}$) relationship

Line 1: title
Line 2: [**form** **weight**]

form	format of data	(a20)
weight	epistemic uncertainty weight	(g10.3)

Line 3: [**parameter1** **parameter2 …..etc**]
parameter1..etc: parameters of the moment-based analytical collapse fragility function

See the example below where the format label (2g10.3) states that there are 2 parameters each with the format g9.3. For a lognormal distribution the parameters are the mean (not median) and lognormal standard deviation. Note that the brackets are required.

When multiple hypotheses are available (i.e. epistemic uncertainties), simply leave a space and then follow the same format as for the first set of data. Note that the number of epistemic uncertainties in collapse should equal that for the structural response

012345678901234567890123456789012345678901234567890 - this line is for reference and does not appear in the file

```
Collapse IM data for a 10 storey structure using Sa(T1) – epistemic 1
                  (2G10.3)        0.500
       0.900        0.470

Collapse IM data for a 10 storey structure using Sa(T1) – epistemic 2
                  (2G10.3)        0.500
       0.900        0.470
```

012345678901234567890123456789012345678901234567890   - this line is for reference and does not appear in the file

4. Theory of SLAT

4.1 General Overview

The mathematical framework used in SLAT is based around the PEER-framework formula which, based on the theorem of total probability allows the computation of the mean annual frequency of exceedance of some decision variable (Deierlein *et al.* 2003):

$$\lambda(DV) = \iint \sum G(DV|DS)|\Delta G(DS|EDP)||dG(EDP|IM)||d\lambda(IM)| \qquad (1)$$

where IM = intensity measure (e.g. PGA); EDP = engineering demand parameter (e.g. peak interstorey drift); DS = damage state; DV = decision variable; $G(x|y) = G(X \geq x|Y=y)$ is the complementary cumulative density function (CCDF) of X given Y; $\lambda(z)$ is the annual frequency of exceeding z; $dG(x|y)$ and $d\lambda(z)$ are the differentials of $G(x|y)$ and $\lambda(z)$, respectively.

The key assumption of conditional independence allows the framing formula (Eq1) to be separated into four different relationships (which are typically solved by different expert personnel), and then these four relationships are integrated together to provide decision variables for stakeholders.

$\lambda(IM)$ is the ground motion hazard curve which typically describes the annual probability (or frequency) of exceeding some level of ground motion intensity measure (Kramer 1996).

$G(EDP|IM)$ is the CCDF of the EDP|IM relationship which describes the relationship between seismic demand and intensity. It can be determined in numerous ways, most rigorously by multiple non-linear dynamic analyses, but also by other simplified methods.

$G(DS|EDP)$ is the CCDF of the DS|EDP (fragility) relationship which describes the probability of different levels of damage for a given demand (Porter *et al.* 2007).

$G(DV|DS)$ is the CCDF of the DV|DS (loss) relationship which describes the distribution of losses and/or downtime to repair a damaged component or distribution of casualties (Aslani 2005, Mitrani-Reiser 2007)

4.2 Solution algorithms for equations solved within SLAT

4.2.1 Loss|EDP relationship

The loss|EDP relationship for a particular component is obtained by summing over all of the various damage states the loss given a certain damage state and the probability of that damage state for the given value of demand. In particular the first two moments of the loss|EDP relationship (mean and variance) can be computed by:

$$\mu_{L|EDP} = \sum_{i=1}^{N_{DS}} \mu_{L|DSi} P_{DSi|EDP} \qquad (2a)$$

$$\sigma^2_{L|EDP} = \mu_{L^2|EDP} - \left(\mu_{\mathrm{L|EDP}}\right)^2 = \sum_{i=1}^{N_{DS}} \left(\mu^2_{L|DSi} + \sigma^2_{L|DSi}\right) P_{DSi|EDP} - \left(\mu_{\mathrm{L|EDP}}\right)^2 \tag{2b}$$

where N_{DS} is the number of damage states; $\mu_{L|DSi}$ and $\sigma^2_{L|DSi}$ is the mean and variance, respectively, in the loss for the given damage state; $P_{DSi|EDP}$ is the probability of being in damage state *i* given EDP.

4.2.2 EDP hazard relationhip

The EDP hazard, λ_{EDP}, gives the annual frequency of exceeding various values of EDP, and is obtained by integrating together the ground motion hazard and the CCDF of the demand intensity (EDP|IM) relationship.

$$\lambda_{EDP} = \int G_{EDP|IM} \left| \frac{\lambda_{IM}}{dIM} \right| \mathrm{d}IM \tag{3a}$$

$$G_{EDP|IM} = G_{EDP|IM,NC}\left(1 - P_{C|IM}\right) + P_{C|IM} \tag{3b}$$

where λ_{IM} is the ground motion hazard curve; $P_{C|IM}$ is the probability of collapse given IM; $G_{EDP|IM,NC}$ is the probability of exceeding EDP given IM and no collapse. If collapse is not considered in the analysis then $P_{C|IM}$ is simply set to zero.

4.2.3 Collapse hazard relationship

The collapse hazard, λ_{C}, gives the annual frequency of collapse and is obtained by integrating the ground motion hazard with the probability of collapse given IM.

$$\lambda_C = \int P_{C|IM} \left| \frac{\lambda_{IM}}{dIM} \right| \mathrm{d}IM \tag{4}$$

4.2.4 Loss-IM relationship (individual component)

The Loss|IM relationship for a single component can be obtained by integrating together the loss|EDP and EDP|IM relationships. In particular the first two moments of this relationship can be found by:

$$\mu_{L_i|IM} = \int \mu_{L_i|EDP} f_{EDP|IM} \mathrm{d}EDP \tag{5a}$$

$$\sigma^2_{L_i|IM} = \mu_{L^2_i|IM} - \left(\mu_{\mathrm{L}_i|\mathrm{IM}}\right)^2 = \int \left(\mu^2_{L_i|EDP} + \sigma^2_{L_i|EDP}\right) f_{EDP|IM} \mathrm{d}EDP - \left(\mu_{\mathrm{L}_i|\mathrm{IM}}\right)^2 \tag{5b}$$

$$f_{EDP|IM} = -\frac{dG_{EDP|IM}}{dEDP} \tag{5c}$$

where $f_{EDP|IM}$ is the probability density function of the EDP|IM relationship.

4.2.5 Direct Loss-IM relationship (entire structure)

For the case of no collapse the loss|IM relationship for direct losses for the entire structure can be obtained by summing the direct repair losses to all of the individual components. The mean and variance of the total direct repair loss (given no collapse) can therefore be computed as:

$$\mu_{L_T|IM,NC} = \sum_{i=1}^{N_C} \mu_{L_i|IM} \tag{6a}$$

$$\sigma^2_{L_T|IM,NC} = \sum_{i=1}^{N_C}\sum_{j=1}^{N_C} \rho_{L_i|IM,L_j|IM}\sigma_{L_i|IM}\sigma_{L_j|IM} \tag{6b}$$

When collapse is considered the moments of the loss|IM relationship can be obtained from:

$$\mu_{L_T|IM} = \mu_{L_T|IM,NC}\left(1-P_{C|IM}\right)+\mu_{L_T|C}P_{C|IM} \tag{6c}$$

$$\begin{aligned}\sigma^2_{L_T|IM} = {} & \sigma^2_{L_T|IM,NC}\left[1-P(C\mid IM)\right]+\sigma^2_{L_T|C}P(C\mid IM) \\ & +\left(\mu_{L_T|IM,NC}-\mu_{L_T|C}\right)^2 P(C\mid IM)\left[1-P(C\mid IM)\right]\end{aligned} \tag{6d}$$

4.2.6 Downtime Loss-IM relationship (entire structure)

For the case of no collapse the loss|IM relationship for downtime for the entire structure can be obtained by defining repair groups (RG). A RG has two distinct parts: various PG's comprising the RG which must be repaired in a serial manner, and (ii) various other precursor repair groups which must be first completed, before work on the particular repair group may commence. Mathematically speaking the time to complete repairs in repair group *i* given IM, $L_{RG_i}|IM$, is given by:

$$L_{RG_i}|IM = \sum_{j=1}^{N_{PG,RG_i}} L_j|IM + \max_{j=1:N_{RG,pre}}\left[L_{RG_j}|IM\right] \tag{7a}$$

where N_{PG,RG_i} is the number of PG's in RG *i*; and $N_{RG_i,pre}$ is the number of precursory RG's for RG *i*. This definition of RG's as been comprised of various PG's as well as various precursor RG's has intentionally been made similar to typical Gantt chart construction scheduling software, such as Microsoft Project (Microsoft Project). As, generally speaking, analytical moments for Eq7 do not exist, Monte Carlo solution is used to determine these moments.

When collapse is considered the moments of the loss|IM relationship can be obtained from:

$$\mu_{L_{RG}|IM} = \mu_{L_{RG}|IM,NC}\left(1-P_{C|IM}\right)+\mu_{L_{RG}|C}P_{C|IM} \tag{7b}$$

$$\begin{aligned}\sigma^2_{L_{RG}|IM} = {} & \sigma^2_{L_{RG}|IM,NC}\left[1-P(C\mid IM)\right]+\sigma^2_{L_{RG}|C}P(C\mid IM) \\ & +\left(\mu_{L_{RG}|IM,NC}-\mu_{L_{RG}|C}\right)^2 P(C\mid IM)\left[1-P(C\mid IM)\right]\end{aligned} \tag{7c}$$

4.2.7 Annual loss relationships

The annual loss due to seismic events can be obtained by integrating together the ground motion hazard and the loss|IM relationships. In particular, the first two moments of the annual loss are:

$$\mu_{L_T} = \int \mu_{L_T|IM} f_{IM}\,\mathrm{d}IM \tag{8a}$$

$$\sigma^2_{L_T} = \mu_{L_T^2} - \left(\mu_{\mathrm{L_T}}\right)^2 = \int\left(\mu^2_{L_T|IM}+\sigma^2_{L_T|IM}\right)f_{IM}\,\mathrm{d}IM - \left(\mu_{\mathrm{L_T}}\right)^2 \tag{8b}$$

$$f_{IM} = \left|\frac{\lambda_{IM}}{dIM}\right| \tag{8c}$$

where the probability density for the ground motion occurrence in a single year has been obtained from the ground motion hazard based on the Poisson assumption.

4.2.8 Loss hazard relationship

The loss hazard, λ_{Lt}, gives the annual frequency of exceeding various values of loss in the structure and can be obtained by integrating together the ground motion hazard and the loss|IM relationship.

$$\lambda_{L_T} = \int G_{L_T|IM} \left| \frac{\lambda_{IM}}{dIM} \right| \mathrm{d}IM \tag{9a}$$

$$G_{L_T|IM} = G_{L_T|IM,NC}\left(1 - P_{C|IM}\right) + G_{L_T|C} P_{C|IM} \tag{9b}$$

See the example problems for further information and the references at the end of this section

4.3 Correlations

Correlations describe the tendency of (for example, two) random variables to display dependence in their realizations. For example, two random quantities which are positively (but not perfectly) correlated will tend to both produce larger than mean values at the same time (and conversely, smaller than mean values at the same time). More information on correlations can be found in any general Statistics text book. In SLAT, all correlations are person product-moment (linear) correlations.

Correlations can be of both aleatoric and epistemic in nature, and below all 8 different correlations which are included in SLAT are discussed below.

COR_LDS Aleatoric correlation for Loss|DS relationship between different components (i.e. $\rho_{L_{i'}|DS_i, L_{j'}|DS_j}$)

Aleatoric correlation in the loss-damage state (L|DS) relationship is due to the fact that the repair procedures of various (but different) components could be similar. In such cases, if the cost to repair one type or component is more expensive than predicted, it is likely that another component which requires similar repair methods will also cost above average. An example of this would be the cost to repair damage to a beam-column joint, and a column slab connection, which require similar repair methods.

COR_DSEDP Aleatoric correlation for DS-EDP relationship between different components (i.e. $\rho_{DS_{i'}|EDP_i, DS_{j'}|EDP_j}$)

Aleatoric correlation in the loss-damage state (L|DS) relationship is due to the fact that different components which are made of similar materials will likely be related interms of their fragility. For example a beam and a slab which are made from the same batch of concrete will likely be very highly correlated.

COR_EDPIM Aleatoric correlation for EDP|IM relationship between different demand parameters (i.e. $\rho_{EDP_{i'}, EDP_{j'}|IM}$)

Aleatoric correlation in the EDP|IM relationship is due to the dynamic behaviour of the structure which is exposed to the ground shaking. An example, in the case of a multi-storey building, it is likely that if a certain ground motion causes larger than average displacements on the 3rd floor, then the displacements on the second of forth floors will also be larger than average (i.e. a positive correlation), while the correlation between the 3rd and 20th floors is likely to be uncorrelated.

CORE_LDS Epistemic correlation for L-DS relationship within a single component (i.e. $\rho_{\mu L|DS_1,\mu L|DS_2}$)

Two options are available for the epistemic correlation of the Loss|DS relationship. There currently is not information in literature to quantify the correlation. However, as epistemic uncertainty in the Loss|DS relation would be due to different quotes given by different contractors there may be some correlation.

CORE_DSEDP Epistemic correlation for DS|EDP relationship within a component ($\rho_{\mu DS|EDP_1,\mu DS|EDP_2}$)

Three options are available for the epistemic correlation of the Loss|DS relationship. Bradley (2009) discusses how this can be determined for individual fragility functions

It should be noted that currently as epistemic uncertainties in the seismic hazard, structural response and collapse are considered in a logic tree fashion then epistemic correlations are directly accounted for in this case.

4.4 Integration methods

The probabilistic nature of the governing loss estimation equations means that integrations are required to be performed over the entire domain of the random variables. In SLAT aleatory and epistemic uncertainties are treated and propagated separately, and therefore options on integrations are separate for the two.

4.4.1 Aleatory integrations

Aleatory integrations are required to solve the PEER equation in its form given in Eq1. The integrations can be performed using numerical integration algorithms, or using simplified first-order accurate methods.

Bradley *et al.* (2009) propose a Magnitude-oriented Adaptive Quadrature (MAQ) for the specific purpose of computing the integrals within the PEER framing formula. The method is an extension of the adaptive quadrature and Romberg integration methods, and was shown to be significantly more efficient (computationally) at evaluating the required integrals. Further information can be found in this reference. In particular note that the limits of integration are not required to be defined within the input file and are determined within the program. Therefore only the error tolerance and maximum number of function evaluations are required.

Using a first order accurate Taylor-series for each of the random variables determined via integration, Baker and Cornell (2008) propose the use of the FOSM method for solution of the PEER framing equations. The FOSM method is computationally efficient in the sense that the integrals are replaced with single equations to be evaluated. Care should be taken however to ensure that the second-order effects (which are neglected) are insignificant, which is primarily related to the standard deviation in the random variables. Despite this restriction, the FOSM method may be used in some cases as an 'order-of-magnitude' estimate. The accuracy of the FOSM method for a particular structure can be found in Bradley and Lee (2009)

4.4.2 Epistemic integrations

Epistemic integrations are required when epistemic uncertainties are introduced into the PEER framing equations. Currently, SLAT employs a monte carlo simulation framework to generate realizations of all the epistemic uncertainties and solve the integral equations.
In the seismic hazard and structural and collapse analysis (i.e. λ_{IM}, EDPIM and PCIM), epistemic uncertainties are given in the form of alternative models with various weights (i.e. logic trees). This is adopted to ease the determination of the complex epistemic correlation structure within these relationships. Uniformly distributed random numbers are used to determine which end node of the logic tree is used in each simulation
The fragility and loss models (i.e. DSEDP, LDS, and L|C) use a continuous variable formulation. In this case uncorrelated normal random numbers are generated for all of the different components which are defined in the performance groups. Epistemic correlation between the parameters within a particular component are accounted for by multiplying the uncorrelated standard normal random numbers but the Cholesky decomposition of the epistemic correlation matrix.
For those parameters above whose epistemic uncertainty is considered in continuous variable form two values are typically supplied. These are the "uncertainty in the mean of lnX|Y' and the 'uncertainty in the variance of lnX|Y'. The term 'uncertianty' is referring to the standard deviation. The reason lnX|Y (as opposed to X|Y) is given is that then the distribution can be assumed normal for both meanlnX|Y and varlnX|Y based on asymptotic probability theory.
Finite sample uncertainty in the EDPIM relationship is not currently considered. The developer recommends performing this in a pre-processing fashion.

4.4.3 Relative Errors of integration

The relative errors of integration describe the relative error at which the integral is deemed to converge. For the aleatory correlations using the MAQ algorithm, this will affect the discretization size of the integrations over the random variable domains, whereas for the FOSM method (for both aleatory and epistemic uncertainties) the relative error given is not used (i.e. there is no guarantee that the answer will be to the accuracy given, and in most cases it wont be). Using the monte-carlo simulation for epistemic uncertainties, the relative error controls the convergence of the monte-carlo process (i.e. if the relative error is achieved before the maximum number of iterations, then the simulation will terminate) convergence in the number of MC simulations for epistemic uncertainty is currently not implemented. The error in the aleatory uncertainty computation is bounded by 0.1% (i.e. if a tolerance above this is given it is reduced to 0.1%).

4.4.4 Maximum number of function evaluations

The maximum number of function evaluations for aleatory uncertainty (when using MAQ) is required to limit the number of computations performed. This will likely be exceeded when the value of a particular integral is near-zero or if the relative error for convergence is small.

As a general rule of thumb, for the MAQ algorithm it was found that for REL_TOL=1e-3 then AMAXITS=300 is sufficient, while for REL_TOL=1e-4, AMAXITS should be set to about 450. If the maximum number of function evaluations is exceeded then a warning message will be printed to the output file (and screen).
The number of function evaluations for the monte-carlo simulation of epistemic uncertainties describes the number of simulations to perform.

4.5 Output plotting

This indicators describe the type of analyses to carry out. The first input line asks for output of the data which is input into the analysis, and it is recommended to new users that these be the only output values initially, which should be checked to match the desired input. The second line describes output which is computed by the use of solving the governing integrals. The range of values of the output is defined in the **output ranges** section of the input file.

4.6 Intensity Measure – rate of exceedance (IM-R) relationship

The λIM relationship describes the exceedance frequency of a particular ground motion parameter IM.. The IM may be PGA,PGV,S_a etc. The rate is given interms of the (annual) frequency (or probability) of exceedance

In SLAT there are several methods in which the IM-R relationship may be prescribed (all of which are a scalar format), which may broadly be described as parametric or non-parametric.

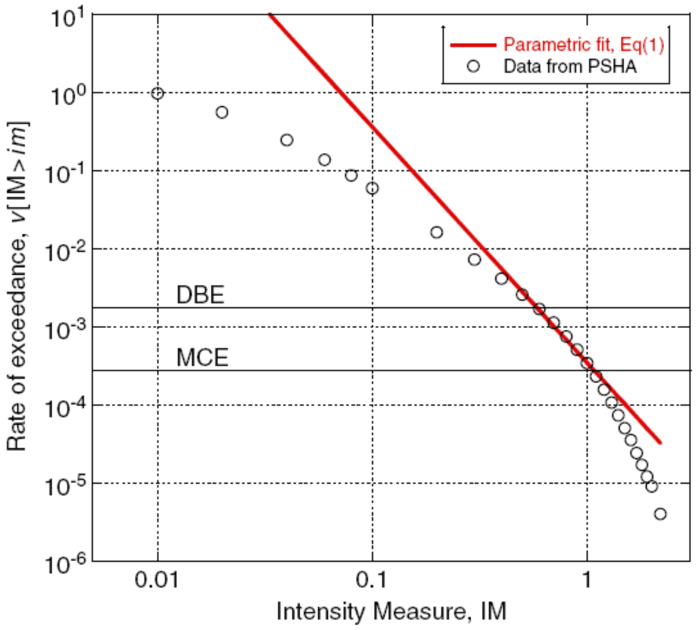
4.6.1 Non-parametric:

Raw data can be either given in the form of a 3 column array.

4.6.2 Parametric:

Power model
Parameters [k_0 k]
Formulation $v[im] = k_0 IM^{-k}$;

This figure is primarily used as it can give a closed-form solution for the demand, or loss hazard. It should not be used in general however as it will over approximate the hazard outside the region of interest significantly.

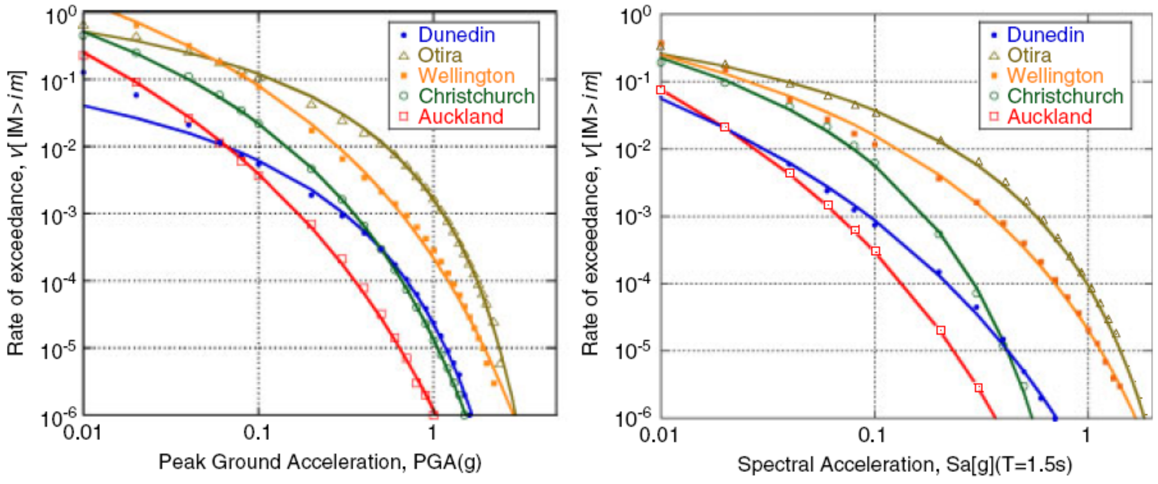


<u>Hyperbolic model</u>

Parameters [ν_{asy} IM_{asy} α]

Formulation $$\nu[im] = \nu_{asy}\exp\left[\frac{\alpha}{\ln\left(im/IM_{asy}\right)}\right];$$

This model was proposed by Bradley *et al.* (2007), as an improvement to the power model above. It has curvature in the log-log space and therefore captures the true hazard curve more accurately.



4.7 Engineering demand parameter-intensity (EDP|IM) relationship

The EDP|im relationship describes the variation in seismic demand on a structure as a function of the level of intensity. The EDP is the measure of seismic demand which may be the interstorey drift, floor acceleration etc. The IM is the measure of ground motion intensity and may take the form of Sa, PGA, PGV, S_i etc.

In slat there are several methods in which the EDP|IM relationship may be prescribed (all of which are a scalar format), which may broadly be described as parametric or non-parametric.

4.7.1 Non-parametric:

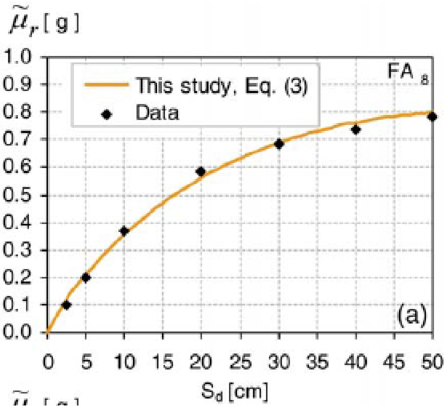
Raw data can be either given in the form of a 4 column array or IDA format.

4.7.2 Parametric mean:

Power model
Parameters [a b]
Formulation $\mu_{EDP|IM} = aIM^{b}$;
Figure showing plot of this rule
reference

Hyperbolic model
Parameters [a b]
Formulation $\mu_{EDP|IM} = \dfrac{aIM}{1-bIM}$
Figure showing plot of this rule
A is the initial stiffness and 1/b is the maximum intensity
reference

Aslani model
Parameters [α_1 α_2 α_3]
Formulation $\mu_{EDP|IM} = \alpha_1(\alpha_2)^{IM}[IM]^{\alpha_3}$



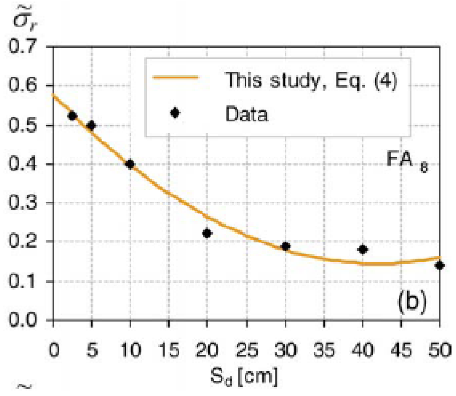
4.7.3 Parametric Dispersion

Power model
Parameters [a b]
Formulation $\sigma_{\ln EDP|IM} = aIM^{b}$
Figure showing plot of this rule
reference

Parabolic model

Parameters [$\beta_1\,\beta_2\,\beta_3$]

Formulation $\sigma_{\ln EDP|IM} = \beta_1 + \beta_2\left(IM\right) + \beta_3\left(IM\right)^2$



4.8 User-defined fragility functions

User-defined fragility functions are used to define fragility and loss functions which are not currently built-in to the SLAT library. As every endeavor is made to keep the SLAT database up-to-date, then it is envisaged that the user-defined fragility functions will be used to model miscellaneous components in a relatively crude manner. As such the input options for the user defined fragility functions are simplified in some senses compared to those built into the SLAT library (e.g. it is assumed that epistemic correlations between the mean values of each of the damage states is perfect). If you have any fragility functions which you would like to see incorporated into the SLAT library please contact the developers at the address given on the second page.

4.9 Performance group data

Performance groups are defined as a group of components (with the same loss and fragility) which are subjected to the same demand variable (i.e. all the beam column joints on the 4th floor of a structure, which are subjected to the 4th floor drift demand). These components are grouped as they will likely incur the same levels of damage, and thus if repaired the unit cost to repair each component will depend on the number of items to repair (with unit cost reducing as the number of items increases).

4.10 Global collapse

The case of global collapse is treated as a separate entity in the loss analysis for several reasons. In the case of no collapse the total loss to the structure is defined as the summation of losses to individual components within the building. However, for the case of global collapse, despite some components not being damaged, it is likely that the entire building will be demolished, and thus the cost to repair the entire building will be incurred.

Global collapse is defined via a lognormal collapse fragility curve (future editions of SLAT will allow for a non-lognormal fragility curve), which allows for both aleatory and epistemic uncertainties.

Global collapse for most structures is defined by side-sway collapse (inevitably due to significant P-delta effects, and reducing lateral capacity). However, for older non-ductile structures, shear failures which cause loss of vertical carrying capacity can also be a significant contributor toward global collapse. Failure mechanisms such as loss of vertical carrying capacity can be significant in older (non-ductile) structures and should be accounted for (either explicitly in dynamic analysis, or implicitly by post-processing the structural analysis results).

4.11 Limitations and future developments

It is noted that while Equation 1 is in terms of rates, SLAT can solve the time-dependent problem in terms of probabilities. In this case, simply use $\lambda(IM)$ to be the probability of exceeding the given ground motion IM for a specified time period. Then all of the outputs, $\lambda(z)$, now represent the probability of excceding z in the given time period.

The above statement takes into account the time dependence of the ground motion, but still assumes that the building is fully repaired to its original state following each event. Thus, currently the program cannot consider aftershock effects. This is a current research area

If large damage occurs in a region caused by an earthquake the high demand for repair typically causes an increase in the cost of materials (supply vs. demand) and is referred to as loss amplification. Such features are not currently accounted for due to a lack models for such phenomena.

Human injuries are not currently considered, but will be available in the future versions.

SLAT current considers only the ground motion shaking at a single site. There is potential to extend it to handle spatially distributed problems such as transportation networks. Currently it is best to use SLAT to obtain the loss|IM relation for a structure and then post-process to account for spatially distributed ground motion and the causes of downtime in the system etc.

While SLAT can consider epistemic uncertainties in the DSEDP and LDS relationships, there is a lack of data to determine these values and their correlations. This is currently an active research topic, and short term estimates are being developed.

Determination of correlations in the DSEDP and LDS relationships is difficult due to a lack of knowledge and empirical data. Future versions of SLAT will allow the correlation coefficients to have epistemic uncertainty so that this lack of knowledge can be explicitly modeled.

4.12 References:

Aslani, H., 2005. Probabilistic earthquake loss estimation and loss disaggregation in buildings, Stanford University, Stanford, CA, 382pp.

Aslani, H. and Miranda, E., 2005a. Fragility assessment of slab-column connections in existing non-ductile reinforced concrete buildings. *Journal of Earthquake Engineering* **9**, 777–804.

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Baker, J. W. and Cornell, C. A., 2008. Uncertainty propagation in probabilistic seismic loss estimation. *Structural Safety* **30**, 236-252.

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Bradley, B. A., Dhakal, R. P., Cubrinovski, M., Mander, J. B. and MacRae, G. A., 2007. Improved seismic hazard model with application to probabilistic seismic demand analysis. *Earthquake Eng. Struct. Dyn.* **36**, 2211-2225.

Bradley, B. A. and Lee, D. S., 2009. Correlations in structure-specific seismic loss estimation. *Earthquake Eng. Struct. Dyn.*

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Cornell, C. A., Jalayer, F., Hamburger, R. O. and Foutch, D. A., 2002. Probabilistic basis for 2000 SAC federal emergency management agency steel moment frame guidelines. *Journal of Structural Engineering* **128**, 526–533.

Deierlein, G. G., Krawinkler, H. and Cornell, C. A., 2003. A framework for performance-based earthquake engineering, *7th Pacific Conference on Earthquake Engineering*, Christchurch, New Zealandpp.

Kramer, S. L., 1996. *Geotechnical Earthquake Engineering*, Prentice-Hall, Upper Saddle River, NJ., 653pp.

Mackie, K. R. and Stojadinovic, B., 2007. Performance-based seismic bridge design for damage and loss limit states. *Earthquake Eng. Struct. Dyn.* **36**, 1953-1971.

Microsoft Project, http://en.wikipedia.org/wiki/Microsoft_Project.

Mitrani-Reiser, J., 2007. An Ounce of Prevention: Probabilistic Loss Estimation for Performance-based Earthquake Engineering, California Institute of technology, Pasadena, CA, 173pp.

Porter, K., Kennedy, R. and Bachman, R., 2007. Creating Fragility Functions for Performance-based Earthquake Engineering. *Earthquake Spectra* **23**, 471-489.

5. postSLAT

postSLAT is a program developed for extracting the output from SLAT which is contained in the binary output file.

5.1 Running the program

The program is run in interactive mode. To run the program double click on the executable file postSLAT.exe. The program will prompt the user for the output file name from SLAT.exe.

The program then prompts for the user to select what type of output they request, other details and the name of the output file to write to. Should the user select an output type which was not computed in the SLAT analysis, postSLAT will simply write an error message noting that this option was not computed in the SLAT analysis.

postSLAT allows output of the results of the analysis, as well as output of the input data used in the analysis. Inexperienced users in particular should therefore check that the data which was input to the analysis has been correctly interpreted by the program.

The best illustration of the capabilities of postSLAT can be found via the example programs given in the following section

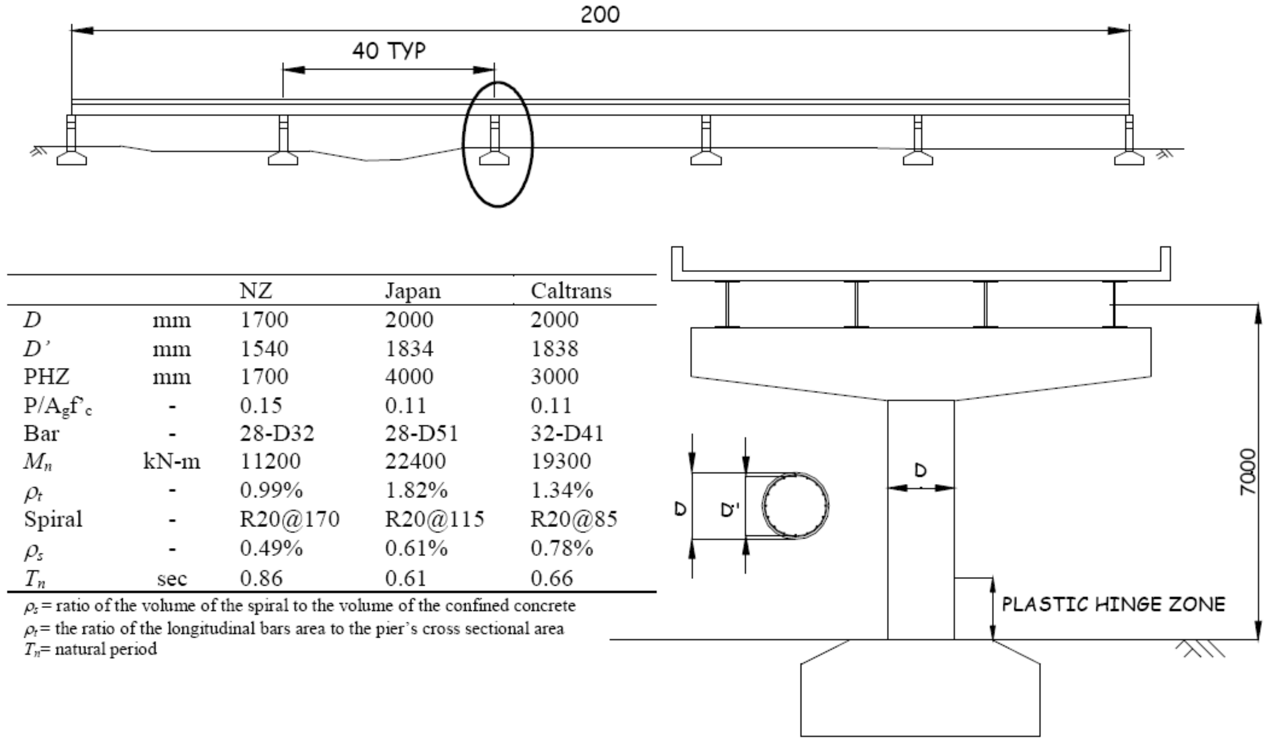
6. Example problems

6.1 Overview

The purpose of this section is to illustrate to beginning users some examples of input files for standard problems. The problems have been designed in increasing order of complexity, so readers should start at the first example and progress as their familiarity with the program increases.

6.2 Example 1: New Zealand highway bridge

Consider the bridge structure in the figure below which is a typical New Zealand highway bridge.



		NZ	Japan	Caltrans
D	mm	1700	2000	2000
D'	mm	1540	1834	1838
PHZ	mm	1700	4000	3000
$P/A_g f'_c$	-	0.15	0.11	0.11
Bar	-	28-D32	28-D51	32-D41
M_n	kN-m	11200	22400	19300
ρ_t	-	0.99%	1.82%	1.34%
Spiral	-	R20@170	R20@115	R20@85
ρ_s	-	0.49%	0.61%	0.78%
T_n	sec	0.86	0.61	0.66

ρ_s = ratio of the volume of the spiral to the volume of the confined concrete
ρ_t = the ratio of the longitudinal bars area to the pier's cross sectional area
T_n = natural period

Figure 8.1: Highway bridge used in example 1

6.2.1 Ground motion hazard

The bridge is assumed to be located in Christchurch, New Zealand, and the ground motion hazard curve in Figure 8.2 gives the exceedance rates of various levels of peak ground acceleration likely to occur at the site of the bridge. This hazard curve is parameterized using the hyperbolic model (see theory for details). Epistemic uncertainties in the hazard model are not considered

The parameters of these models for this problem are:

Hyperbolic model: $v[im] = v_{asy} \exp\left[\dfrac{\alpha}{\ln\left(im / IM_{asy}\right)}\right]$

$v_{asy} = 1221$; $IM_{asy} = 29.8$; $\alpha = 62.2$

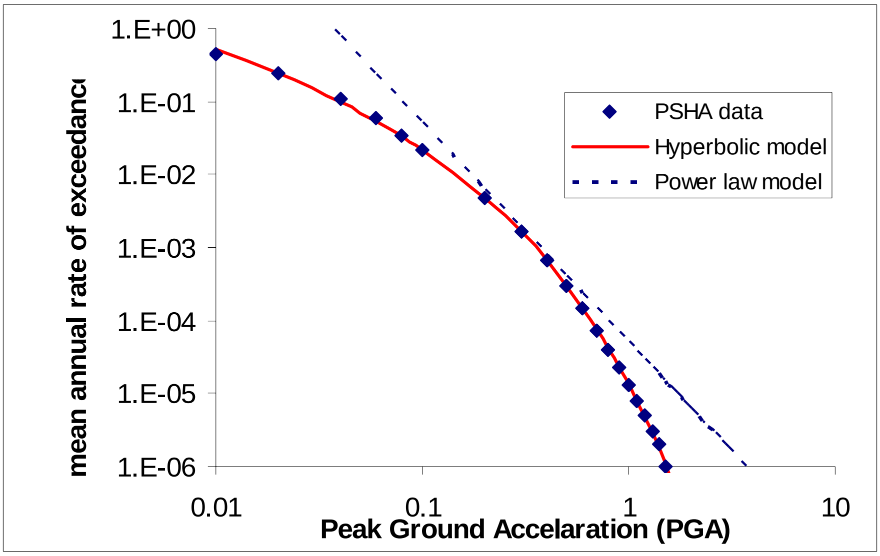


Figure 8.2: Ground motion hazard used in example 1.

6.2.2 Structural response

In this example earthquake induced ground motion shaking is assumed to occur in the transverse direction of the bridge. If the restraining effects of the abutments are ignored, then it is reasonable to consider the transverse vibration of the bridge analogous to that of a single degree of freedom oscillator.

Based on the mass and stiffness of the bridge pier shown in Figure 8.1 the capacity spectrum method is used to determine an approximate relationship for the seismic response (measured in terms of the deck drift) relative to the seismic intensity (PGA), this approximate relationship is then approximated by a power model with the following parameters

mean

Power model: $\mu_{EDP|IM} = aIM^{b}$;

a = 0.1; b = 1.5

dispersion (aleatory)

Power model: $\sigma_{\ln EDP|IM} = aIM^{b}$;

a = 0.5; b = 0.0

That is the aleatory uncertainty is assumed to be a constant (i.e. independent of IM) value of 0.5 (epistemic uncertainty is not possible using parametric relationships). The EDP|IM curve is shown in Figure 8.3

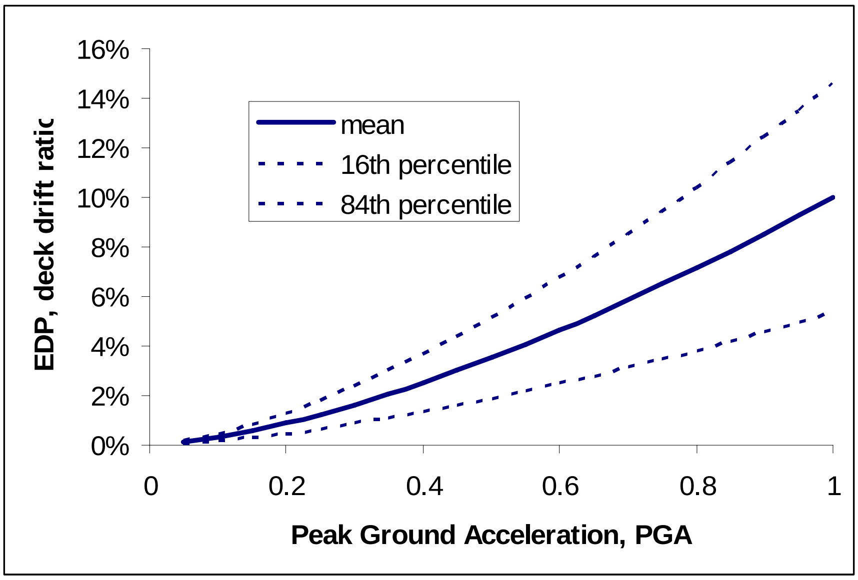


Figure 8.3: EDP|IM relationship for example 1.

6.2.3 Damage and loss estimates

In this example on the direct costs are assumed for damage to the bridge (and not casualties or asset downtime). Table C1 gives the four different damage states (no damage is not considered as a damage state) used (NZ drift limits used) and the corresponding loss ratios (the bridge has a replacement value of NZ$1 Million). The drift limits in Table 8.1 give the mean EDP values for the damage states. It is assumed that a dispersion of 0.4 is the aleatory uncertainty in each of the four damage states, and also in all of the loss values. Again, epistemic uncertainties are not considered in the damage or loss functions.

As this function has been developed for the purpose of this example then it will be entered as a user defined function within the input file.

Table 8.1: damage and loss estimates for the example bridge

	Damage State	*Failure Mechanism*	*Repair required*	*Outage*	*Drift Limit (%)*			*Loss Ratio (%)*
					NZ	*Japan*	*Caltrans*	
DS1	None	Pre-Yielding	None	None	--	--	--	0
DS2	Minor/Slight	Minor spalling	Inspect, Patch	< 3 days	0.62	0.53	0.53	3
DS3	Moderate	Bar buckling	Repair components	< 3 weeks	2.30	1.60	1.90	8
DS4	Major/Extensive	Bar fracture	Rebuild components	< 3 months	4.40	4.60	5.10	25
DS5	Complete/ Collapse	Collapse	Rebuild structure	> 3 months	5.64	5.66	6.16	100

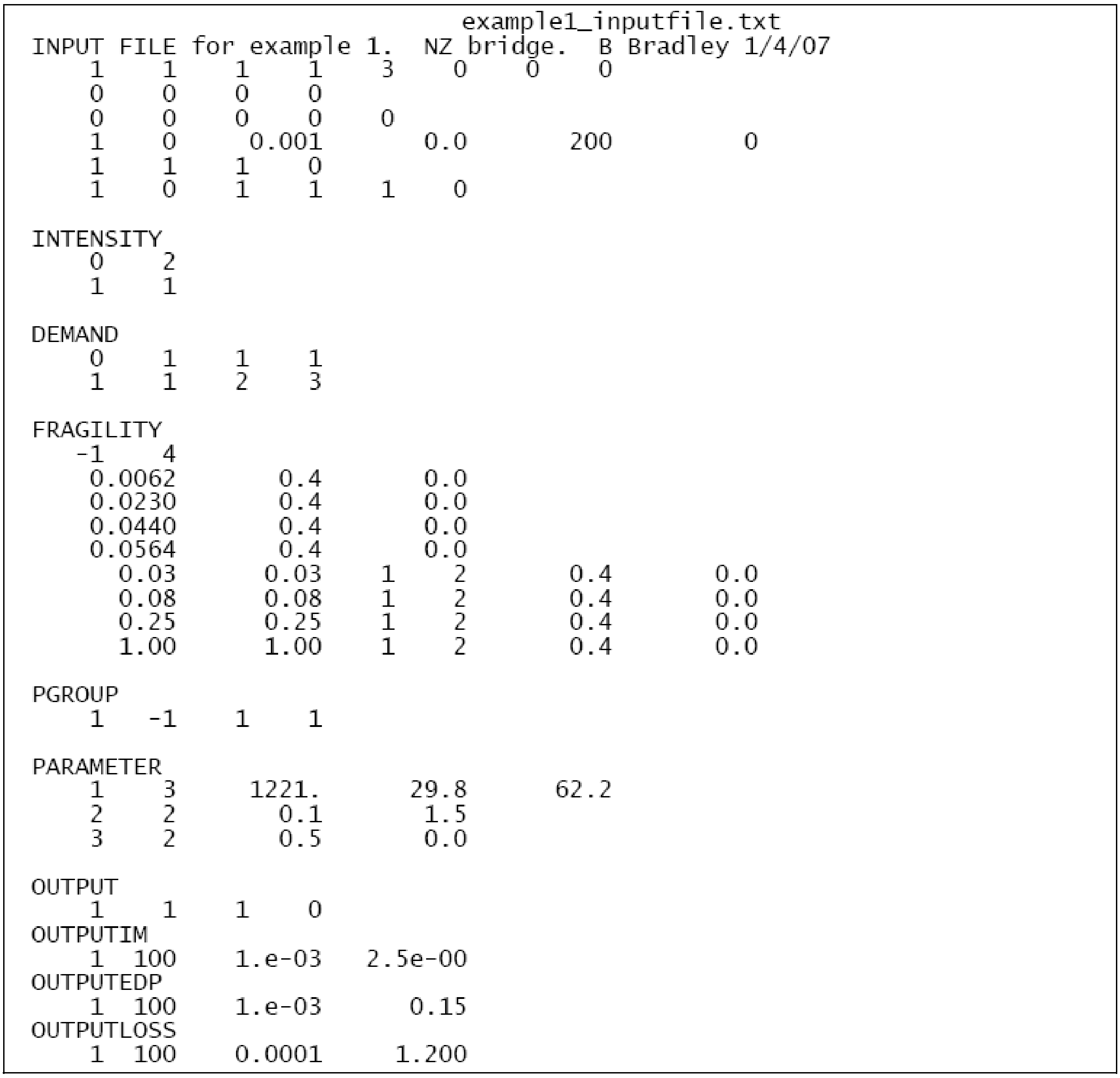
6.2.4 Additional information

To keep this problem simple the occurrence of collapse is neglected, and epistemic uncertainties and deaggregation are not performed. As there is only a single component representing the behaviour of the entire system then there is no need for any correlations to be defined.

The MAQ algorithm will be used for performing the integration with an error tolerance of 0.001 and a maximum of 200 function evaluations for each integration.
Outputs of the Loss|EDP, vEDP, Loss|IM, EAL, and vL data is requested.

6.2.5 The input file

Based on the data given in the previous problem description the input file prepared for SLAT is shown in Figure 8.4 below.

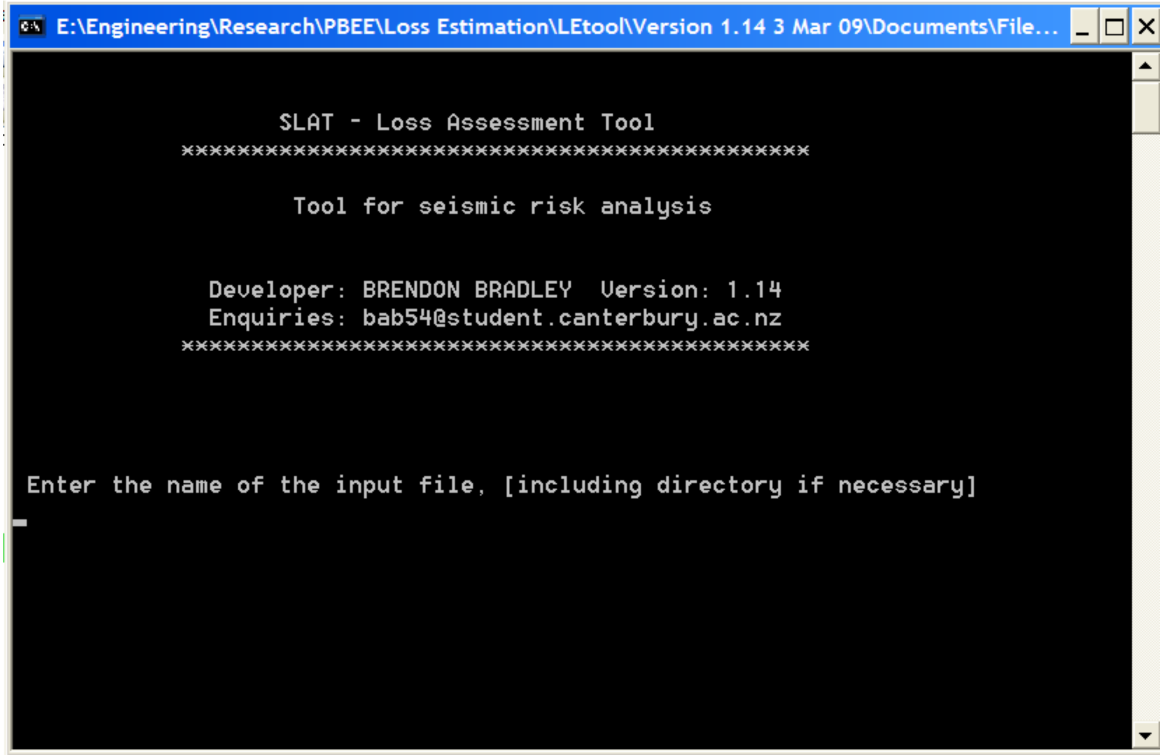


```
                              example1_inputfile.txt
INPUT FILE for example 1.  NZ bridge.  B Bradley 1/4/07
    1    1    1    1    3    0    0    0
    0    0    0    0
    0    0    0    0    0
    1    0     0.001      0.0       200         0
    1    1    1    0
    1    0    1    1    1    0

INTENSITY
    0    2
    1    1

DEMAND
    0    1    1    1
    1    1    2    3

FRAGILITY
   -1    4
    0.0062       0.4       0.0
    0.0230       0.4       0.0
    0.0440       0.4       0.0
    0.0564       0.4       0.0
      0.03      0.03    1    2       0.4       0.0
      0.08      0.08    1    2       0.4       0.0
      0.25      0.25    1    2       0.4       0.0
      1.00      1.00    1    2       0.4       0.0

PGROUP
    1   -1    1    1

PARAMETER
    1    3     1221.      29.8      62.2
    2    2       0.1       1.5
    3    2       0.5       0.0

OUTPUT
    1    1    1    0
OUTPUTIM
    1  100    1.e-03   2.5e-00
OUTPUTEDP
    1  100    1.e-03      0.15
OUTPUTLOSS
    1  100    0.0001     1.200
```

Figure 8.4: Input file for example 1

6.2.6 Running the program

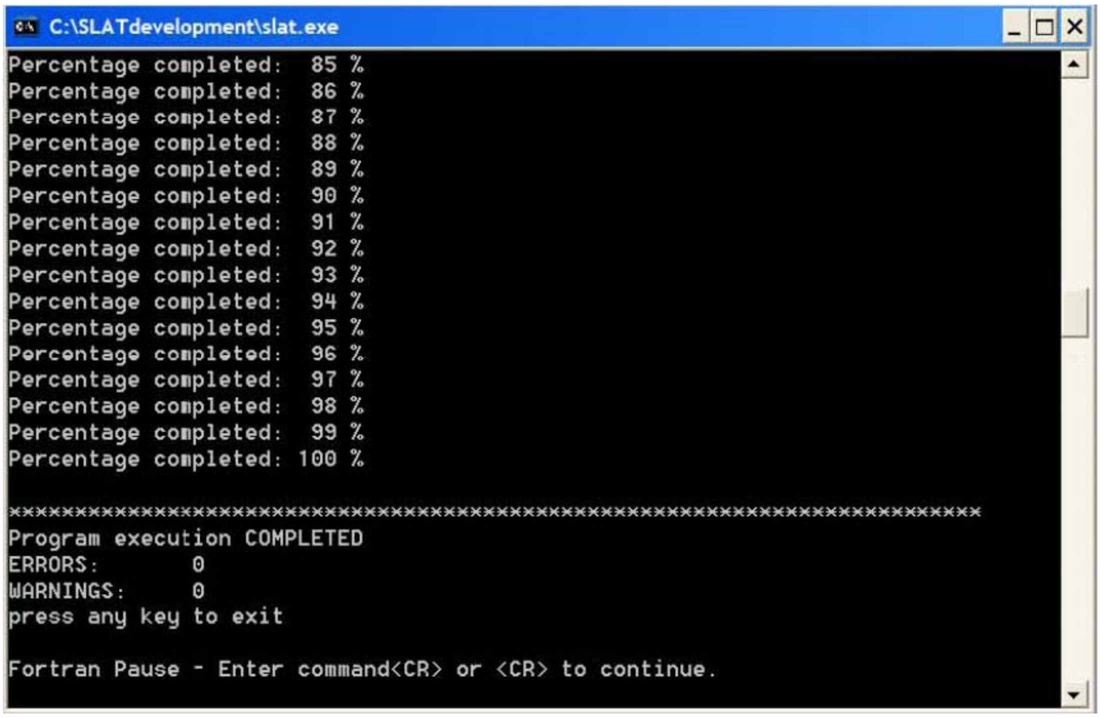
Figure 8.5 illustrates the view that should be observed when initiating the SLAT program. Here we have named the input file as “example1_inputfile.txt”, and the output file as “outputfile1_inputfile.txt”.
The program then carries out the analysis and displays the progress.



```
              SLAT - Loss Assessment Tool
          *********************************************

               Tool for seismic risk analysis


          Developer: BRENDON BRADLEY  Version: 1.14
          Enquiries: bab54@student.canterbury.ac.nz
          *********************************************



 Enter the name of the input file, [including directory if necessary]
```

Figure 8.5: Initial screen shown when the SLAT tool is opened

Once the program is completed successfully the statement “Program execution COMPLETED” will be displayed with the number of errors and warnings also indicated (Figure 8.6). This is the end of running SLAT. A summary of the results of the analysis are written to the output file (the name of which was defined in the SLAT window). Extraction the detailed results must be completed using the program postSLAT.

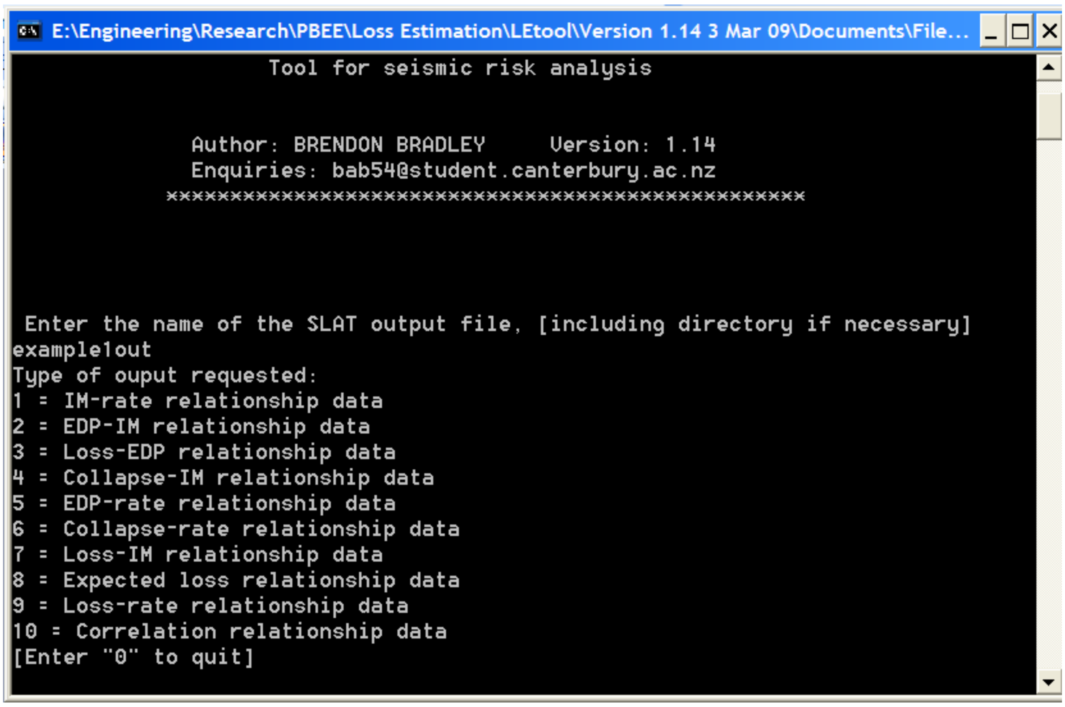


```
Percentage completed:  85 %
Percentage completed:  86 %
Percentage completed:  87 %
Percentage completed:  88 %
Percentage completed:  89 %
Percentage completed:  90 %
Percentage completed:  91 %
Percentage completed:  92 %
Percentage completed:  93 %
Percentage completed:  94 %
Percentage completed:  95 %
Percentage completed:  96 %
Percentage completed:  97 %
Percentage completed:  98 %
Percentage completed:  99 %
Percentage completed: 100 %

*************************************************************************
Program execution COMPLETED
ERRORS:        0
WARNINGS:      0
press any key to exit

Fortran Pause - Enter command<CR> or <CR> to continue.
```

Figure 8.6: View of the SLAT window once the program has executed successfully

6.2.7 Running postSLAT to get output data

Once the execution of SLAT is completed the results of the analysis are written to a binary file which is opened by the post-processor program postSLAT. When initiating postSLAT the user will be asked to enter the name of the binary output file. Note that response entered by the user should not contain the binary extension ".bin". Once the binary file is read the following options shown in Figure 8.7 will appear.



```
                    Tool for seismic risk analysis


              Author: BRENDON BRADLEY     Version: 1.14
              Enquiries: bab54@student.canterbury.ac.nz
            **************************************************




 Enter the name of the SLAT output file, [including directory if necessary]
example1out
Type of ouput requested:
1  = IM-rate relationship data
2  = EDP-IM relationship data
3  = Loss-EDP relationship data
4  = Collapse-IM relationship data
5  = EDP-rate relationship data
6  = Collapse-rate relationship data
7  = Loss-IM relationship data
8  = Expected loss relationship data
9  = Loss-rate relationship data
10 = Correlation relationship data
[Enter "0" to quit]
```

Figure 8.7: Option window in postSLAT

Depending on the type of analysis and results computed some of the available types of output may not be applicable. If a user selects one such option the program will prompt the user that the option is not available and return to the main option screen.

For beginning users the first thing that should be checked is that the input data which was described in the SLAT input file has been correctly entered/interpreted. For the analysis run in this example this can be done by retrieving output types 1-3 (note that currently there is not separate relationships for L-DS and DS-EDP, and therefore the damage and loss data is summarised as L-EDP curves).

6.2.8 Outputs of analysis

We will proceed with presenting the results of the analysis in the order of the type of output available as shown in Figure 8.7.

The loss|EDP relationship

The loss|EDP relationship is obtained by summing over all the damage states the loss due to the given damage state and likelihood of the damage state for the given level of EDP (see equation 2). Figure 8.8 illustrates the output of the loss|EDP relationship for example 1. The results have been presented in two forms. In the first, the mean and standard deviation of the loss|EDP relationship are given, while the second shows the mean and ±1 standard deviation curves. Note that standard deviation in SLAT is output in terms of the standard deviation in the logarithm of the variable since it is generally assumed that the variables are lognormally distributed. In such case the standard deviation of the non-logarithm can be determined from Equation xx which is repeated here also:

$$\sigma_x = \mu_x \sqrt{\exp\left(\sigma_{\ln x}^2\right) - 1} \qquad \text{(D1)}$$

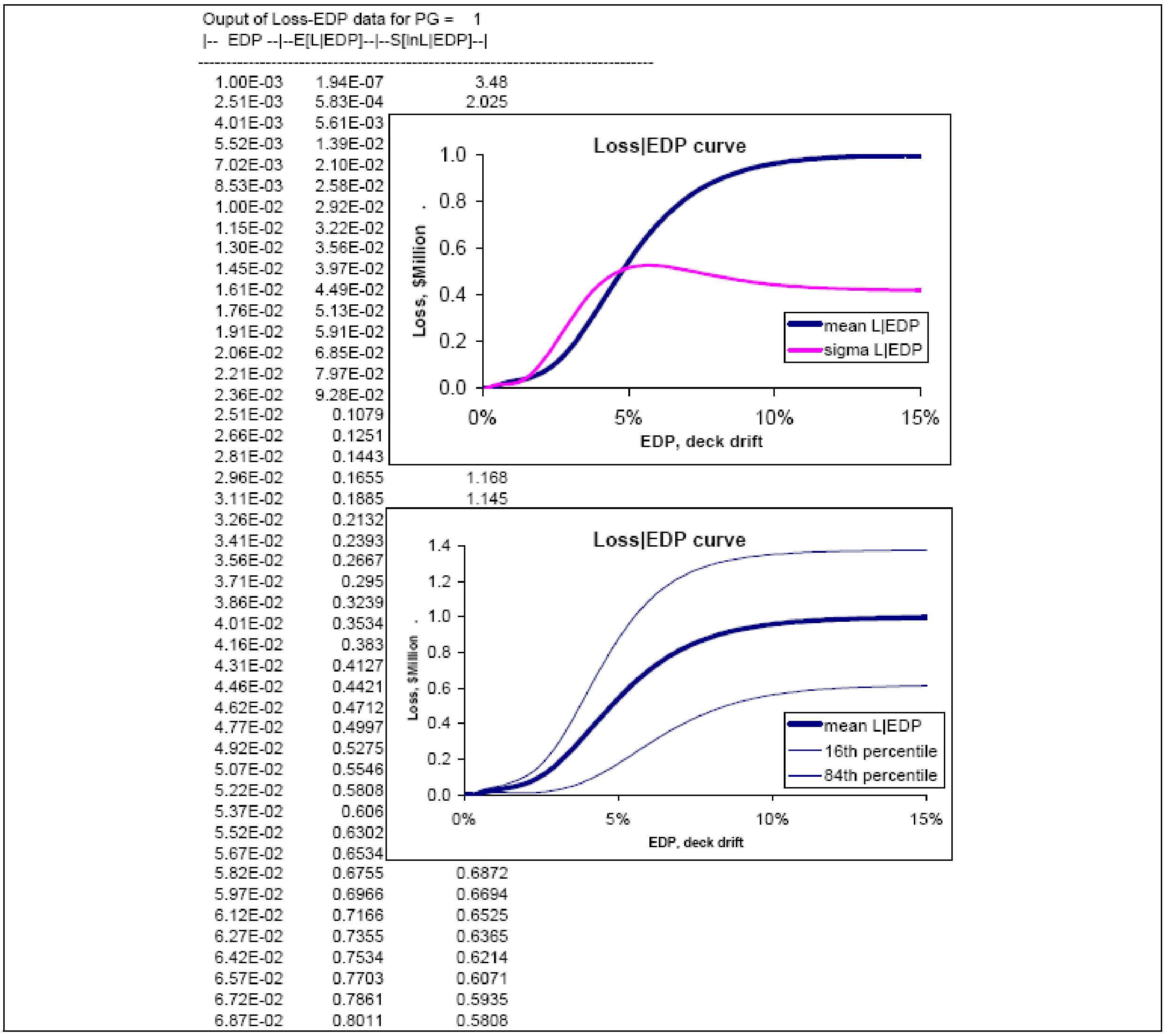
Where mux is the mean of x (non-logarithm form) sigmalnx is the logarithmic standard deviation and exp() is the exponential function

Assuming a lognormal distribution the various percentiles of the distribution can be obtained from Equation xx which is repeated here also:

$$x_{p\%} = \mu_x \exp\left(-0.5\sigma_{\ln x}^2 + z\sigma_{\ln x}\right) \qquad \text{(D2)}$$

Where xp% is the p%-percentile value for x, and z is the standard normal variate (note that for the median z=0 and for the 16th and 84th percentiles z = -1 and +1, respectively).

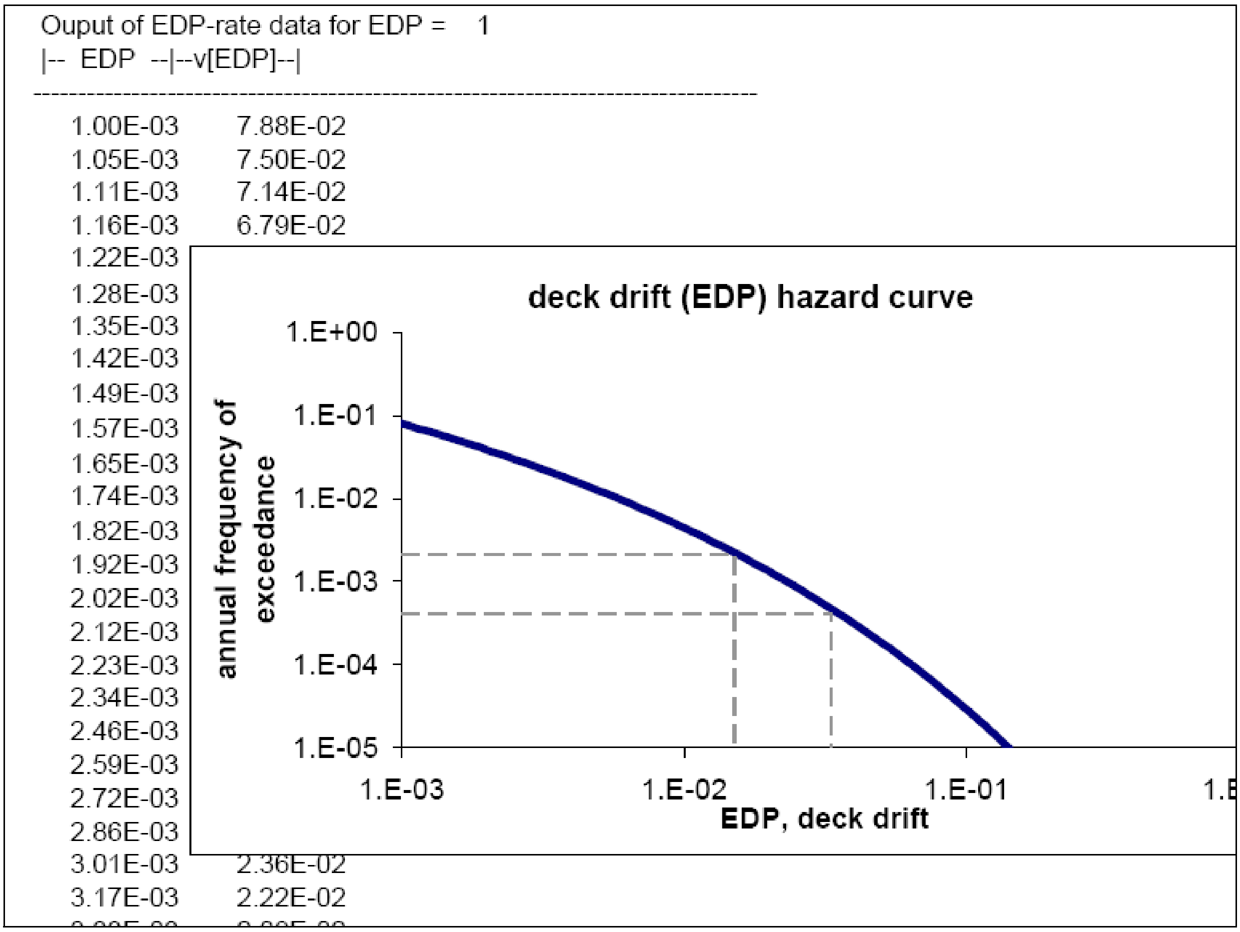
Note that as the level of drift becomes very large (say > 10%) the mean and the standard deviation of the loss become almost constant. This occurs because for such large drift demands the probability of being in any damage state except the last is close to zero. Hence the loss|EDP relationship tends to the relationship for the final damage state (which is mean loss $1M and dispersion 0.4).



```
Ouput of Loss-EDP data for PG =    1
|--  EDP --|--E[L|EDP]--|--S[lnL|EDP]--|
--------------------------------------------------------------------------------
 1.00E-03    1.94E-07        3.48
 2.51E-03    5.83E-04       2.025
 4.01E-03    5.61E-03
 5.52E-03    1.39E-02
 7.02E-03    2.10E-02
 8.53E-03    2.58E-02
 1.00E-02    2.92E-02
 1.15E-02    3.22E-02
 1.30E-02    3.56E-02
 1.45E-02    3.97E-02
 1.61E-02    4.49E-02
 1.76E-02    5.13E-02
 1.91E-02    5.91E-02
 2.06E-02    6.85E-02
 2.21E-02    7.97E-02
 2.36E-02    9.28E-02
 2.51E-02      0.1079
 2.66E-02      0.1251
 2.81E-02      0.1443
 2.96E-02      0.1655       1.168
 3.11E-02      0.1885       1.145
 3.26E-02      0.2132
 3.41E-02      0.2393
 3.56E-02      0.2667
 3.71E-02       0.295
 3.86E-02      0.3239
 4.01E-02      0.3534
 4.16E-02       0.383
 4.31E-02      0.4127
 4.46E-02      0.4421
 4.62E-02      0.4712
 4.77E-02      0.4997
 4.92E-02      0.5275
 5.07E-02      0.5546
 5.22E-02      0.5808
 5.37E-02       0.606
 5.52E-02      0.6302
 5.67E-02      0.6534
 5.82E-02      0.6755      0.6872
 5.97E-02      0.6966      0.6694
 6.12E-02      0.7166      0.6525
 6.27E-02      0.7355      0.6365
 6.42E-02      0.7534      0.6214
 6.57E-02      0.7703      0.6071
 6.72E-02      0.7861      0.5935
 6.87E-02      0.8011      0.5808
```

Figure 8.8: Extract of the output of the loss|EDP data from the analysis.

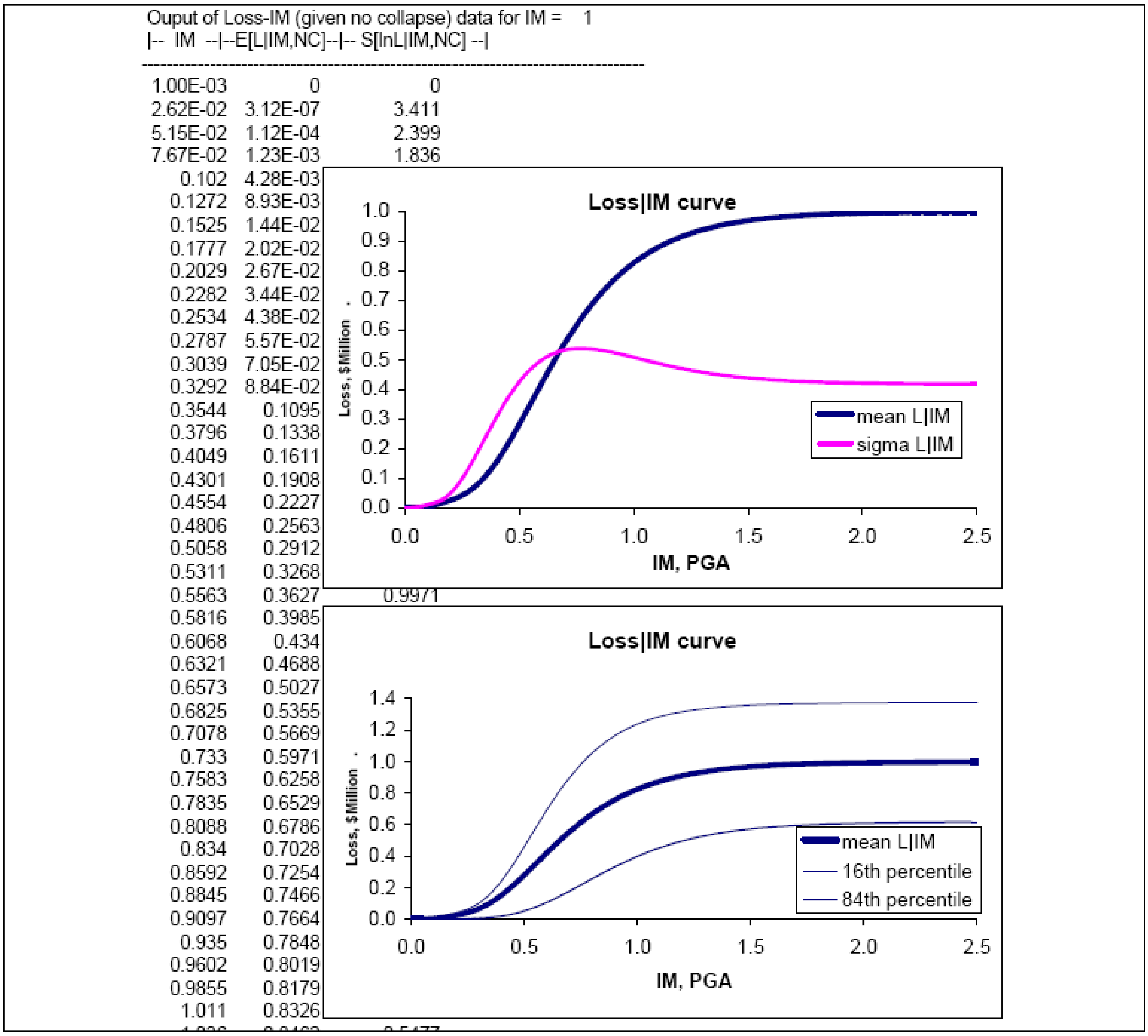
The demand (EDP) hazard curve can be determined by combining the IM hazard and the EDP|IM relationships (see equation 3). Note that because the EDP|IM relationship is of a power model form (which is linear in log-log space) then the shape of the EDP hazard curve (concave from below in log-log space) is similar to that of the ground motion hazard curve. Figure 8.9 illustrates the raw data and the graph of the demand hazard curve using the hyperbolic model for the ground motion hazard. Also shown are lines indicating the demand for the 475- and 2475- year return period events (which have corresponding 10% and 2% probabilities of exceedance in 50 years). These are typical return period design levels for immediate occupancy and collapse safety. The hazard curve shows that for these frequencies the demands are 1.5% and 3.3% deck drift, respectively. Note that these values are different than that if one read from the IM hazard curve the PGA for these return periods and then read then mean EDP values for these IM levels. The reason for this is that the hazard curve accounts for the fact that a certain level of seismic demand is not unique for a given level of ground motion shaking (i.e. there is uncertainty in the value of EDP given IM). Therefore a reduction in the uncertainty in the EDP|IM relationship (by selection of an IM which correlates well with the EDP being examined) will allow for a reduction in the hazard curve.



```
 Ouput of EDP-rate data for EDP =    1
 |-- EDP  --|--v[EDP]--|
 --------------------------------------------------------------------------------
    1.00E-03     7.88E-02
    1.05E-03     7.50E-02
    1.11E-03     7.14E-02
    1.16E-03     6.79E-02
    1.22E-03
    1.28E-03
    1.35E-03
    1.42E-03
    1.49E-03
    1.57E-03
    1.65E-03
    1.74E-03
    1.82E-03
    1.92E-03
    2.02E-03
    2.12E-03
    2.23E-03
    2.34E-03
    2.46E-03
    2.59E-03
    2.72E-03
    2.86E-03
    3.01E-03     2.36E-02
    3.17E-03     2.22E-02
```

Figure 8.9: extract from the demand hazard curve computation

The loss given intensity relationship can be obtained by combining the loss|EDP and EDP|IM relationships (see equation 5). Figure 8.10 illustrates the Loss|IM relationship for example 1. Again, as for the presentation of the loss|EDP results given in Figure 8.8 the results have been presented for the mean and standard deviation as well as the mean and two different percentiles. As an example of the application of the results the figures show that if a Magnitude 8 event on the Alpine fault caused a shaking of 0.5g PGA at the site then the mean loss would be $280,000 with a standard deviation of $400,000. In terms of confidence bounds, since within one standard deviation of the mean represents 66% probability, then for this M8 event the loss has a 66% probability of being within $80,000 and $450,000. Note that there is a large amount of uncertainty here and therefore the need to consider the losses within a probabilistic framework as opposed to a single deterministic loss estimate.



```
Ouput of Loss-IM (given no collapse) data for IM =    1
|--  IM  --|--E[L|IM,NC]--|-- S[lnL|IM,NC] --|
--------------------------------------------------------------------------------
 1.00E-03          0            0
 2.62E-02   3.12E-07        3.411
 5.15E-02   1.12E-04        2.399
 7.67E-02   1.23E-03        1.836
    0.102   4.28E-03
   0.1272   8.93E-03
   0.1525   1.44E-02
   0.1777   2.02E-02
   0.2029   2.67E-02
   0.2282   3.44E-02
   0.2534   4.38E-02
   0.2787   5.57E-02
   0.3039   7.05E-02
   0.3292   8.84E-02
   0.3544     0.1095
   0.3796     0.1338
   0.4049     0.1611
   0.4301     0.1908
   0.4554     0.2227
   0.4806     0.2563
   0.5058     0.2912
   0.5311     0.3268
   0.5563     0.3627       0.9971
   0.5816     0.3985
   0.6068      0.434
   0.6321     0.4688
   0.6573     0.5027
   0.6825     0.5355
   0.7078     0.5669
    0.733     0.5971
   0.7583     0.6258
   0.7835     0.6529
   0.8088     0.6786
    0.834     0.7028
   0.8592     0.7254
   0.8845     0.7466
   0.9097     0.7664
    0.935     0.7848
   0.9602     0.8019
   0.9855     0.8179
    1.011     0.8326
```

Figure 8.10: extract from the loss|IM curve computation

6.2.9 Expected loss over service life and expected annual loss

The expected loss per annum can be obtained by combining the expected loss|IM relationship with the ground motion hazard (λ_{IM}) relationship (see Equation 7). For this example it is found that the expected annual loss (without accounting for the time value of money) is $676. By accounting for the time value of money (using a discount rate of 6%) Figure 8.11 gives the expected loss and expected annual loss over time curves. Note that the discount rate computed should take into account a deduction due to likely inflation (which will result in increased repair costs) over the time period of investment.

```
Ouput of Annual loss for IM =    1
|-- E[ALt] --|--S[ALt]--|
--------------------------------------------------------------------------------
 6.76E-04       2.559           0


Ouput of Annual loss for IM =    1; lambda=0.060
|--t(yrs)--|-- E[ALt] --|--EAL(/year)--|
--------------------------------------------------------------------------------
           1   6.56E-04    6.56E-04
           2   1.27E-03    6.37E-04
           3   1.86E-03    6.19E-04
           4   2.40E-03    6.01E-04
           5   2.92E-03    5.84E-04
           6   3.41E-03    5.68E-04
           7   3.86E-03    5.52E-04
           8   4.30E-03    5.37E-04
           9   4.70E-03    5.22E-04
          10   5.08E-03    5.08E-04
          11   5.44E-03    4.95E-04
          12   5.78E-03    4.82E-04
          13   6.10E-03    4.69E-04
          14   6.40E-03    4.57E-04
          15   6.69E-03    4.46E-04
          16   6.95E-03    4.35E-04
          17   7.21E-03    4.24E-04
          18   7.44E-03    4.13E-04
          19   7.66E-03    4.03E-04
          20   7.87E-03    3.94E-04
          21   8.07E-03    3.84E-04
          22   8.26E-03    3.75E-04
          23   8.43E-03    3.67E-04
          24   8.60E-03    3.58E-04
          25   8.75E-03    3.50E-04
          26   8.90E-03    3.42E-04
          27   9.04E-03    3.35E-04
          28   9.17E-03    3.27E-04
          29   9.29E-03    3.20E-04
          30   9.41E-03    3.14E-04
          31   9.51E-03    3.07E-04
          32   9.62E-03    3.01E-04
          33   9.71E-03    2.94E-04
          34   9.80E-03    2.88E-04
          35   9.89E-03    2.83E-04
          36   9.97E-03    2.77E-04
          37   1.00E-02    2.71E-04
```

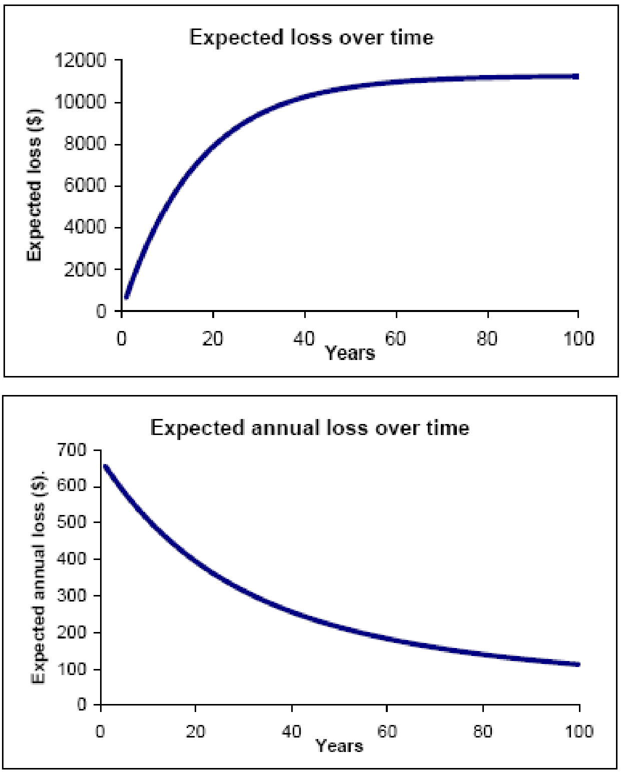
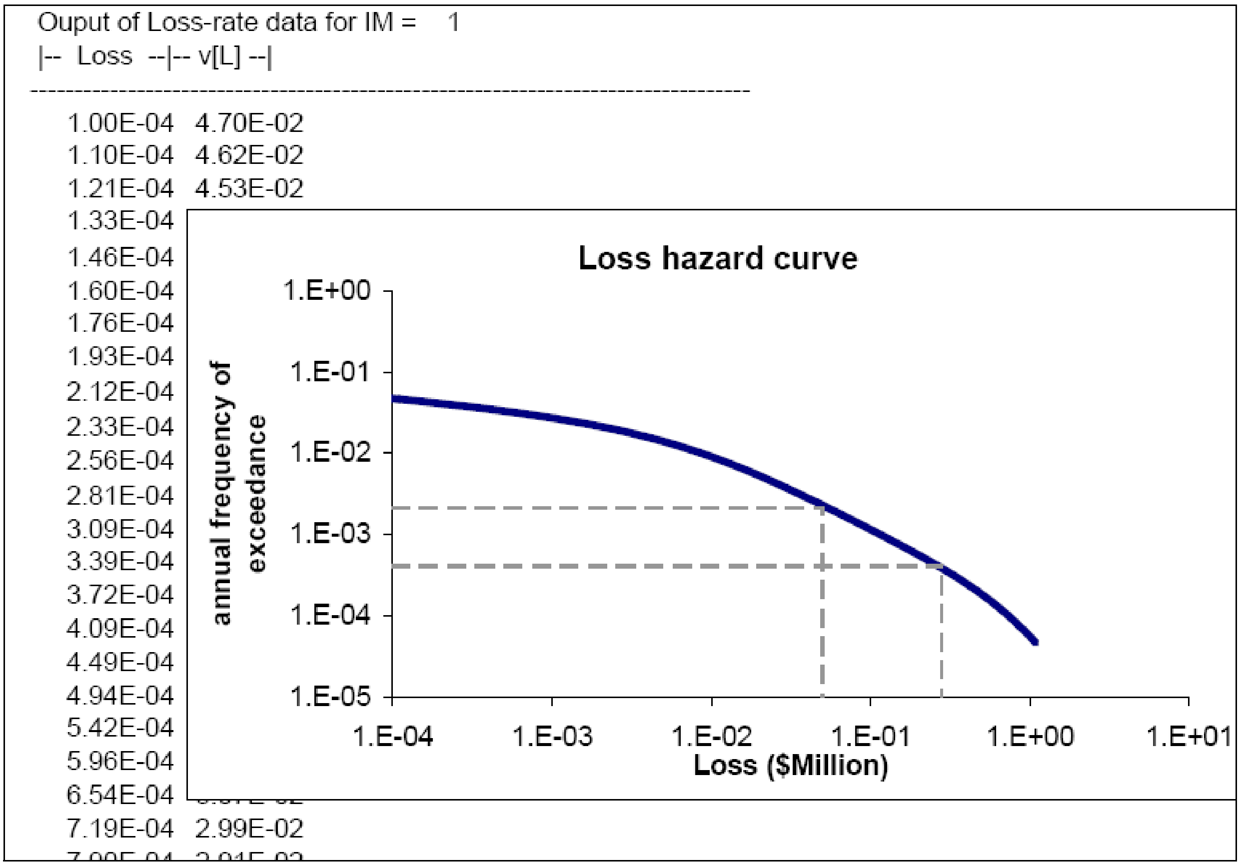


Figure 8.11: extract from the expected loss curve computation

The loss hazard curve can be computed by combining the loss|IM relationship and the ground motion hazard curve (see Equation 8). The curve gives the mean annual frequency of exceeding a specified level of loss. The graph shows the loss hazard curve superimposed with the 10% and 2% probability in 50 year frequencies. The curve allows one to say that there is a 10% probability in 50 years of exceeding a loss of $50,000, and a 2% probability in 50 years of exceeding $280,000.



```
 Ouput of Loss-rate data for IM =    1
 |--  Loss  --|-- v[L] --|
--------------------------------------------------------------------------------
    1.00E-04  4.70E-02
    1.10E-04  4.62E-02
    1.21E-04  4.53E-02
    1.33E-04
    1.46E-04
    1.60E-04
    1.76E-04
    1.93E-04
    2.12E-04
    2.33E-04
    2.56E-04
    2.81E-04
    3.09E-04
    3.39E-04
    3.72E-04
    4.09E-04
    4.49E-04
    4.94E-04
    5.42E-04
    5.96E-04
    6.54E-04
    7.19E-04  2.99E-02
```

Figure 8.12: extract from the loss hazard curve computation

6.2.10 Some additional comments

This first example was used to display some of the most simple features of the SLAT program. In particular, in a more detailed analysis the following would be used: The bridge would be decomposed into a multi-degree of freedom structure and analysed using a more detailed structural analysis program. The loss and damage states would relate to specific components of the bridge (i.e. pier, deck, abutments) and loss would consider disruption costs and casualties. Epistemic uncertainties and component correlations could also be considered, as well as global collapse of the bridge.

6.3 Example 2: 10-storey RC moment frame building

The following example problem presents a loss-assessment of a 10 storey reinforced concrete moment resisting frame structure. This example (along with discussion related to the interpretation of results) has been submitted for publication in a peer-review archival journal:

Bradley BA, Dhakal RP, Cubrinovski M, McRae GA, Lee DS. Seismic Loss Estimation for Efficient Decision Making. Bulletin of the New Zealand Society of Earthquake Engineering 2008. (Submitted)

The case study structure used herein to illustrate the use of seismic loss estimation tools in decision making process is based on the Red Book building which acts as a design example of the New Zealand Concrete Code. Figure 8.13 illustrates plan and elevation views of the building layout. The primary lateral load carrying system consists of four one-way perimeter moment resisting frames which are 3 bays long. Vertical loads are transferred primarily through interior columns with gravity beams supporting one-way floor units. Although originally designed for a site in Christchurch, in this study it was assumed that the structure is located at a site in Wellington. The soil is assumed to be class A and stiff enough so that local site effects are not significant in modifying the bedrock ground motion.

A 2D model of perimeter frame was developed using the time-history analysis program Ruaumoko2D. Due to the symmetry of the structure, it was assumed that the 3D response could be reasonably approximated by separate 2D analyses in each of the two primary directions. A fixed-base model was used in the analysis and as a result soil-structure-foundation interaction was neglected. The structure was modelled using a lumped mass model and non-linear (beam) elements based on the modified Takeda hysteresis, with the appropriate section properties determined using fibre-based biaxial section modelling. The structural model had a fundamental period of 1.5 seconds.

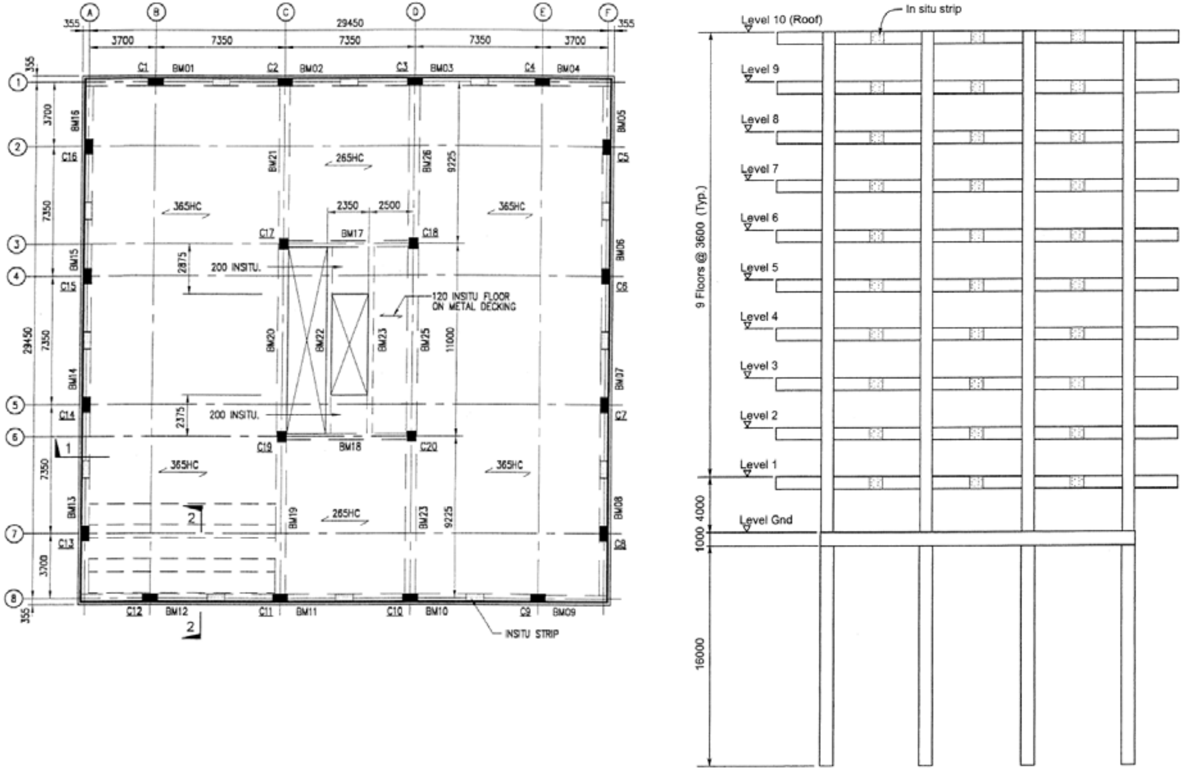


Figure 8.13: (a) Plan, and (b) elevation of the Red Book building.

6.3.1 Seismic hazard

As the fundamental period of the structure is 1.5 seconds, the 5% damped spectral acceleration at this period, S_a(T=1.5s,5%) (or simply S_a for brevity) is chosen as the ground motion intensity measure (IM). This selection of ground motion IM is based on the observation from past researchers that the spectral acceleration at the fundamental period of the structure is an ‘efficient’ IM at predicting the drift demands in the structure.

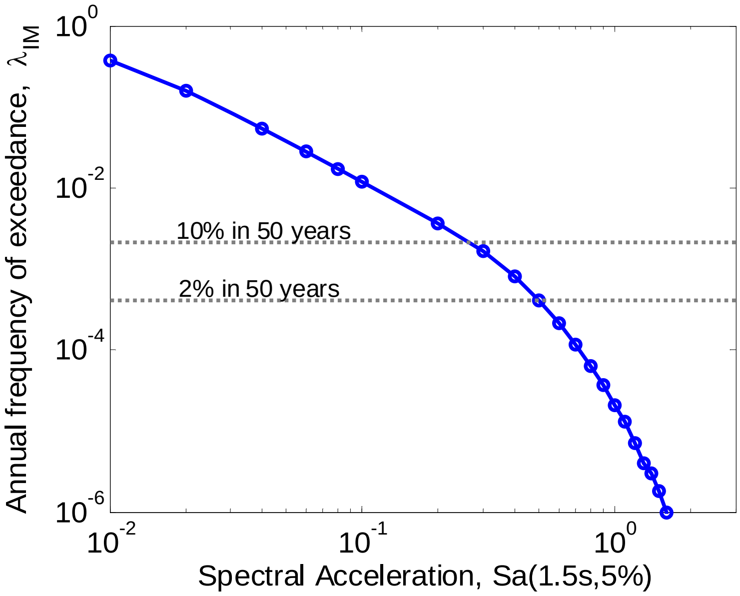


Figure 8.14: Ground motion hazard curve for Wellington, New Zealand, (Stirling et al, 2002).

6.3.2 Seismic response analysis

Seismic response analysis of the structure was performed using non-linear time history analysis with a suite of ground motions scaled over a wide range of ground motion intensities to account for the variability in structural response due to differences in ground motions of the same intensity (termed record-to-record randomness). A suite of 40 ground motion records were used for conducting the non-linear time history analyses.

The suite of ground motions were scaled to S_a values ranging from 0.1-1.5g in increments of 0.1g. Thus in total, 600 non-linear time history analyses were completed using 40 different ground motion records at 15 different intensities.

Figure 8.15 illustrates two results representing the maximum interstorey drifts (the Engineering Demand Parameter, EDP) on the second and eighth floors of the analysed structure as a function of the ground motion IM. Each of the points in the figures is the result of a single time history analysis when global structural collapse did not occur, while the two lines indicate the mean response for a given level of intensity with and without consideration of global collapse, respectively. The fewer number of analysis points in the figure as the level of ground motion intensity is due to the fact that a larger proportion of ground motions cause collapse (and are therefore not displayed).

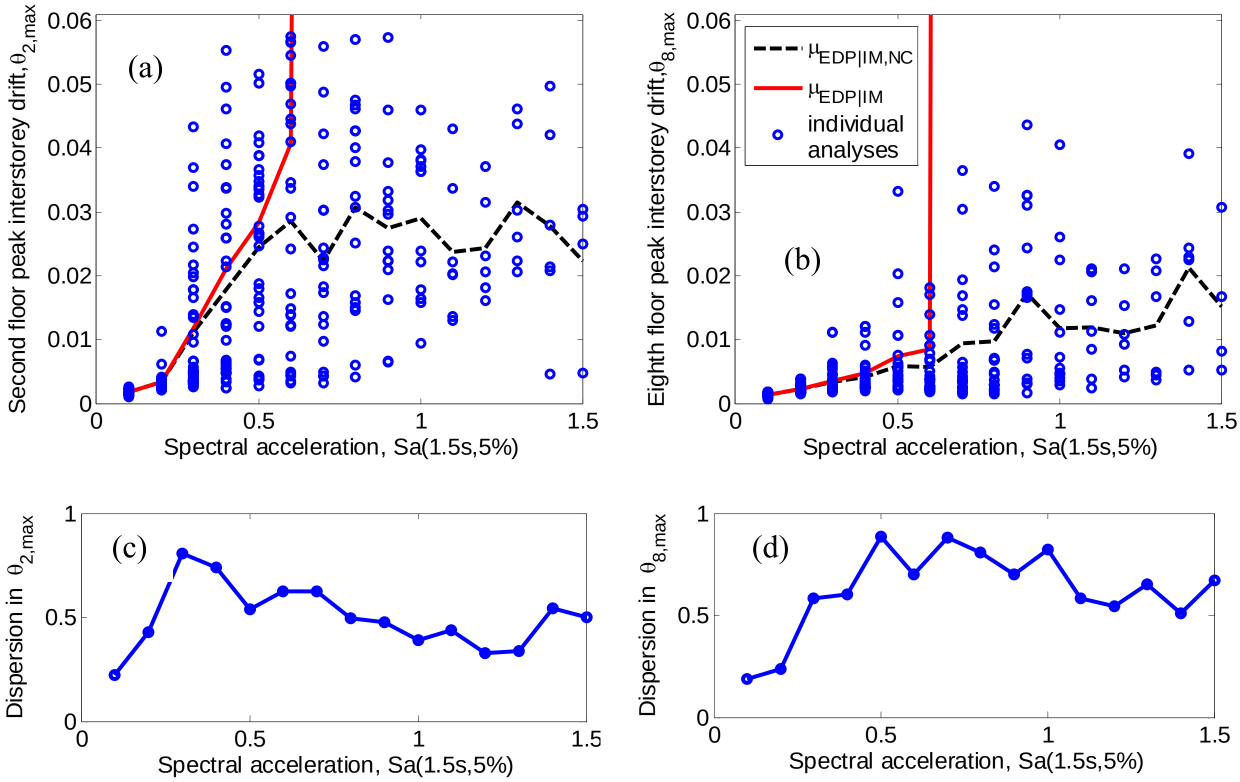


Figure 8.15: Examples of IDA plots of maximum interstorey drift for the (a) first storey; (b) seventh story; (c) dispersion in first storey response; and (d) dispersion in seventh storey response.

The variation in the seismic demand through different elevations is illustrated in Figure 8.16 which shows the (mean) peak interstorey drifts and (mean) peak floor accelerations as a function of the elevation in the building. Note that the values in the figure represent the mean of many ground motion records and each of the different values will not likely occur at the same time (i.e. these are not profiles a specific step in time). As is typical for a multi-storey frame structure the drift demands are observed to be the most severe in the lower half of the structure, while the (total as opposed to relative) acceleration demands are approximately constant over the height of the structure for low levels of shaking, but become larger in the lower stories for high levels of ground motion when significant damage in the lower floors occurs (i.e. the damaged floors begin to isolate the upper region of the structure).

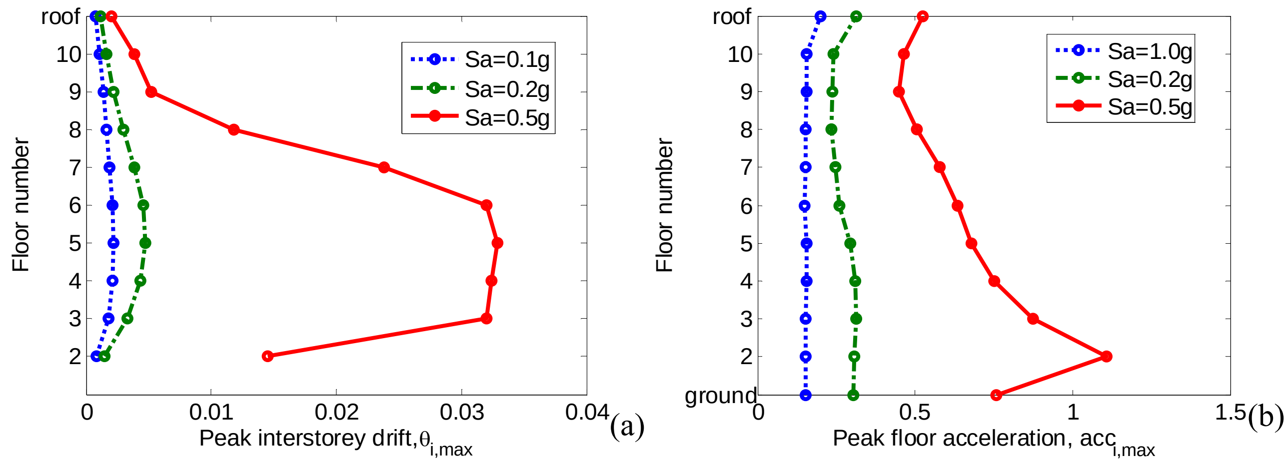


Figure 8.16: Variation in (a) mean drift and (b) mean acceleration demands over the height of the structure.

6.3.3 Occurrence of global collapse

Traditionally, the occurrence of structural collapse has been associated with some prescribed level of seismic demand, such as interstorey drift or component plastic deformation. This however does not account for the redundancy of structural systems which allows for redistribution of damage and global stability despite local failures. Here collapse is defined as the state in which sidesway instability occurs in one or more storeys. Collapse due to loss of vertical carrying capacity (LVCC) (due to axial and critical shear failures) is not considered due to a lack of structural analysis tools which can reliably capture these phenomena. From the results of seismic response analyses a collapse fragility curve can be constructed by first determining the probability of collapse for various levels of ground motion intensity (based on the proportion of records which cause structural collapse), and then typically fitting these raw data points with a lognormal distribution. Figure 8.17 illustrates the collapse fragility curve for the case study structure.

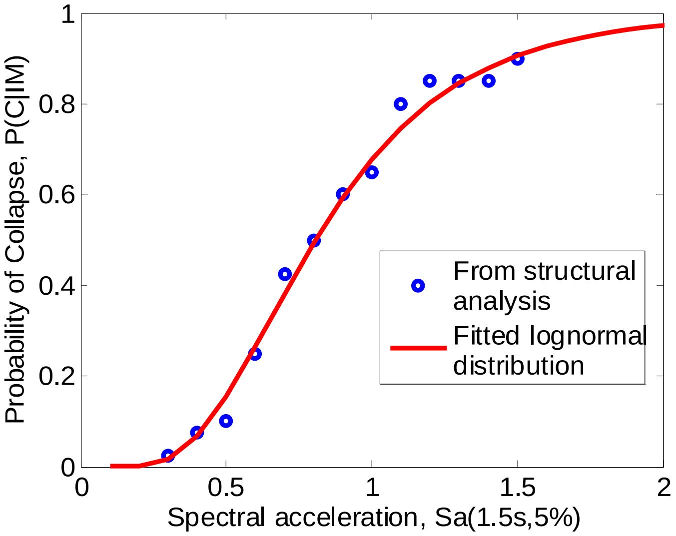


Figure 8.17: Collapse fragility curve for case study structure

6.3.4 Input file

Due to the length of the input file it is not given here directly in the text. The input file can be found in the folder for example 2, along with the ground motion hazard, and one of the demand files.

6.3.5 Structural response and collapse hazards

The results of the seismic response analysis can be combined with the ground motion hazard to provide the rates of exceedance for various levels of seismic demand on the structure.
As historical and recent earthquake reconnaissance indicate that structural collapse is the primary source of casualties and loss of life caused by earthquakes, then the annual rate of structural collapse is a key performance criterion for use in seismic assessment of structures.

For the case study structure considered in this paper it was found that the annual rate of collapse is 2.15×10^{-4}, which (based on the Poisson assumption) corresponds to a 1.1% probability of global collapse of the structure over a service life of 50 years.

Similar to the annual rate of collapse, the seismic response for a particular EDP can be combined with the ground motion hazard curve to obtain the annual rate of exceeding various levels of EDP

Figures 8.18a and 8.18b illustrate the EDP hazard curves for interstorey drifts and accelerations, respectively for the investigated structure. Several things should be noted from Figure 8.6 in relation to the results from the structural analysis and the ground motion hazard.

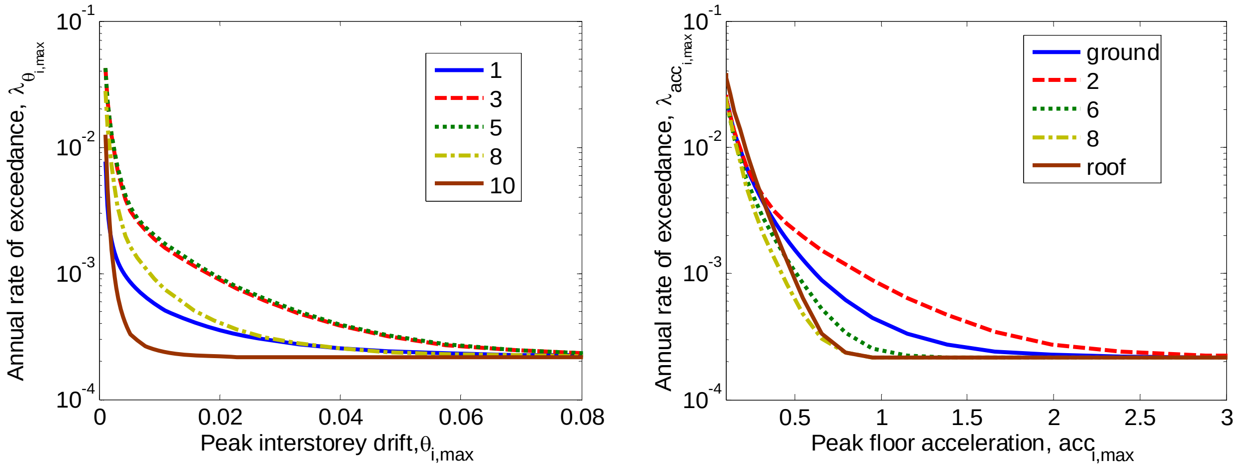


Figure 8.18: EDP hazard curves of (a) peak interstorey drift; and (b) peak floor accelerations for the case study structure.

6.3.6 Component inventory

Table 8.2 gives the variation in the different components used in the example problem.

Table 8.2: Quantities used in the case study example

Component	Description	Quantity
Ductile beam-column joints	Post 1960s ductile beam column joints (2 beams)	24 / floor
Columns	Gravity columns (and seismic columns on first floor)	20 on 1st floor, 4 on all other floors
Slab-beam-column connections	Connection of slab to seismic frame	24 / floor
Partition	Drywall partitions and finish	721 m^2 / floor
Exterior glazing	1.5m x 1.8m standard glass panes	99 panes / floor
Acoustical ceiling	0.6m x 1.2m tiles with Aluminium frames	693 tiles / floor
Automatic sprinklers	3.7m sections of sprinkler piping	23 sections / floor
Servers and network equip	Typical	\$260,000 on floors 3,6, and 10
Computers and printers	Typical	\$93000 / floor

Bookcases and file cabinets	Typical	$16200 / floor
Roof mounted equipment	Coolers, airconditioning etc.	$600,000 on roof
Workstation desks	Typical	$21600 / floor
Generic acceleration sensitive	fire protection systems, HVAC, Heating, cooling, pumps, plumbing, toilets	$100,000 / floor
Generic drift sensitive	vertical piping, bath tubs, F.H.C, Ducts	$100,000 / floor

6.3.7 Loss given intensity relationships

Figure 8.19 illustrates the L|IM relationships for two different components in the case study structure. The first is an RC joint which was located in the second floor of the structure, while the second is a drywall partition located in the 8th storey of the structure. For both components, as would be expected, the loss due to direct damage increases as the ground motion shaking increases.

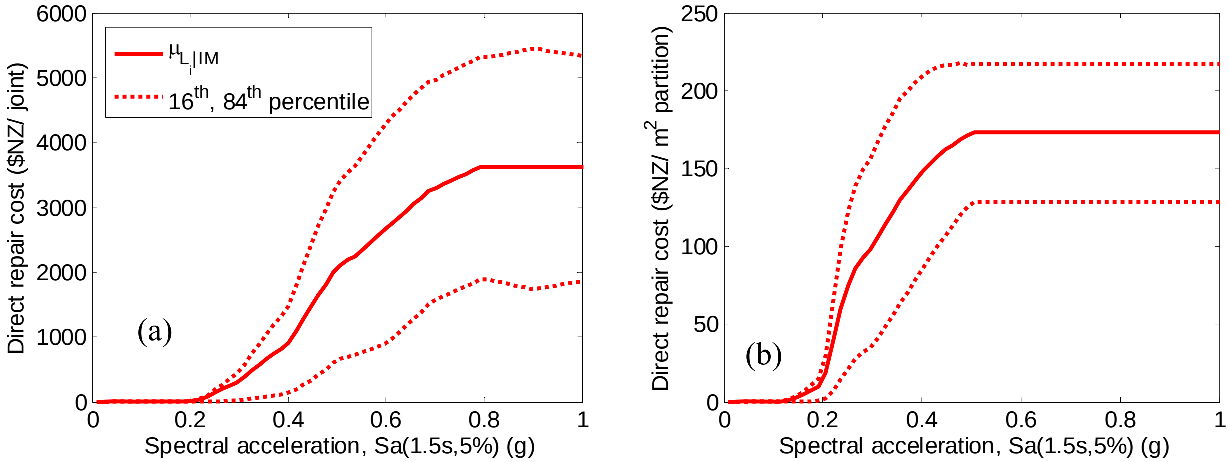


Figure 8.19: Loss given intensity relationships for (a) RC beam-column joint and (b) drywall partition.

Figure 8.20 illustrates the loss|IM relationship for the entire structure for: (a) loss given IM and no collapse; (b) loss given collapse; and (c) loss given IM with no conditioning on collapse or no collapse.

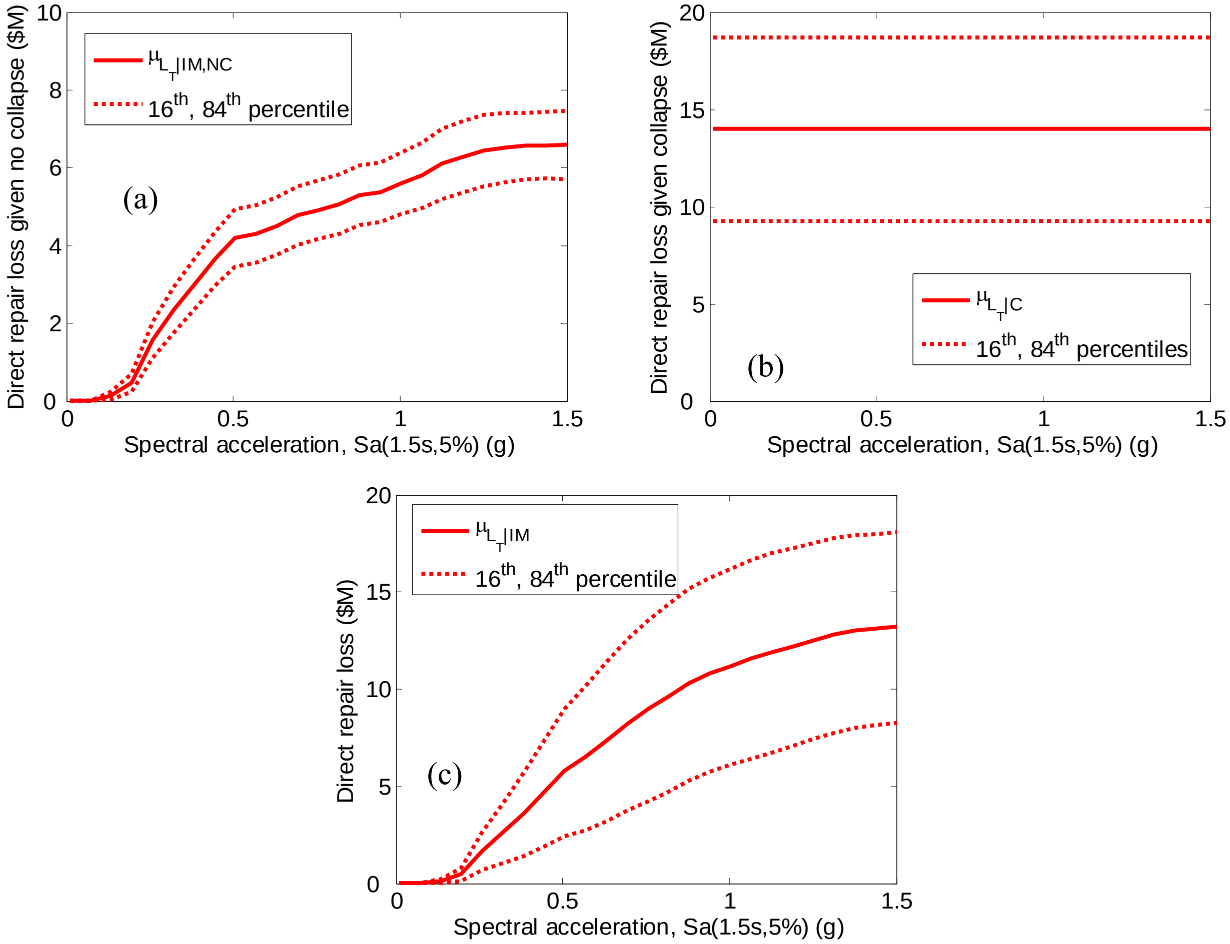


Figure 8.20: Loss given intensity for the entire structure given: (a) collapse does not occur; (b) collapse occurs; and (c) both collapse and non-collapse cases considered.

Since the total loss given IM is an accumulation of damage to many different components on various floors of the structure it is insightful to deaggregate the loss to investigate key contributors (and therefore how the loss can be reduced most effectively)

Figure 8.21 illustrates the deaggregation of the total loss by collapse and non-collapse cases for the analysed structure. As one would expect, for small levels of ground motion the probability of collapse is very small and therefore the majority of the loss is due to damage to individual components when the structure does not collapse. As the level of ground motion intensity increases the contribution of losses due to collapse increases.

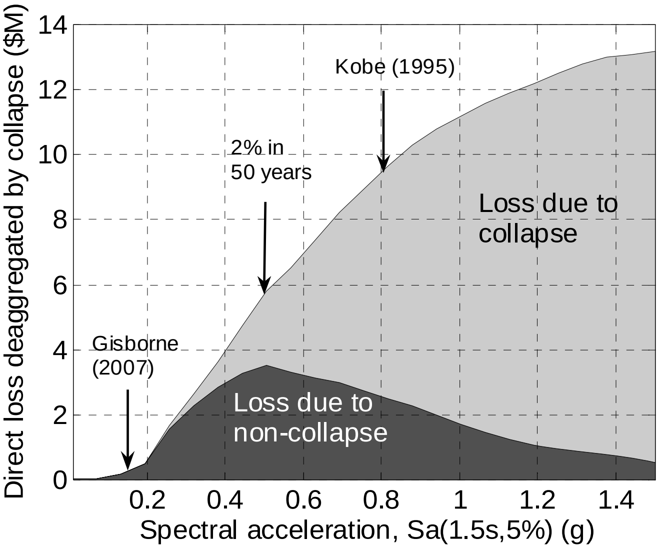


Figure 8.21: Deaggregation of the mean loss given intensity to collapse and non-collapse losses for the case study structure.

Figure 8.21 illustrates that for small levels of ground motion shaking a large portion of the total loss in structures is due to that which occurs in the absence of global collapse. Thus in the case of no-structural collapse, further insight can be obtained by deaggregation of the expected loss given no collapse. Figure 8.22 illustrates the deaggregation of the L|IM,NC relationship by different component types.

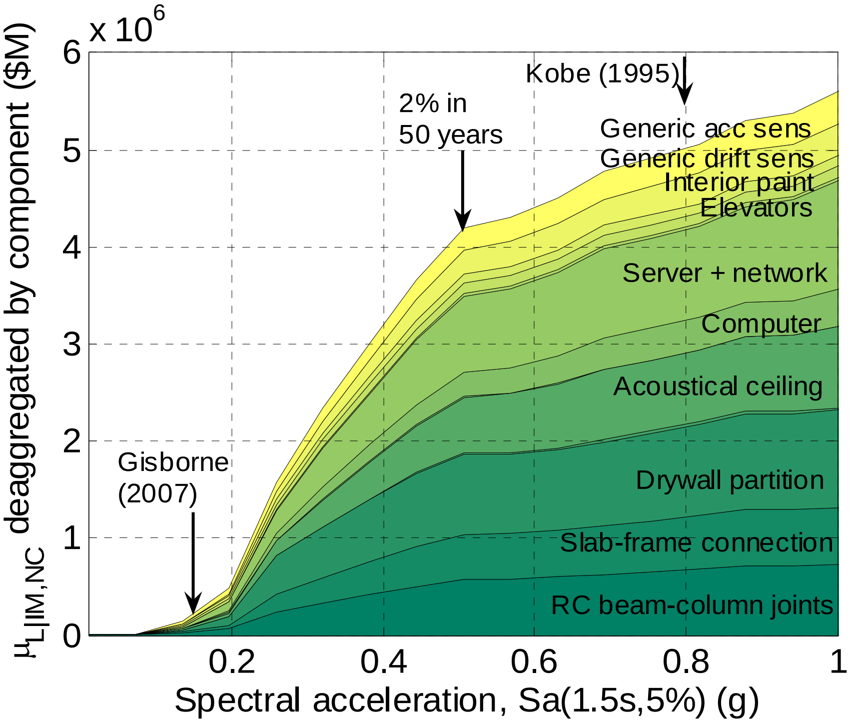


Figure 8.22: Deaggregation of the mean loss given no collapse relationship to contributions from different components.

Figure 8.23 illustrates the deaggregation of the loss given no collapse for a ground motion shaking of IM=0.15g S_a which is approximately that observed in the 2007 Gisborne earthquake

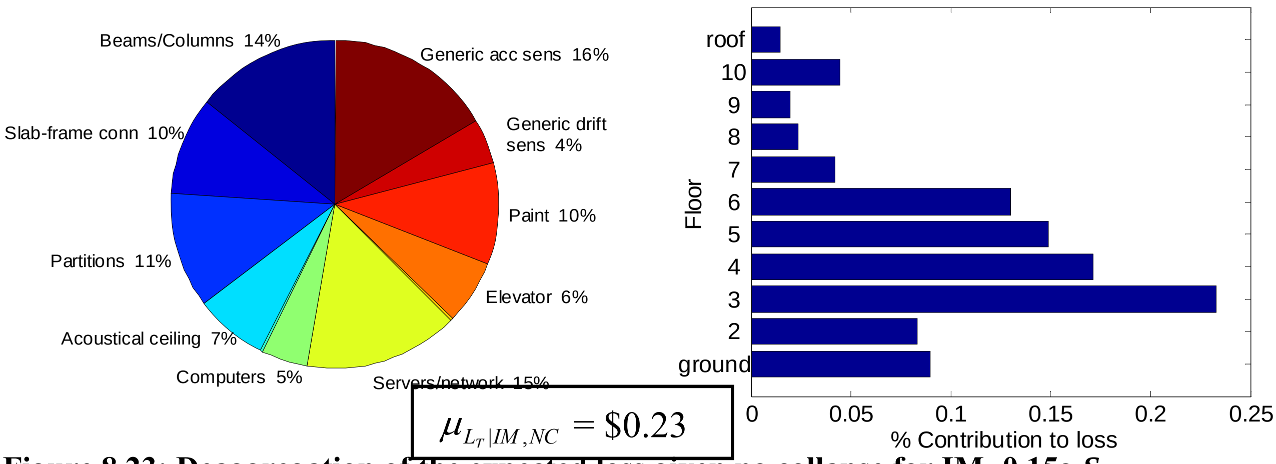


Figure 8.23: Deaggregation of the expected loss given no collapse for IM=0.15g S_a (Gisborne, 2007) by: (a) component type and (b) by floor.

Figure 8.24 illustrates the L|IM,NC deaggregation for IM = 0.5g S_a which is the level of ground motion shaking with a 2% probability of exceedance in 50 years (return period approximately 2475 years) at the site. For this level of shaking the expected loss was estimated to be \$4.2 M.

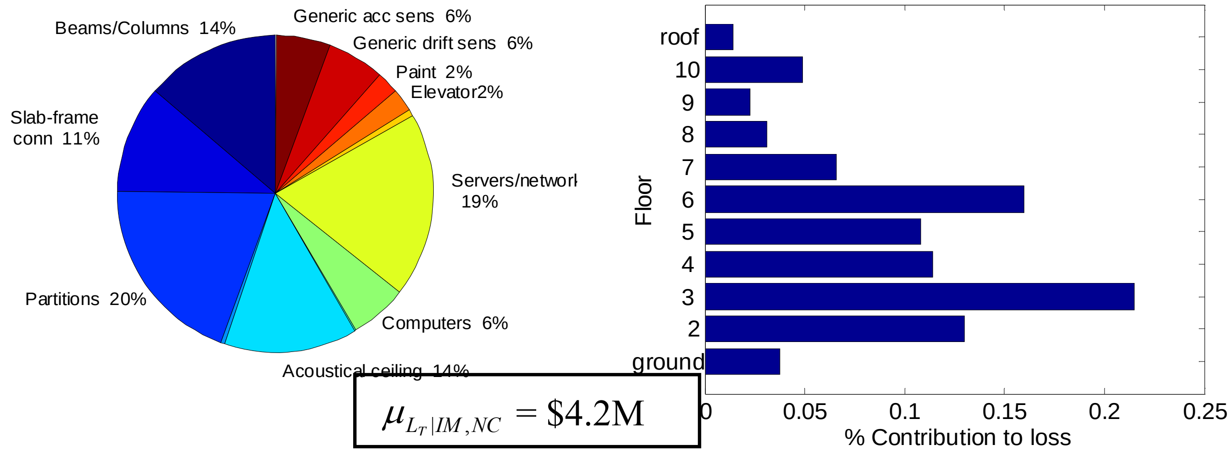


Figure 8.24: Deaggregation of the expected loss given no collapse for IM=0.50g S_a (2% in 50 year probability of exceedance) by: (a) component type and (b) by floor.

6.3.8 Expected annual loss

Expected Annual Loss (EAL = μ_{L_T}) is a seismic performance measure which is particularly useful for decision makers as it contains information on the seismic performance of a structure over a range of different levels of ground motion intensity within a single number. For the case study structure in was found that the EAL was \$14,300 which relates to approximately 0.1% of the replacement cost of the structure. Figure 8.24a illustrates the net present value (NPV) of the expected loss over time for the structure based on a discount rate of 6%. Figure 8.24b illustrates the deaggregation of the EAL as a function of ground motion intensity. It indicates that the majority of the EAL is attributed to the occurrence of ground motions between 0.25-0.75g S_a (with smaller ground motions not causing significant damage, and larger ground motions occurring very infrequently).

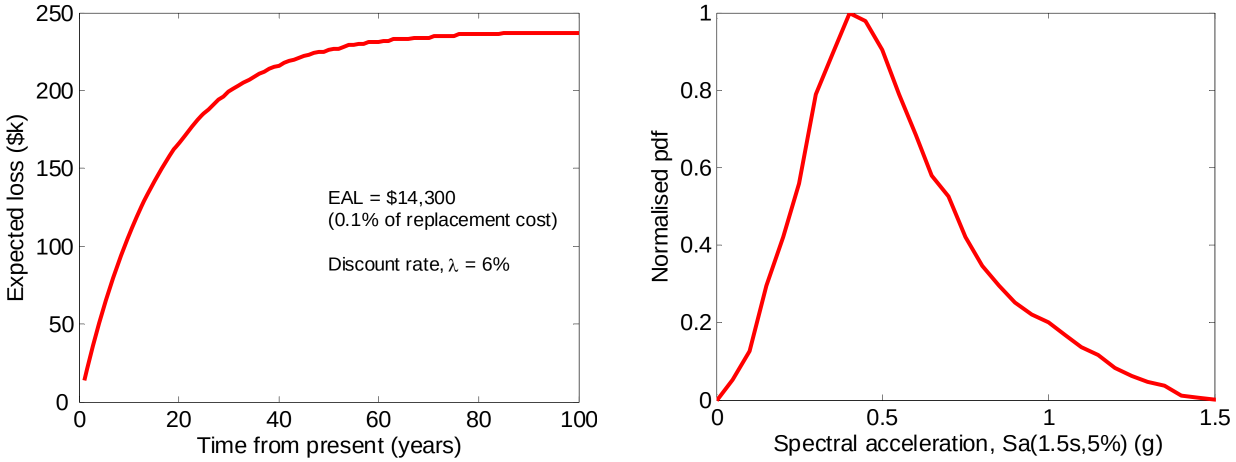


Figure 8.24: Expected loss results for case study structure: (a) over time considering net discount rate; and (b) deaggregation of EAL by intensity measure.

6.3.9 Loss hazard

Figure 8.25 illustrates the loss hazard curve for the case study structure. For reference, the 10% and 2% probability of exceedance in 50 year curves are shown which have loss values of approximately $1.5 M and $4.5 M, respectively. The loss-hazard curve is another figure (in addition to the expected loss) which can be useful in loss-based decision making.

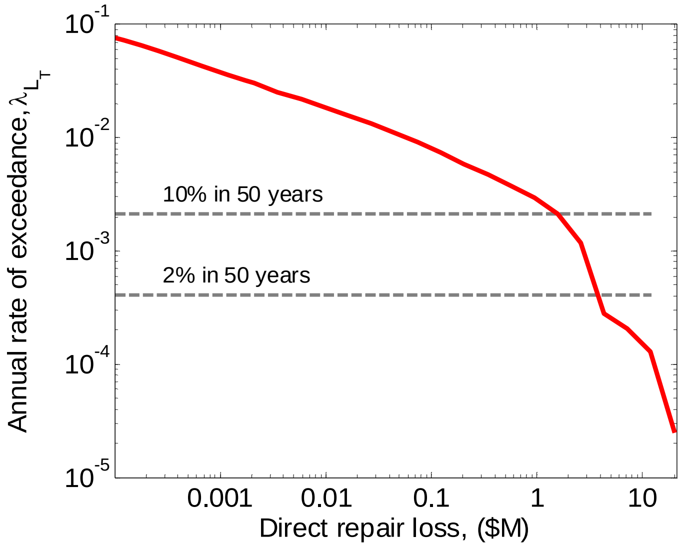


Figure 8.25: Loss hazard curve for the case study structure.

7. Fragility and Loss library

7.1 Overview

The following section gives details on the fragility and loss function library available within SLAT. While every effort has been made to keep this library as up-to-date as possible, if users find a component has fragility and loss functions which are not in this library then please notify the developers.

As the number of fragility functions increase we will adopt a more rigorous classification system, however while there is relatively few a simple system is adopted. Fragility functions are grouped based on the categories: structural, non-structural drift sensitive, and non-structural acceleration sensitive. While repair time values for many of the library components have been input into the program, the values are somewhat arbitrary (and thus not presented here). Significant research is required in this area. In particular, the reduction in the per component repair time, when multiple components are being repaired is an important feature

7.2 Structural components: 1-100

1: Post 1994 Welded-steel moment frame
2: Ductile CIP RC beams/ Ductile CIP RC columns
3: Concrete column-slab connections
4: Non-ductile RC Columns (pre 1960)
5: Interior Beam-column joints (pre 1960)

7.3 Non-structural drift sensitive components: 101-200

101: Exterior Wall OSB and stucco Type 3a
102: Exterior Skin-Glass Curtainwall - Type 1
103: Interior Walls GWB on Wood studs
104: Interior Partitions Type 9a
105: Drywall partition and finish
106: Paint
107: Exterior glazing
108: Generic drift sensitive non-structural components

7.4 Non-structural acceleration sensitive components: 201-300

201: Unanchored Bookcase
202: Exterior Roofing Concrete tile type 2
203: Ceiling Systems Suspended acoustical tile type1
204: Conveying - Hydraulic elevator
205: Roof Mounted Equipment
206: Miscellaneous housewares and art objects
207: Home Entertainment Equipment
208: Desktop Computers (unfastened)
209: Servers and network Equipment
210: Tall File Cabinet
211: Automatic sprinklers
212: desktop computer (fastened)
213: Ceiling Systems Suspended acoustical tile type2

214: Generic acceleration sensitive non-structural components

Fragility Number = 1
Name: Post 1994 Welded-steel moment frame

Unit: each
Component or System: Specific user input number of joints
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Local beam flange and web buckling.	Heat straightening of buckled region.	0.03	0.35
DS2	DS1 plus lateral-torsional distortion of beam in hinge region	Heat straightening and/or replacement of portion of beam around hinge region.	0.04	0.35
DS3	Low-cycle fatigue fracture of beam flanges in hinge region.	Replace large portion of beam in distorted and fractured region. Will likely require engineered shoring of beam during repairs.	0.05	0.35

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	5000	8000	6	12	0.3
DS2	10000	15000	6	12	0.3
DS3	45000	60000	6	12	0.4

Fragility Number = 2
Name: Ductile CIP RC beams

Unit: each
Component or System: Ductile RB beams designed according to capacity design (i.e. no damage in column or beam column joint).
Demand: Storey drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Widespread light cracking; or a few cracks > 1mm; or light shear cracks tending to flatten toward 30°.	Only minimal loss of use, possible some minor repair needed to restore structure to its design strength.	0.005	0.40
DS2	Significant cracking, e.g. 90° cracks > 2mm; 45° cracks > 2mm; 30° cracks > 1mm.	Structure closed for several weeks for major repairs.	0.01	0.45
DS3	Very large flexure or shear cracks, usually accompanied by limited spalling of cover concrete.	Structure damaged beyond repair and must be demolished.	0.03	0.5
DS4	Very severe cracking and spalling of concrete; buckling, kinking or fracture of rebar.	Structure has completely or partially collapsed.	0.06	0.6

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	1143	1143	6	12	0.42
DS2	3214	3214	6	12	0.4
DS3	4900	4900	6	12	0.37
DS4	4900	4900	6	12	0.37

Fragility Number = 3
Name: Column slab-connections **Aslani and Miranda, (2005a)**

Unit: each
Component or System: each
Demand: Storey drift (half of that of the above and below floors)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	*Light Cracking*: Light cracking corresponds to crack widths smaller than 0.3mm (0.013 in) which become visible at distances of about 2.0m (6.6 ft).	Actions associated with this damage state typically consist of either "no repair" or a "light repair" by applying a coating on the concrete surface to conceal the projection of cracks	0.004	0.39
DS2	*Severe Cracking*: This damage state involves extensive cracking with crack widths between 0.3mm (0.013 in) and 2mm (0.08 in).	For this level of cracking most concrete repair guidelines suggest epoxy injection	0.0095	0.25
DS3	*Punching Shear Failure*: This damage state corresponds to severe cracking characterised by a roughly circular tangential cracking around the column area of slab, radial cracks extending from that area, and considerable spalling of the concrete cover	Repair actions involve significant labour and cost, and consist of concrete spall repair and rebar replacement	0.02	0.62
DS4	*Loss of Vertical Carrying Capacity* (*LVCC*): At this damage state component loses its vertical carrying capacity, and collapses under its gravity load.	Structure has completely or partially collapsed.	0.0428	0.36

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	590	590	6	12	0.59
DS2	2360	2360	6	12	0.63
DS3	5900	5900	6	12	0.67
DS4	5900	5900	6	12	0.67

Fragility Number = 4
Name: RC Column with light transverse reinforcement (pre-1960) (Aslani 2005)

Unit: each
Component or System: each
Demand: Storey drift (half of that of the above and below floors)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	*Light Cracking*:	Actions associated with this damage state typically consist of either "no repair" or a "light repair" by applying a coating on the concrete surface to conceal the projection of cracks	0.0035	0.37
DS2	*Severe Cracking*:	For this level of cracking most concrete repair guidelines suggest epoxy injection	0.0071	0.44
DS3	*Shear Failure*:	Repair actions involve significant labour and cost, and consist of concrete spall repair and rebar replacement	0.02	0.58
DS4	*Loss of Vertical Carrying Capacity* (*LVCC*): At this damage state component loses its vertical carrying capacity, and collapses under its gravity load.	Structure has completely or partially collapsed.	0.031	0.63

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	177.0	177.0	6	12	0.59
DS2	883.0	883.0	6	12	0.63
DS3	3530	3530	6	12	0.67
DS4	3530	3530	6	12	0.67

Fragility Number = 5
Name: RC beam-column joint (pre-1960) (Aslani 2005)

Unit: each
Component or System: each. Accounts for two beams entering the joint in the same planar direction (i.e. interior joint).
Demand: Storey drift (half of that of the above and below floors)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	*Severe cracking in beam*		0.0035	0.36
DS2	*Severe Cracking* in column		0.0071	0.36
DS3	*Severe cracking in joint*		0.017	0.37
DS4	*Joint spalling*		0.030	0.25
DS5	*Loss of Vertical Carrying Capacity* (*LVCC*): At this damage state component loses its vertical carrying capacity, and collapses under its gravity load.	Structure has completely or partially collapsed.	0.047	0.22

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	363.4	363.4	6	12	0.59
DS2	1090.2	1090.2	6	12	0.59
DS3	1453.5	1453.5	6	12	0.63
DS4	3634	3634	6	12	0.67
DS5	3634	3634	6	12	0.67

Fragility Number = 101
Name: Exterior Wall OSB and stucco Type 3a

Unit: Square meter
Component or System: Square meters of stucco wall oriented in a specified direction per floor
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Cracking of Stucco and Gypboard	Repair stucco crack and repaint, repaint gypboard crack	0.002	0.4
DS2	Severe cracking of stucco, cracked gypboard, cracked glass	Grout stucco crack and repaint; tape, mud, sand and paint gypboard cracks, replace cracked glass panel(s) and "cleanup"	0.01	0.4
DS3	"Wood stud failure, sill plate splitting and failure, stucco/gypboard wall panel failure, glass fallout (DS3)	Replace entire wall (Wood framing, Stucco, OSB and gypboard); replace glass panels	0.04	0.4

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	22.8	26.3	90	900	0.4
DS2	100	109.10	90	900	0.4
DS3	471.6	552.9	90	900	0.4

Fragility Number = 102
Name: Exterior Skin-Glass Curtainwall - Type 1

Unit: Square meter
Component or System: Full height glass curtain wall made of annealed or xxx glass
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Glass cracking	Replace the cracked glass panel(s)	0.031	0.3
DS2	Severe cracking of stucco, cracked gypboard, cracked glass	Grout stucco crack and repaint; tape, mud, sand and paint gypboard cracks, replace cracked glass panel(s) and "cleanup"	0.034	0.3

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	322.2	600	23	900	0.2
DS2	363.8	663.8	23	900	0.2

Fragility Number = 103
Name: Interior Walls GWB on Wood studs

Unit: Square meter
Component or System: Square meter of partition wall oriented in a specified direction per square meter of floor area at a specified level.
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Cracked GWB	Taping, sanding, and painting. Includes no mechanical repairs Includes no door repairs	0.002	0.4
DS2	Major cracks, buckling of gypsum wallboards at corners of walls	Replacing gypboard panels, and then taping, sanding and painting	0.01	0.4
DS3	Wood stud failure, sill plate splitting and failure, gypboard wall panel failure	Replace entire partition walls	0.03	0.4

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	32.7	37.0	9	900	0.2
DS2	52.9	61.8	9	900	0.2
	124.7	146.9	9	900	0.2

Fragility Number = 104
Name: Interior Partitions Type 9a

Unit: Square meter
Component or System: Full height 5/8 inch gypsumboard screwed on metal studs. No slip track or window panels.
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Visible damage and small cracks in gypsum boards that can be repaired with taping, pasting and painting. No window and door damage	Taping, patching and painting	0.0025	0.7
DS2	Extensive cracking or crushing in gypsum boards and minimal or no damage to metal studs. Re-hang door.	Replacing the gypsum boards, and then taping, and paintingRe-hang doors	0.006	0.5
DS3	Severe damage to gypsum boards and enough damage to metal studs and runners	Remove damaged materials Reframe walls; Repair damaged electrical; Install new Gyp; Tape, Sand and Paint; Includes some door repairs; Includes some minor mechanical repairs	0.014	0.4

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	32.7	37.0	9	900	0.2
DS2	52.9	61.8	9	900	0.3
	121.3	143.6	9	900	0.3

Fragility Number = 105
Name: Drywall partition and finish (excl painting) (Mitrani-Reiser, 2007)

Unit: Square meter
Component or System: Square meter of Drywall partition
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Visible damage and small cracks in gypsum boards that can be repaired with taping, pasting and painting. No window and door damage	Taping, patching and painting	0.0039	0.17
DS2	Extensive cracking or crushing in gypsum boards and minimal or no damage to metal studs. Re-hang door.	Replacing the gypsum boards, and then taping, and painting Re-hang doors	0.0085	0.23

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	29.9	29.9	9	900	0.2
DS2	178.7	178.7	9	900	0.2

Fragility Number = 106
Name: Drywall Paint (Mitrani-Reiser, 2007)

Unit: Square meter
Component or System: Painting of damaged walls.
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Visible damage and small cracks in gypsum boards that need re-painting.	painting	0.0039	0.17

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	16.7	16.7	9	900	0.2

Fragility Number = 107
Name: Exterior glazing (horizontal wall system) (Porter, 2000)

Unit: Square meter
Component or System: Horizontal wall system type glazing (usually in 5x6" panes).
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Cracking	Replace glass	0.04	0.36
DS2	Fallout	Replace glass	0.046	0.33

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	131.7	131.7	9	900	0.26
DS2	131.7	131.7	9	900	0.26

Fragility Number = 108
Name: Generic drift sensitive non-structural component (Aslani 2005)

Unit: no units
Component or System: Used to model generic drift sensitive systems such as: vertical piping, bath tubs, F.H.C, Ducts. Hence to adjust to the likely mean cost for the particular case study use the quantity (i.e. if for the actual building expected total value of generic components was $100,000, then set quantity to 1000).
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Slight damage		0.004	0.5
DS2	Moderate damage		0.008	0.5
DS3	Extensive damage		0.025	0.5
DS4	Complete damage		0.05	0.5

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	250.0	250.0	-	-	0.63
DS2	1000.0	1000.0	-	-	0.63
DS3	5000.0	5000.0	-	-	0.63
DS4	10000.0	10000.0	-	-	0.63

Fragility Number = 201
Name: Unanchored Bookcase

Unit: each
Component or System: Includes 6 foot and 8 foot high book cases. Fully loaded, not secured to wall or floor, 1/2 inch gap between back of bookcase and gypboard-metal stud wall.
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Overturns, contents fall out, fragile contents break.		0.4	0.3

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	75	150	6	50	0.2

Fragility Number = 202
Name: Exterior Roofing Concrete tile type 2

Unit: Square metre
Component or System: Square metre of roof area
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Tile dislodged - requires repair	Repair or replace dislodged tiles. Assume repair to 20% of roof area.	1.5	0.4
DS2	Major portion of tiles dislodged, requires full roof replacement	Replace full roof Assumes that plywood underlayment is intact and needs no repairs	1.9	0.4

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	44.8	56.2	90	900	0.3
DS2	109.4	120.6	90	900	0.2

Fragility Number = 203
Name: Ceiling Systems Suspended acoustical tile type1

Unit: Square metre
Component or System: Suspended ceiling system with T bars and acoustical ceiling tiles (2x4), ceiling tiles not exceeding 2 lbs/sf, installed in accordance with ICBO standard 25-2 or IBC (CISCA zones 3 and 4 and ASTM 635 and 636), no tile retainer clip. To finish later
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Some tiles displaced and fallen, usually in the perimeter of the room.	Turn off all mechanical systems. Remove fallen debris. Remove any residual water. Verify sound condition of ducting. Verify that structure above is sound. Install new ceiling tiles.	0.55	0.4
DS2	Significant tile falling and buckling of T bars (usually in the perimeter of the room).	Remove all damaged materials Inspect all mechanical systems Reinstall new T-bar Repair damaged mechanical system Install new ceiling tile	1.0	0.4

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	43.2	58.4	9	900	0.4
DS2	277.8	297.9	9	900	0.4

Fragility Number = 204
Name: Conveying - Hydraulic elevator

Unit: Each
Component or System: Single Cab Hydraulic 3 stop passenger elevator 3500 lb capacity w/ standard finishes
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Elevator does not work (because of various reasons, see related table). Major repairs needed	Repair elevator (depends on the type of damage, see related table).	0.4	0.3

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	33600	56000	3	5	0.2

Fragility Number = 205
Name: Roof Mounted Equipment

Unit: Each
Component or System: Chillers, fans, air handlers on vibration isolators with restraints and anchorage designed and installed per ASCE 7 requirements for normal occupancy. Flexible utility lines provided.applies to HVAC Units for 70,000 sf office
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Nonfunctioning		1.6	0.5

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	150000	220000	2	8	0.6

Fragility Number = 206
Name: Miscellaneous housewares and art objects

Unit: Each
Component or System: Miscellaneous houswares,'China and art objects, includes China cabinet assumed unanchored
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Fall off shelf, shelf over turns, objects break	Replace	0.2	0.5

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	20000	20000	1	100	0.4

Fragility Number = 207
Name: Home Entertainment Equipment

Unit: Each
Component or System: Speakers or televisions resting on shelves, stereos, etc. - assume unanchored.
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Falls off wall, slides off shelf, does not function	Replace	0.2	0.5

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	2500	2500	1	100	0.4

Fragility Number = 208
Name: Desktop Computers - unfastened

Unit: Each
Component or System: Speakers or televisions resting on shelves, stereos, etc. - assume unanchored.
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Monitors and computers. Assumes computers are on desk and not on floor. Also assumes monitor and computer not secured.	Replace	1.2	0.6

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	1000	2500	10	100	0.4

Fragility Number = 209
Name: Servers and network Equipment

Unit: Each
Component or System: Servers and network devices
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Equipment overturns and is rendered inoperative	Replace	0.8	0.5

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	40000	50000	2	6	0.4

Fragility Number = 210
Name: Tall File Cabinet

Unit: Each
Component or System: 3- or 4-drawer tall, 1-drawer wide metal file cabinet, full of paper, freestanding in both directions. Drawers are not locked, may not all be latched shut.
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	File cabinet overturns. Drawers may open before overturning, causing overturning. Some papers fall out. Cabinet may be damaged.	Replace	1.0	0.7

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	100	250	6	50	0.4

Fragility Number = 211
Name: Automatic sprinklers (Mitrani-Reiser, 2007)

Unit: Each
Component or System: Replacement of fractured pipe, and cost of wetted equipment and walls
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	File cabinet overturns. Drawers may open before overturning, causing overturning. Some papers fall out. Cabinet may be damaged.	Replace	32.0	1.4

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	900	900	6	50	1.0

Fragility Number = 212
Name: Desktop Computers - fastened

Unit: Each
Component or System: Speakers or televisions resting on shelves, stereos, etc. - assume unanchored.
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Monitors and computers. Assumes computers are on desk and not on floor. Also assumes monitor and computer not secured.	Replace	3.5	0.25

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	1000	2500	10	100	0.4

Fragility Number = 213
Name: Ceiling Systems Suspended acoustical tile type2

Unit: Square metre
Component or System: Suspended ceiling system
Demand: Acceleration (g)

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Collapse of suspended ceiling	Replace	302/(l+w)	0.81

Cost:

DS number	Min Cost	Max Cost	Lower limit	Upper limit	Dispersion Loss
DS1	23.8*A	23.8*A	9	900	0.5

Note that l is the length of the acoustical ceiling, and w is the width of the ceiling. A is the area (i.e. A=l.w).

These two quantities (l+w, and A) should be supplied at the end of the PGROUP line of the input file

Fragility Number = 214
Name: Generic acceleration sensitive non-structural component (Aslani 2005)

Unit: no units
Component or System: Used to model generic acceleration sensitive systems such as: fire protection systems, HVAC, Heating, cooling, pumps, plumbing, toilets. Hence to adjust to the likely mean cost for the particular case study use the quantity (i.e. if for the actual building expected total value of generic components was $100,000, then set quantity to 1000).
Demand: Storey Drift

Damage states:

DS number	Description	Repair Required	Median EDP	Dispersion (beta) EDP
DS1	Slight damage		0.25	0.6
DS2	Moderate damage		0.50	0.6
DS3	Extensive damage		1.0	0.6
DS4	Complete damage		2.0	0.6

Cost:

DS number	Min Cost ($)	Max Cost ($)	Lower limit	Upper limit	Dispersion Loss
DS1	200.0	200.0	-	-	0.63
DS2	1200.0	1200.0	-	-	0.63
DS3	3600.0	3600.0	-	-	0.63
DS4	10000.0	10000.0	-	-	0.63