CEE 288 Earthquake Hazard & Risk Analysis
HW8 – Potential Loss Analysis Using ATC & HAZUS

Meyer Library

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[Study Site]

The site for this study is Meyer Library (shown aerially in Fig1).

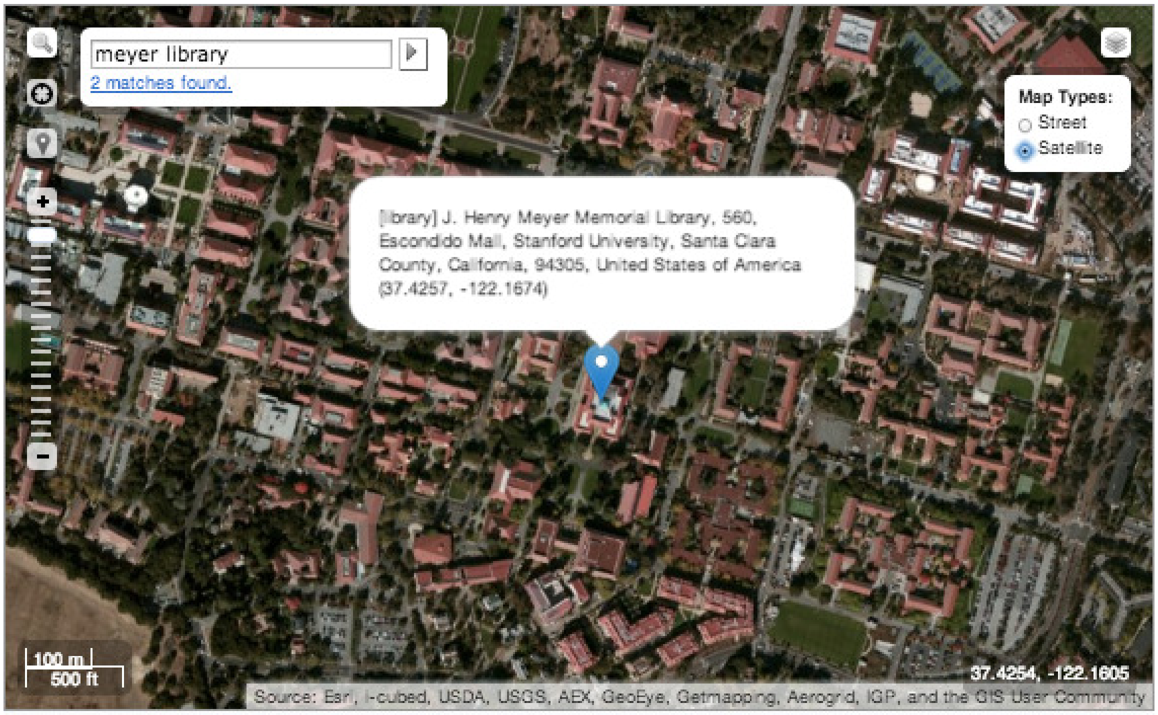

Fig1: Meyer Library Site (Source: USGS)

The information about the building is summarized in Table1, 2 & 3). Many assumptions are made to benchmark the analysis, and the particularly important ones are:

1. The "Total Gross" square footage of the building – 140873 ft^2 – is used to run the analysis in this report (Table1).
2. The deterministic replacement cost is \$700/sq.ft to match the mean of the probabilistic replacement cost; the retrofit cost is \$475/sq.ft (Table2)
3. The cost component is broken down into (1) content, which includes office equipment and high tech equipment, (2) nonstructural, which includes mechanical and electrical, (3) structural, as well as (4) downtime loss (Table2 & 3)
    i. Since the library is likely intended to be a nonprofit organization, it has no revenue, and thus no direct monetary loss due to downtime. Rather, the downtime loss is estimated from developing a student welfare loss metric, that is university's annual library budget of about \$13.3M (Table3). Given the library budget is largely generated from tuition, and can thus be seen as student's purchase of library services, the loss of such services due to the library's downtime (measured in budget amount) is the downtime loss.
    ii. For Meyer Library particularly, the metric is based on: (1) Meyer library's book collection in proportion to the school's entire library system, and (2) Stanford's undergraduate population in proportion to the school's entire student population. Because Meyer is both a library with a permanent book collection and (commonly referred to as) an "undergraduate" study space, we gather it's not enough to merely proportion the university's annual budget to that ratio of library books in Meyer. Thus, added is an additional percentage equal to the ratio of undergraduate students.
4. Based on the "Geography" and "Building Type" data, hazard curves were generated: the resultant annual frequency of exceedence for given ground acceleration were subsequently converted to those for MMI and for ground displacements (for ATC and HAZUS analysis, respectively), using linear interpolation (Fig2, computed using Matlab).

Floor Usage			
	Assignable	Usable	Gross
FLR	sq ft	sq ft	sq ft
0	16880	24785	26117
1	12505	19596	20770
2	24147	26326	28590
3	22098	24334	26204
4	11507	13581	14515
5	0	5112	5500
M	17022	17829	19177
Total	104159	131563	**140873**

Table1. Floor Usage (Source: Stanford Facilities Info Management System)

	Building General Information		
	Geography		**Notes/Units**
	Lat	37.43	degree
	Lon	-122.17	degree
	Soil Class	C	Assuming Same Soil Class as from HW7
	Vs30	537	Resultant from Class C Soil
	Building Type		
	Date Built	1966	
	ATC Class	88	
	ATC Social Function Class	H	ref no. 24
	HAZUS Class	C1M	
	Building Period	0.75	Building Period, for C1M Type
	Cost		
	Determinisitc Replacement Cost	700	$/sq.ft, from HW8
		98.6	$ millions, based on gross square footage
	Probabilistic Replacement Cost	600	$/sq.ft, today value, lower
		700	$/sq.ft, today value, mean
		800	$/sq.ft, today value, upper
		0.3	coefficient of variation
	Determinisitc Retrofit Cost	475	$/sq.ft, 1996 value
		66.9	$ millions, 1996 value
		697.15	$/sq.ft, 2013 value (Inflation Source: usinflationcalculator.com)
		98.2	$ millions, 2013 value
	Actual Proposed Renovation Cost	45	$ millions, 2013 value (Sorce: stanforddaily.com)
	Cost per Usage		
	Office	9.86	$ millions, 10% of Total Replacement Cost
+	High Tech	1.97	$ millions, 2% of Total Replacement Cost
=	**Content**	11.83	$ millions, 12% of Total Replacement Cost
	Electrical	9.86	$ millions, 10% of Total Replacement Cost
+	Mechanical	14.79	$ millions, 15% of Total Replacement Cost
=	**Nonstructural**	24.65	$ millions, 25% of Total Replacement Cost
	Structural	62.12	$ millions, remaning 63% of Total Replacement Cost

Table2. General Building Information: Geographic Location, Building Type, Cost per Usage

Down Time Cost		
Metric 1: Volumn of Books		
All Libraries Combined	8500000	(Source: ala.org/tools/libfactsheets/alalibraryfactsheet22)
Meyer Library	600000	(Source: Stanford University Budge Plan 12/13)
Metric 2: Number of Students		
University Students	15870	Total number at Stanford
Undergraduate Students	6999	Total number at Stanford - Meyer is an undergrad library
Library Budget		
Annual Increase in Library Budget	1100000	2012 value (Source: Stanford University Budge Plan 12/13)
	0.068	value above inflation (Source: Stanford University Budge Plan 12/13)
2011 Inflation	0.021	(Source: usinflationcalculator.com)
2012 Inflation	0.003	(Source: usinflationcalculator.com)
Library Budget	13.30	$ millons, 2013 (assume no increase, only inflation)
Meyer Library Budget	0.9391	**$ millons, assuming budget is porportional to # of books**
	1.3533	**$ millons, up by percentage of undergraduate/total students**
	0.0037	**$ millons, per day**

Table3. Downtime Cost Calculation

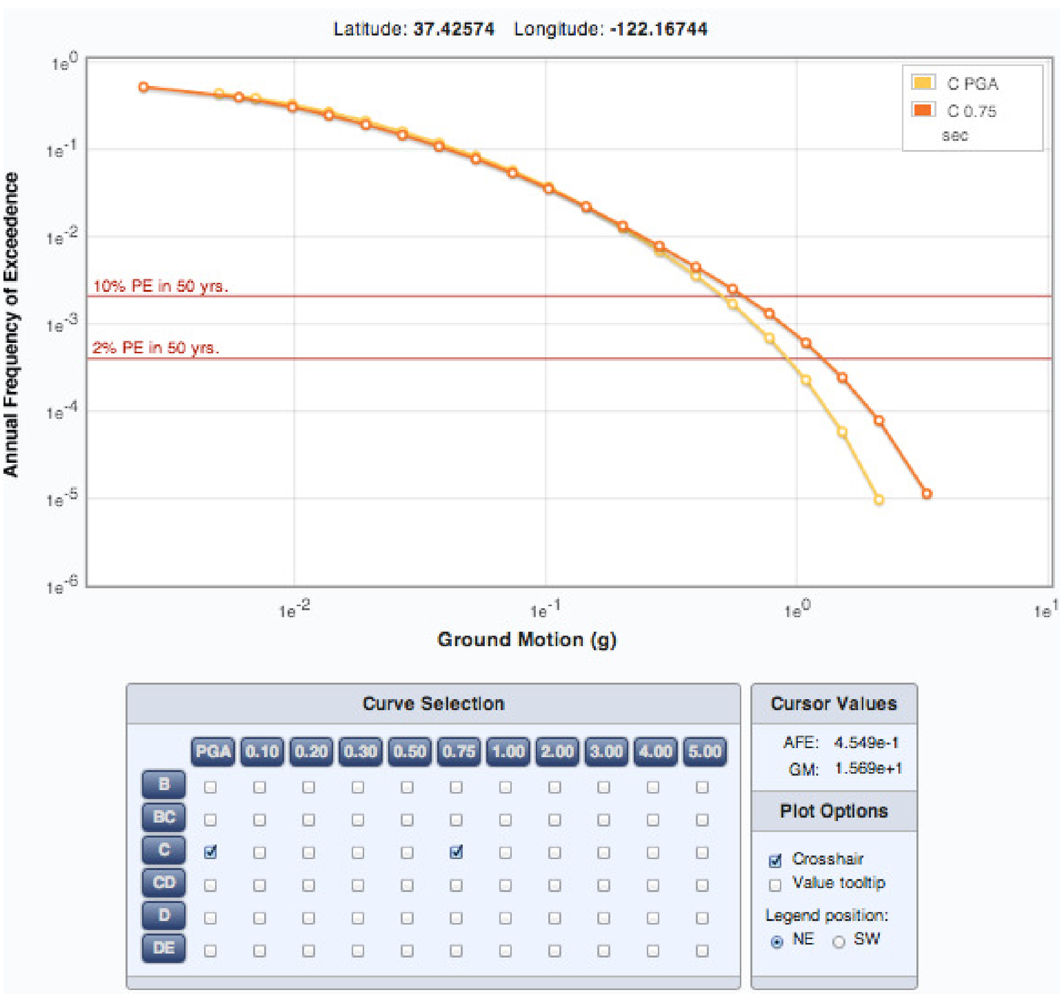

Fig2. Resultant PGA (Part A) and T=0.75s (Part B) Hazard Curve (Source: USGS)

[PART A] Analysis with ATC-13 (1985)

[1] Structural Class

Using Table 3.1 from ATC-13, the chosen structural class for Meyer library is **Class 88,** which by ATC's definition is 'Moment Resisting Non Ductile Concrete Frame (Distributed Frame) – Medium Rise". The choice for this class is based on visual inspection of the building as well as the analysis of the floor plans of the library – (1) the structure is made of reinforced concrete; since it was designed in the 1960's, a reasonable assumption is that the detailing of reinforcement is such that brittle behavior can be expected during earthquakes; (2) the lateral force resisting system consists of moment resisting frames (with very slender columns around the perimeter), and no shear walls are visible on the plans.

[2] Social Function

Using Table 3.2 from ATC-13, the function **class H** (Education) was chosen for Meyer library.

[3] MMI Occurrence & Exceedence

To compute the annual MMI occurrence and exceedence, the PGA first needs to be converted to MMI:

$$\text{Log(PGA)} = 0.25 + 0.25\text{MMI}$$

Then, the annual exceedence rate – V(MMI>mmi) – is linearly extrapolated (Fig3), based on USGS's hazard curve (Fig2); although only MMI of 6 to 12 is needed, MMI of 5 is also computed, to ease the computation of occurrence rate. The annual occurrence rate – V(MMI=mmi) – is the difference between the current MMI and the MMI one magnitude less. Additionally, the annual occurrence rate was normalized to compute the total occurrence rate (which is irrespective of time) – this value was used in estimation of expected damage state and expected loss.

Hazard Rate					
MMI		PGA	V(MMI>mmi)	V(MMI=mmi)	V*(MMI=mmi)
		g	lin. extrapolate	V(j) = V(>j-1)-V(>j)	normalized for total
V	5	0.03	0.1410	/	/
VI	6	0.06	**0.0791**	0.0619	**0.4392**
VII	7	0.10	**0.0383**	0.0408	**0.2897**
VIII	8	0.18	**0.0164**	0.0219	**0.1552**
IX	9	0.32	**0.0058**	0.0106	**0.0750**
X	10	0.57	**0.0016**	0.0042	**0.0297**
XI	11	1.02	**0.0003**	0.0013	**0.0092**
XII	12	1.81	**0.0000**	0.0003	**0.0021**

Table3. MMI Exceedence and Occurrence Rate

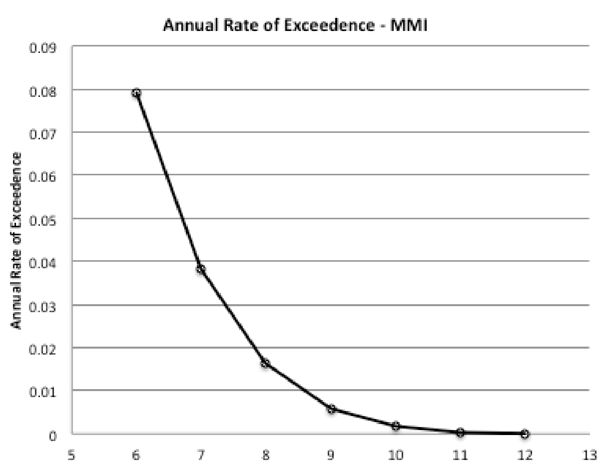

Fig3. MMI Exceedence Rate

[4] Damage – Deterministic Loss

To perform damage estimation, the damage probability matrix (DPM) for all of the building components were gathered (we note that the DPM provided by ATC is in percentage term, and CDF is the cumulative damage fraction):

i. **Structural:** (ATC Class 88; Table3a)

	P(CDF|MMI)						
CDF\MMI	VI	VII	VIII	IX	X	XI	XII
0	0.3						
0.5	30.9	0.3					
5	68.8	96.9	33.6	1.9	0.2		
20		2.8	65.7	65.1	31	3.6	0.5
45			0.7	33	68	70	28
80					1.3	26	71
100							0.4

Table3a. Structural DPM

ii. **Content**: Office Equipment (ATC Class 65; Table3b) and High Tech (ATC Class70; Table3c)

	P(CDF|MMI)						
CDF\MMI	VI	VII	VIII	IX	X	XI	XII
0							
0.5	73.9	0.7					
5	26.1	99.3	97.6				
20			2.4	95.2	76	1	
45				4.8	24	96	65
80						2.7	36
100							

Table3b. Office Equipment DPM

	P(CDF|MMI)						
CDF\MMI	VI	VII	VIII	IX	X	XI	XII
0	2.9						
0.5	44.4	4.5					
5	52.7	89.8	36.8	7.9	0.5		
20		5.7	61.7	63.5	24	1.6	0.1
45			1.5	28.3	65	50	14
80				0.3	10	49	84
100							2.4

Table3c. High Tech DPM

iii. **Nonstructural**: Electrical (ATC Class 66; Table3d) and Mechanical (ATC Class 68; Table3e)

	P(CDF|MMI)						
CDF\MMI	VI	VII	VIII	IX	X	XI	XII
0	0.5	0.2					
0.5	25.4	10.3	1.8				
5	74.1	86.8	64.3	16.9	0.5		
20		2.7	33.5	71.5	45	9.3	1.3
45			0.4	11.6	54	86	51
80					0.5	4.4	48
100							

Table3d. Electrical DPM

	P(CDF|MMI)						
CDF\MMI	VI	VII	VIII	IX	X	XI	XII
0	8						
0.5	79.1	8.8	0.8				
5	12.9	91.2	87.9	36	7.6	1.1	
20			11.3	63.3	74	42	11
45				0.7	19	56	67
80						1.8	22
100							

Table3e. Mechanical DPM

iv. **Downtime:** (Class H; Table3f)

	100% functionality (time in days)			
CDF	MEAN100	MIN100	MAX100	SDEV100
0	0	0	0	0
0.5	5.7	0	20	6.5
5	15.5	2	40	11.6
20	72.1	7	160	51
45	183	90	270	48.6
80	362.1	300	400	25.9
100	562.6	365	800	115

Table3f. Expected Downtime, given CDF

[4a & 4b]

The expected (1) annual CDF and (2) total CDF and its variance are computed by using V(MMI=mmi) and the normalized V*(MMI=mmi) respectively:

$$E[CDF] = \sum_{6}^{12} \sum_{1}^{17} CDF_i * P[CDF_i \mid MMI] * v_{=MMI} = \sum_{6}^{12} \mu_{CDF|MMI} * v_{=MMI}$$

$$Var[CDF] = \sum_{6}^{12} \sum_{1}^{7} (CDF_i - \mu_{CDF|MMI})^2 P[CDF_i \mid MMI] * v_{=MMI} = \sum_{6}^{12} \sigma^2{}_{CDF|MMI} * v_{=MMI}$$

Because the loss is deterministic ($700/ft^2), the expected loss is merely E[CDF]*Loss. The results are shown on the next page – for average annual loss (AAL, Chart1a) and total loss (Chart1b). As expected, the two provides very different answers, though they cannot be compared amongst themselves: AAL is the expected loss per year, where as “total loss” is the expected loss irrespective of time. Additionally, when adding the variances of all components together, it is assumed that the components are independent of each other, since the coefficient of correlation is unknown (though correlation is likely positive, as damage is likely to afflict damage to every component of the building in all given events).

From the charts on the next page (and for both AAL and total loss), we see that expected loss from structural damage constitutes about 95% of the entire building’s expected loss, even thought the structural component is only 68% of the building’s total construction cost (Table2). This finding perhaps can allow us to focus primarily on assessing only the loss from structural damages as an estimate of the building’s overall loss. Lastly, we note that the standard deviations for all values are considerably large, which results in large uncertainties in the actual loss given an event.

ANNUAL AVERAGE LOSS, AAL						
	Building Loss		CDF		Deterministic Loss	
		Replacement Cost ($ millions)	E(CDF) (%)	stdev(CDF)	Loss ($ millions)	stdev(Loss)
	Office	9.86	0.04	3.75	0.0043	0.3701
+	High Tech	1.97	0.09	5.74	0.0017	0.1131
=	**Contents**	**11.83**	**0.05**	**3.27**	**0.0060**	0.3870
	Electrical	9.86	0.09	4.48	0.0085	0.4418
+	Mechanical	14.79	0.08	3.26	0.0125	0.4821
=	**Nonstructural**	**24.65**	**0.09**	**2.65**	**0.0210**	0.6539
	Structural	**62.12**	**1.32**	**2.10**	**0.8187**	1.3041
	Downtime Loss, Due to DS = 3					
		Cost ($/day)	Days	stdev(Days)	Loss ($ millions)	stdev(Loss)
	Downtime	**0.0037**	**15.5000**	**11.6000**	**0.0575**	0.0430
	Total Loss					
					Total Loss ($ millions)	stdev(Loss)
					0.9031	**1.5100**

Chart1a: Average Annual Loss (computed with V(MMI=mmi)

TOTAL LOSS						
	Building Loss		CDF		Deterministic Loss	
		Replacement Cost ($ millions)	E(CDF) (%)	stdev(CDF)	Loss ($ millions)	stdev(Loss)
	Office	9.86	0.31	10.00	0.0303	0.9857
+	High Tech	1.97	0.61	15.28	0.0120	0.3013
=	**Contents**	**11.83**	**0.36**	**8.71**	**0.0423**	1.0307
	Electrical	9.86	0.61	11.93	0.0605	1.1766
+	Mechanical	14.79	0.60	8.68	0.0887	1.2841
=	**Nonstructural**	**24.65**	**0.61**	**7.06**	**0.1492**	1.7416
	Structural	**62.12**	**9.35**	**5.59**	**5.8072**	3.4733
	Downtime Loss, Due to DS = 3					
		Cost ($/day)	Days	stdev(Days)	Loss ($ millions)	stdev(Loss)
	Downtime	**0.0037**	**15.5000**	**11.6000**	**0.0575**	0.0430
	Total Loss					
					Total Loss ($ millions)	stdev(Loss)
					6.0562	**4.0202**

Chart1b: Total Loss (computed with V(MMI=mmi))*

[5] Damage – Probabilistic Loss

To perform the loss analysis based on probabilistic square footage loss, the probability distribution given damage state needs to be established (Fig4a. for CCDF, Fig4b for PMF). The step size is $50/ft^2.

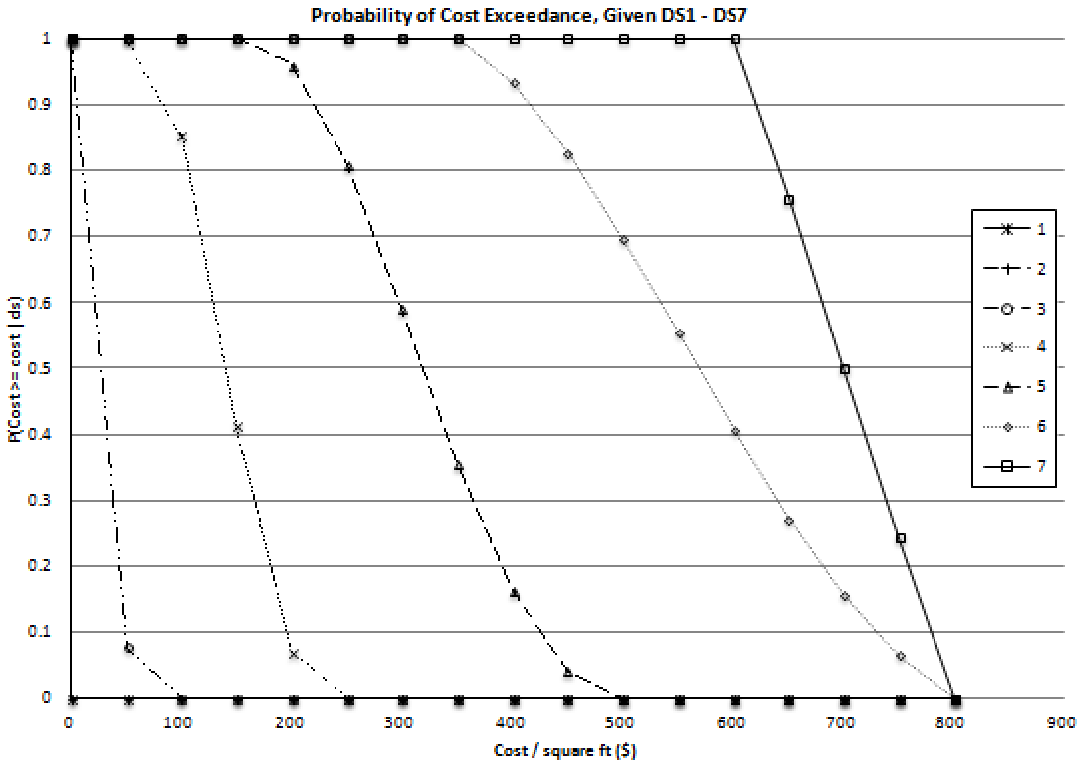

Fig4a. CCDF

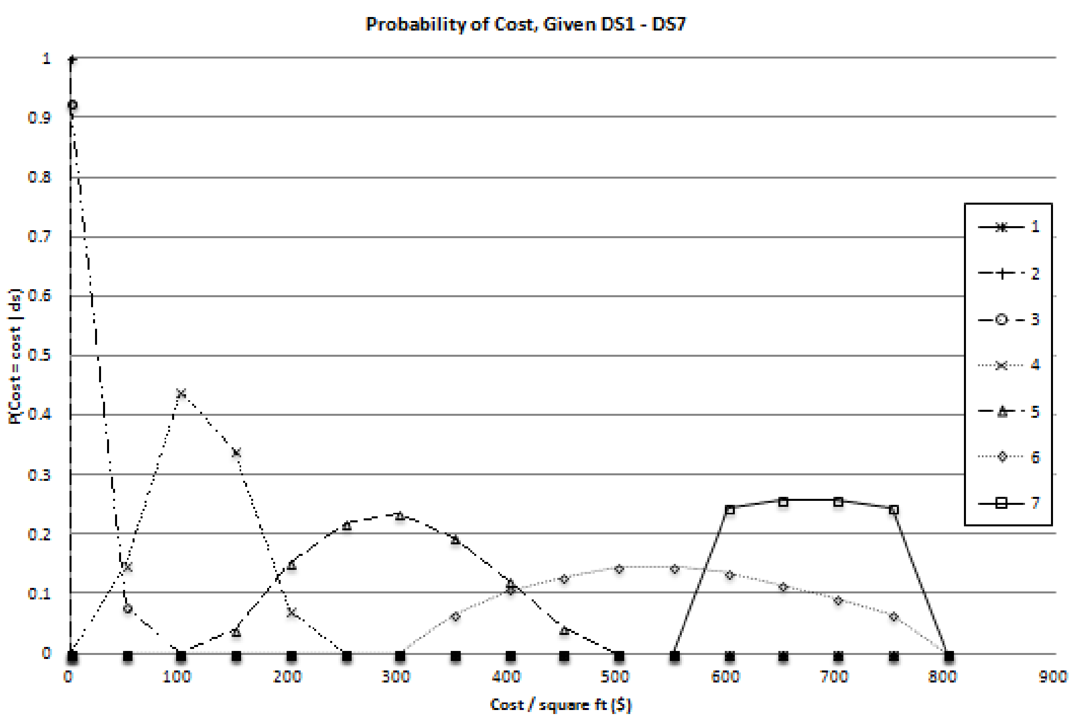

Fig4b. PMF

[5a & b]

Only loss from structural damage is analyzed in this question (i.e. content, non-structural and downtime losses are not considered).

Expected Loss ($ millions)	stdev(Loss)	10% Exceedance Loss ($ millions)
0.8147	**0.4164**	**2.3333**

Chart2: Annual Loss Exceedence (expected & 10% annual rate)

Although the expected loss estimated by using probabilistic loss (Chart2) should equal to the expected loss obtained by using deterministic loss (Chart1a), there are minor differences between the two results (around 0.5% difference). This is due to numerical integration error in case of probabilistic loss (specifically, the PMFs are integrated over the midpoint – this is not displayed well in Fig4a & b). The 10% annual exceedence loss value (Chart2) is obtained by linear interpolation from the annual loss rate curve (Fig5).

$V_{L>l}$ = 10%, L = $2.33 million

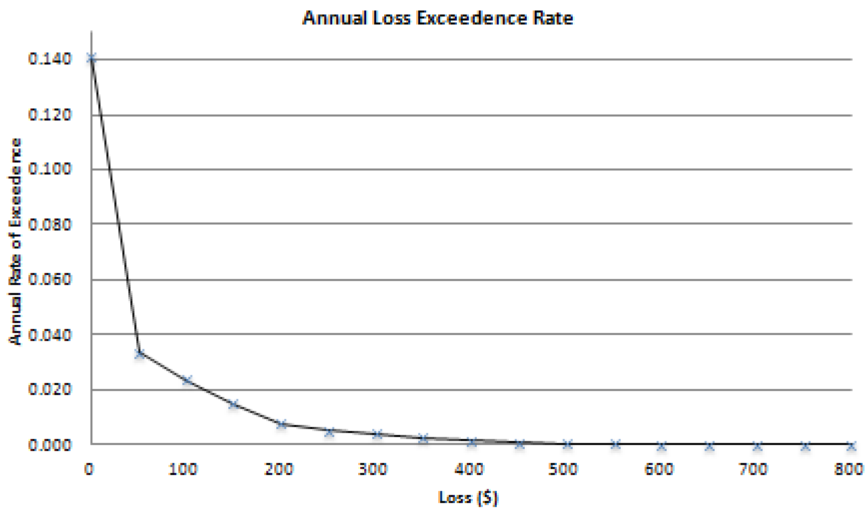

Fig5: Annual Loss Rate

[6] Damage After Retrofit – Deterministic & Probabilistic Loss

Three different options for the retrofit Meyer Library are considered; these are:

i. **Adding shear walls**: to the level that effectively changes converts the building into a "Reinforced Concrete Shear Wall (with Moment-Resisting Frame) – Medium Rise" (ATC Class 4; option acronym in this report: retro1; Table4a)

	P(CDF|MMI)						
CDF\MMI	VI	VII	VIII	IX	X	XI	XII
0	20.4						
0.5	70.3	15.5					
5	9.3	84.5	88.4	28.9	1.4		
20			11.6	71.1	82	39	3.8
45					17	61	89
80							7.5
100							

Table4a. retro1 DPM

ii. **Making moment frame ductile**: to the level that effectively changes converts the building into a “Moment-Resisting Ductile Concrete Frame – Medium Rise” (ATC Class 19; option acronym in this report: retro2; Table4b)

	P(CDF|MMI)						
CDF\MMI	VI	VII	VIII	IX	X	XI	XII
0	0.3						
0.5	41	2.8	0.6				
5	58.7	97	91.2	46.7	9		
20		0.2	8.2	53.3	89	61	20
45					1.7	39	79
80							0.4
100							

Table4b. retro2 DPM

iii. **Making the building safe from damage state 7** (i.e. damage state ‘destroyed’)**:** essentially shifting the damage probability matrix up (option acronym in this report: retro3; Table4c)

	P(CDF|MMI)						
CDF\MMI	VI	VII	VIII	IX	X	XI	XII
0	31.2	0.3					
0.5	68.8	96.9	33.6	1.9	0.2		
5		2.8	65.7	65.1	31	3.6	0.5
20			0.7	33	68	70	28
45					1.3	26	71
80							0.4
100							

Table4c. retro3 DPM

[6 a, b & c]

Since changes are only made to the structural system and since the structural damage amounts to more than 90% of the total loss, only losses from structural damage need to be considered to compare between the various retrofits against the original Class 88 structure (this also goes back to the earlier discussion on the lack of correlation between damages – more specifically, how changes in structural system can change the damage severity in content and nonstructural components). Additionally and similar to issues due to numerical integration from question 5, the expected AAL computed with deterministic loss is slightly different from that computed with probabilistic loss with the same mean; for consistency, the former values are used for comparisons (Char3 & Fig6).

Looking at the result, adding shear walls (retro1) or making the moment frame ductile (retro2) provides comparatively similar savings (47% and 39%, respectively), while upping the building’s structural capacity generally to eliminate damage state 7 (retro3) provides much better saving (74%). From the three considered retrofit options, the first one (i.e. adding the shear walls) is the least costly option – we estimate that the cost for this option would be around $275/ft^2. The resulting total cost in this case would be $38.7 million which is around twice the savings gained by retrofit. The other two options would be much more expensive – making the non-ductile frame ductile (retro 2) would require significant retrofit and the resulting savings (which are less than for retro 1 option) do not justify the investment. Retrofit option 3 would require a combination of retrofit procedures required in options 1 and 2; we estimate that the cost of this retrofit would be between $50 million and $60 million. Therefore, even though it provides higher savings than first two options (~$30 million), the additional cost wouldn’t justify choosing this retrofit option over the option of adding the shear walls.

In addition, it should be recognized that this analysis doesn't take into account the possible additional savings that could be made over the 50 years lifespan from the return on the investment. The Stanford University's annual return rate of 9.3%[1] should also be taken into account when making a final decision.

	Average Annual Loss from Structural Damages		
	Expected Loss ($ millions)	stdev(Loss)	10% Exceedance Loss ($ millions)
original	0.8187	0.4164	2.3333
retro1	0.4347	0.9903	2.1095
retro2	0.4959	1.0136	2.1105
retro3	0.2115	0.8690	1.9964

	Savings from Structural Retrofit Options	
	Average Annual Savings from Retrofit ($ millions)	Expected Savings from Retrofit in 50yrs ($ millions)
retro1	0.3840	19.2003
retro2	0.3228	16.1379
retro3	0.6072	30.3602

Chart3. Loss vs. Savings Differences Between Original Structure and Retrofit Options

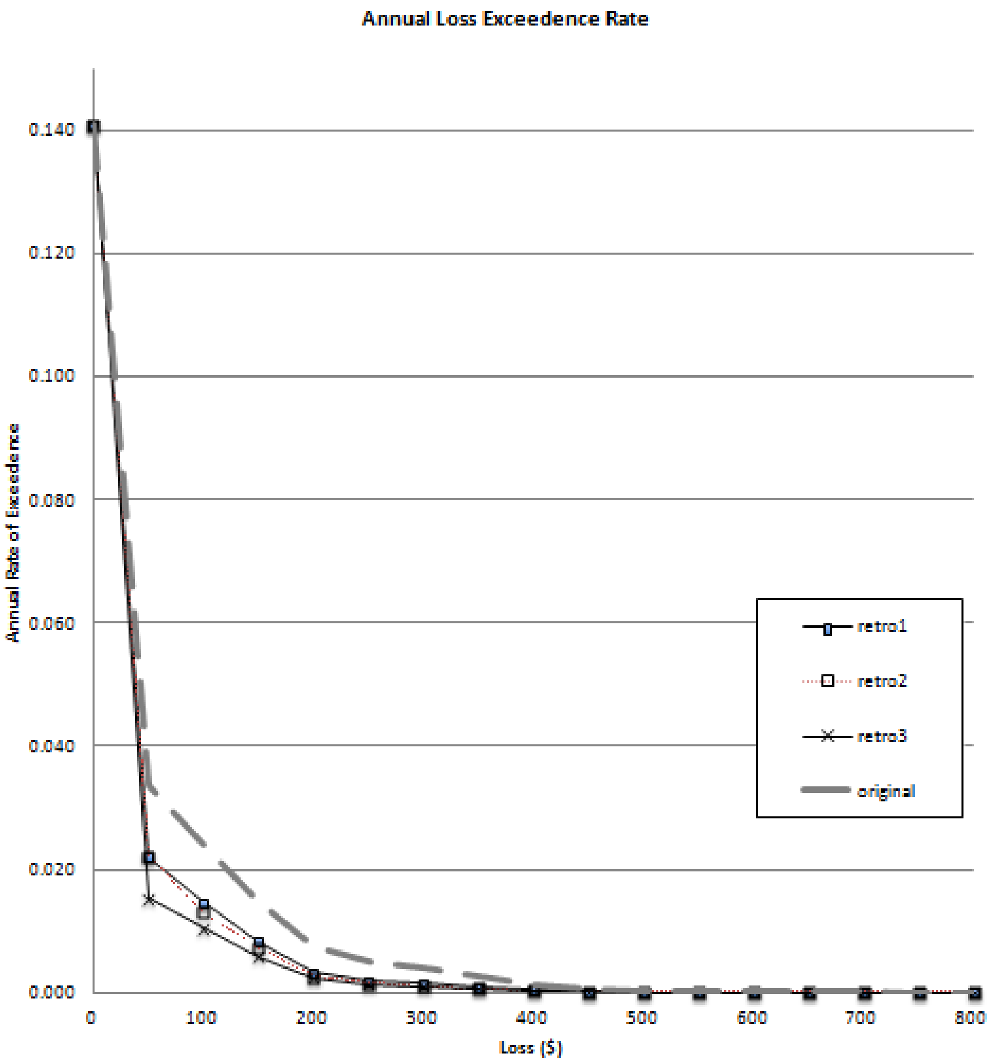

Fig6. *Annual Loss Rate*

[1] Source: smc.stanford.edu/sites/default/files/site_files/Report%20from%20SMC%202011.pdf

PART B – Analysis using HAZUS (2000)

[1] Model building types according to HAZUS

HAZUS methodology lists 36 different general building types. Building type C1M, i.e. mid-rise concrete moment frame, was chosen to classify Meyer Library. The C1 class is the general building type for reinforced concrete moment resisting frames and includes both ductile and non-ductile frames.

[2&3] Predominant period and response spectral acceleration hazard curve from USGS

As stated in part A, the predominant period of the structure was estimated as T = 0.75 seconds. The response spectral acceleration hazard curve was obtained from USGS (Fig.2); since the HAZUS methodology defines fragility curves in terms of spectral displacement, a proper conversion between Sa and Sd was made using equation: Sd = (T/2π)^2 Sa. Linear interpolation was used to obtain equally spaced values of spectral accelerations and spectral displacements.

[4] Construction of fragility functions

The probability of being in or exceeding a given state according to HAZUS methodology is modeled as a cumulative lognormal distribution:

$$P[DS > ds|Sd] = \Phi[\frac{1}{\beta_{ds}} \ln(\frac{Sd}{\widehat{Sd}})] ,$$

where the beta and the median values are defined for each building type. The values for the analysis were taken from table 5.9a for building type C1M and are shown in the table below.

Table 5. Structural Fragility Curve Parameters – High-Code Seismic design level

Structural Class	slight		moderate		extensive		complete	
C1M	Median	Beta	Median	Beta	Median	Beta	Median	Beta
	1.5	0.68	3	0.67	9	0.68	24	0.81

It should be pointed out that the values obtained by using the parameters from table 5 will represent the values for the retrofitted structure. The reason is that the structural system of Meyer Library is a non-ductile RC MRF so the design level for un-retrofitted structure should be either 'moderate code seismic design level' (with ductility parameter 4) or 'low-code'/'pre-code' seismic design level (ductility parameter 3.3). The analysis for un-retrofitted structure will be performed in part 9 in order to gauge the benefits of undertaking a retrofit and making a recommendation.

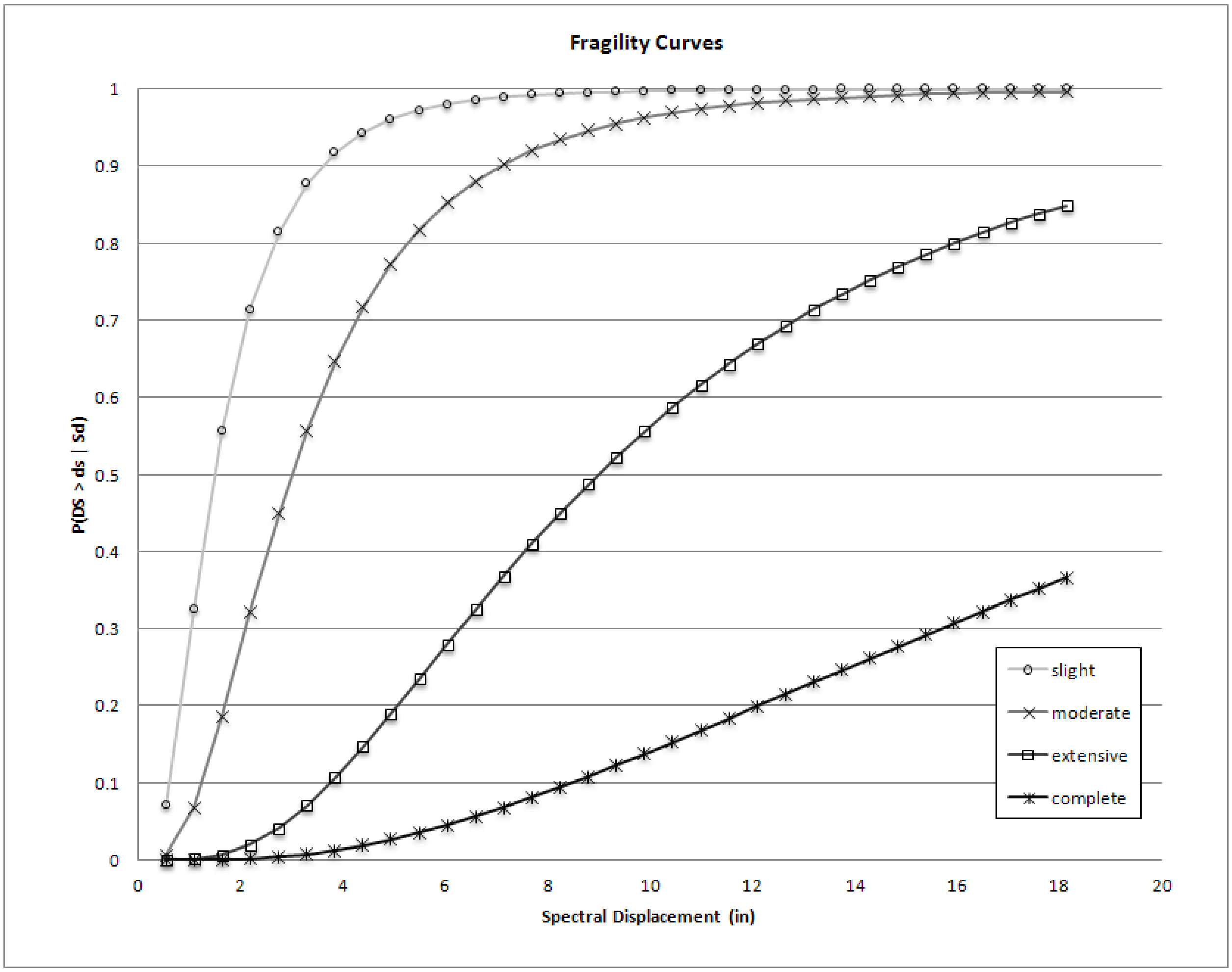

Figure 7. Fragility functions for different damage states

[5] Probabilities of being in each damage state as a function of spectral displacement Sd

Fragility functions give the probability of being in or exceeding a specified damage state given a value of spectral displacement Sd. Using that information the probability of being in a certain damage state can be computed as follows:

P[DS = Complete] = P[DS >= Complete]
P[DS = Extensive] = P[DS >= Extensive] – P[DS >= Complete]
P[DS = Moderate] = P[DS >= Moderate] – P[DS >= Extensive]
P[DS = Slight] = P[DS >= Slight] – P[DS >= Moderate]
P[DS = None] = 1 – P[DS >= Slight]

These calculations were performed using excel and the results are given in the table 6 on the following page.

Table 6. Probability of being in each damage state as a function of Sd

Sa (g)	Sd	none	slight	moderate	extensive	complete
		P(DM=dm|Sd)	P(DM=dm|Sd)	P(DM=dm|Sd)	P(DM=dm|Sd)	P(DM=dm|Sd)
0.1	0.550298483	0.929846185	0.064470231	0.005663766	1.82444E-05	1.57397E-06
0.2	1.100596965	0.675557719	0.257200893	0.066241456	0.000929083	7.08487E-05
0.3	1.650895448	0.443950813	0.369714471	0.180018743	0.005840435	0.000475539
0.4	2.201193931	0.28636966	0.391628414	0.302818726	0.017591496	0.001591704
0.5	2.751492413	0.186149825	0.365194279	0.407968678	0.036939187	0.003748031
0.6	3.301790896	0.122964567	0.320155341	0.486726277	0.062988658	0.007165157
0.7	3.852089379	0.082722992	0.271799351	0.539453749	0.094068699	0.01195521
0.8	4.402387861	0.056670189	0.226841772	0.569992937	0.128352281	0.018142821
0.9	4.952686344	0.039495889	0.187663149	0.58297062	0.164180855	0.025689487
1	5.502984827	0.027969656	0.154633251	0.582689914	0.200192392	0.034514787
1.1	6.053283309	0.020100864	0.127277403	0.572766033	0.235342811	0.044512889
1.2	6.603581792	0.014642521	0.10483318	0.556082018	0.268877642	0.055564639
1.3	7.153880275	0.01079975	0.086502334	0.534866522	0.30028535	0.067546044
1.4	7.704178758	0.008057066	0.071554755	0.510806097	0.329248065	0.080334017
1.5	8.25447724	0.006074608	0.059362701	0.485155825	0.355596772	0.093810093
1.6	8.804775723	0.004624778	0.049403719	0.458835342	0.379273452	0.107862709
1.7	9.355074206	0.003552911	0.041250768	0.432507392	0.400300457	0.122388472
1.8	9.905372688	0.002752454	0.034558313	0.406640045	0.418756464	0.137292724
1.9	10.45567117	0.002149059	0.029048256	0.381555052	0.43475799	0.152489644
2	11.00596965	0.001690222	0.024497307	0.357464998	0.448445435	0.167902038
2.1	11.55626814	0.001338453	0.020726266	0.334501622	0.459972715	0.183460943
2.2	12.10656662	0.001066701	0.017591198	0.312737301	0.469499689	0.199105112
2.3	12.6568651	0.000855253	0.014976299	0.292201271	0.477186733	0.214780443
2.4	13.20716358	0.000689616	0.012788195	0.272891848	0.483190942	0.230439398
2.5	13.75746207	0.000559039	0.010951394	0.254785592	0.487663567	0.246040408
2.6	14.30776055	0.000455482	0.00940469	0.237844159	0.490748352	0.261547317
2.7	14.85805903	0.000372889	0.00809831	0.222019405	0.492580554	0.276928842
2.8	15.40835752	0.00030666	0.006991651	0.207257158	0.49328645	0.292158081
2.9	15.958656	0.000253284	0.006051488	0.193499987	0.492983195	0.307212047
3	16.50895448	0.000210058	0.005250546	0.180689222	0.491778926	0.322071249
3.1	17.05925296	0.00017489	0.004566366	0.168766397	0.489773041	0.336719306
3.2	17.60955145	0.000146153	0.003980398	0.157674268	0.487056578	0.351142602
3.3	18.15984993	0.000122574	0.00347727	0.147357509	0.48371268	0.365329967

[6] Expected value and standard deviation of damage state

In order to calculate expected value and standard deviation of damage state, both probability P[DS=ds$_i$|Sd] as well as P[Sd] are necessary. The former probability was calculated in part 5, while the latter probability can be estimated by using exceedence rates from the hazard curve that was obtained from the USGS site. The rate of observing a particular ground motion intensity measure (in this case Sd is used) can be calculated as follows:

$$v_{=y} = v_{\geq y} - v_{\geq y+\Delta y}$$

The obtained rates can be normalized to get the approximation of observing particular ground motion intensity in the following manner:

$$P[Y = y] = v^*_{=y} = \frac{v_{=y}}{\sum v_{=y}}$$

From that information the probability of being in a particular damage state can be computed ba using the total probability theorem:

$$P[DS] = \sum_{Sd} P[DS = ds_i|Sd] * P[Sd]$$

The expected damage state can then be computed as:

$$E[DS] = \sum DS_i * P[DS_i]$$

where DS_i is the numerical value assigned to the damage state (None = 1, Slight = 2, Moderate = 3, Extensive = 4, Complete = 5). The results are given in the following table:

Table 7. Probabilities of damage states, expected damage state & standard deviation

P[None]	P[Slight]	P[Moderate]	P[Extensive]	P[Complete]
0.7564	0.1479	0.0805	0.0126	0.0026
Expected damage state:			1.3572	
Variance of the damage state:			0.497709136	
Standard deviation of the damage state:			0.705485036	

Table 8. Rates of observing a particular ground motion intensity measure (Y = Sd)

$V_{>=y}$	$V_{=y}$	$V_{=y}$ normalized
0.037812	0.023941	0.633252135
0.013871	0.0064755	0.171280406
0.0073955	0.0028886	0.076405001
0.0045069	0.0012626	0.033396439
0.0032443	0.000948	0.025075102
0.0022963	0.0005475	0.014481665
0.0017488	0.0004772	0.012622193
0.0012716	0.0002278	0.006025431
0.0010438	0.00022775	0.006024108
0.00081605	0.00021354	0.005648246
0.00060251	0.00008523	0.002254379
0.00051728	8.524E-05	0.002254643
0.00043204	0.00008523	0.002254379
0.00034681	0.00008524	0.002254643
0.00026157	0.00003884	0.001027339
0.00022273	0.00002725	0.000720777
0.00019548	0.00002725	0.000720777
0.00016823	0.00002725	0.000720777
0.00014098	0.00002725	0.000720777
0.00011373	0.000027255	0.000720909
0.000086475	0.000012184	0.000322273
0.000074291	5.726E-06	0.000151456
0.000068565	5.727E-06	0.000151482
0.000062838	0.000005726	0.000151456
0.000057112	0.000005727	0.000151482
0.000051385	0.000005726	0.000151456
0.000045659	5.727E-06	0.000151482
0.000039932	5.726E-06	0.000151456
0.000034206	0.000005727	0.000151482
0.000028479	0.000005726	0.000151456
0.000022753	0.000005727	0.000151482
0.000017026	0.000005726	0.000151456
0.0000113	0.000005726	0.000151456
sum	**0.037806426**	**1**

[7] Repair cost ratios $RCS_{DS,i}$ for the structure and occupancy type

Table 8. Repair cost ratios (in % of building replacement cost)

No	Label	Occupancy Class	Structural Damage State			
			Slight	Moderate	Extensive	Complete
32	EDU1	Education - Schools/Libraries	0.4	1.9	9.5	18.9

[8] Expected loss from direct structural damage & annual loss rate curve

The calculations for this part were performed by assuming that the building replacement costs will vary between \$600/ft^2 and \$800/ft^2; truncated normal distribution (mean in the middle of the replacement cost range, coefficient of variation 0.3) was assumed. The following parameters for the truncated normal distribution for each damage state were obtained:

Table 9. Distribution parameters for each damage state

DS	RCS	mean L|DS	sigma L|DS	L min	L max
1	0	0	0	0	0
2	0.4	2.8	0.84	2.4	3.2
3	1.9	13.3	3.99	11.4	15.2
4	9.5	66.5	19.95	57	76
5	18.9	132.3	39.69	113.4	151.2

The expected loss was calculated as follows:

$$E[Loss] = \sum_{all\ DS} \sum_{all\ Sd} \int_{Lmin}^{Lmax} l * f_{L|DS}(l|ds) * P_{DS|Sd}[ds|Sd] * v^{*}_{=Sd}$$

$$= \sum_{all\ DS} \sum_{all\ Sd} \mu_{L|DS} * P_{DS|Sd}[ds|Sd] * v^{*}_{=Sd}$$

The annual loss rate curve was calculated as follows:

$$v_L = \sum_{all\ DS} \sum_{all\ Sd} P[L > l|ds] * P_{DS|Sd}[ds|Sd] * v^{*}_{=Sd}$$

where

$$P[L > l|ds] = 1 - \frac{\Phi\left(\frac{l - \mu_{L|DS}}{\sigma_{L|DS}}\right) - \Phi\left(\frac{L_{min} - \mu_{L|DS}}{\sigma_{L|DS}}\right)}{\Phi\left(\frac{L_{max} - \mu_{L|DS}}{\sigma_{L|DS}}\right) - \Phi\left(\frac{L_{min} - \mu_{L|DS}}{\sigma_{L|DS}}\right)}$$

The expected loss was calculated using an excel spreadsheet and the annual loss rate curve was calculated using Matlab. The following results were obtained:

Table 10. Expected loss

E[Loss], $ per ft^2	2.67
Total [$]	376,129.07

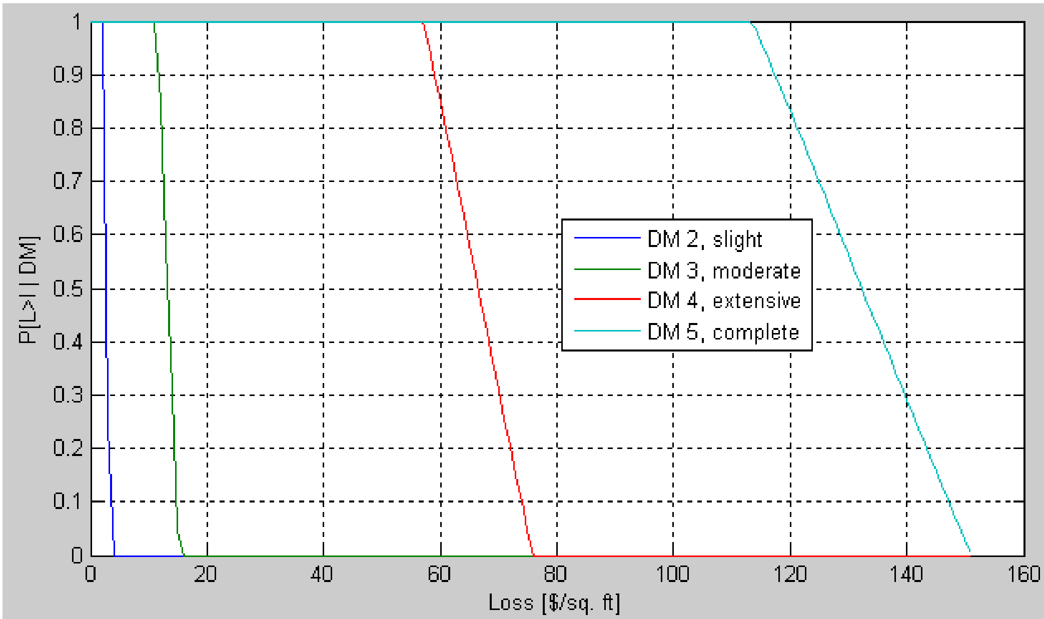

Figure 8. CCDF's for loss for each damage state

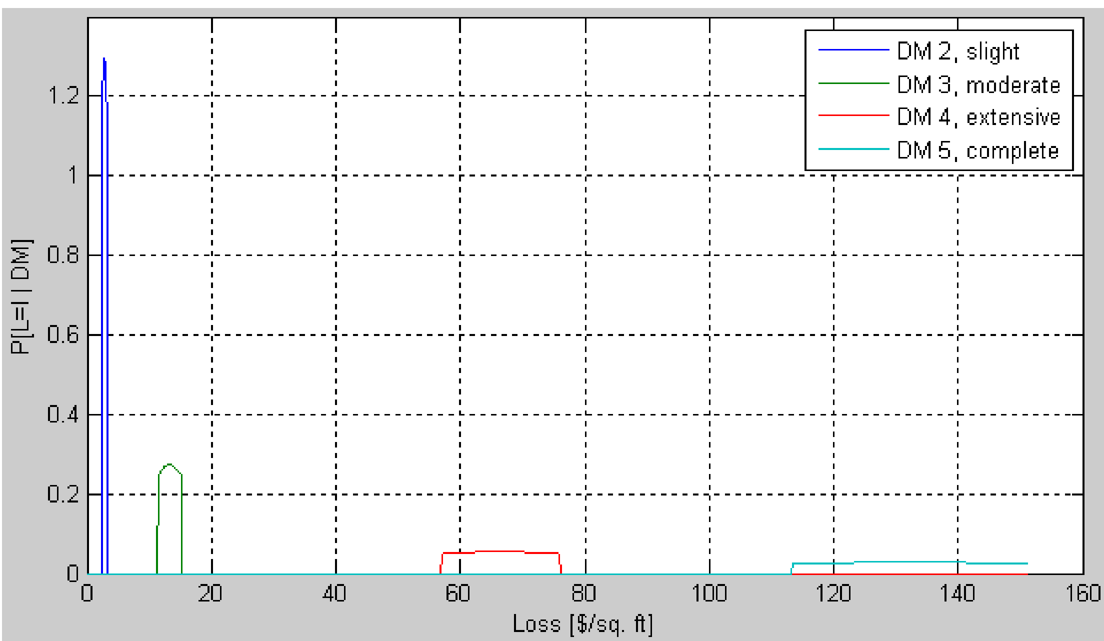

Figure 9. PDF's of truncated normal distributions for each damage state

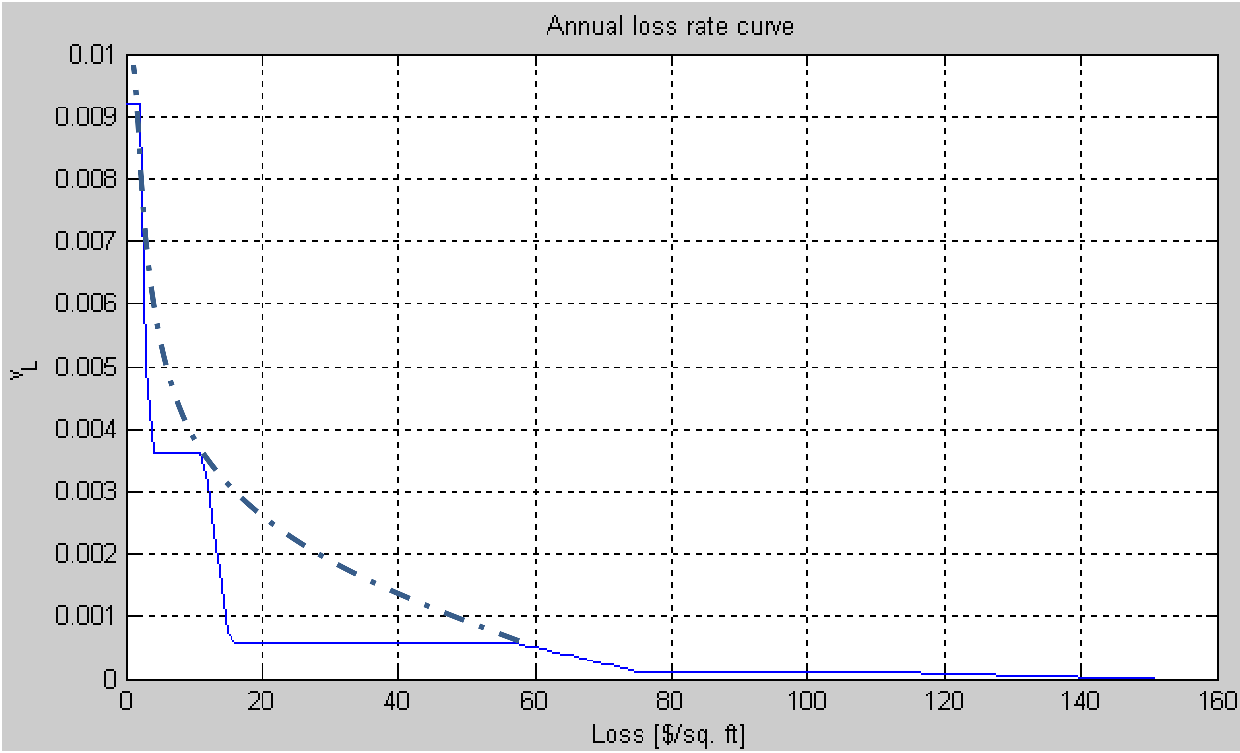

Figure 10. Annual loss rate curve

The following results were obtained from the annual loss rate curve:

Table 11. Annual exceedence losses

Annual exceedence rate	Loss [$ per ft^2]	Total loss [$]
10%	~ 0	~ 0
1/475	34.1	4,803,769.30

The solid line in the figure 10 represents the results of the analysis. The 'jagged' shape of the curve comes from the fact that discrete damage states are considered which in this case also turn out to be non-overlapping. In order to get more realistic results (i.e. recognize the fact that the transition from one damage state to another happens gradually), the values of loss for desired exceedence rate were obtained by linear interpolation (the dashed line on figure 10 represents an interpolated curve, but linear interpolation was used to obtain the values of loss which was deemed to be more conservative and a better approximation given the uncertainties involved).

[9] Expected loss from direct structural damage & annual loss rate curve for un-retrofitted structure

An analogous analysis was performed for the same structure but without an increased capacity, i.e. for the un-retrofitted structure. The increase in capacity in previously performed analysis was modeled by using the structural fragility curve parameters for 'High-Code seismic demand level'. In case of the un-retrofitted structure, parameters for 'moderate code seismic design level' (ductility 4.0) will be used to recognize the fact that the lateral-force resisting system is a non-ductile RC frame. Other modeling parameters were left unchanged from the previous analysis. The results are presented below.

a) *Moderate code design level*

Table 12. Structural fragility curve parameters – Moderate code design level

Structural Class	slight		moderate		extensive		complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
C1M	1.50	0.70	2.60	0.70	7.00	0.70	18.00	0.89

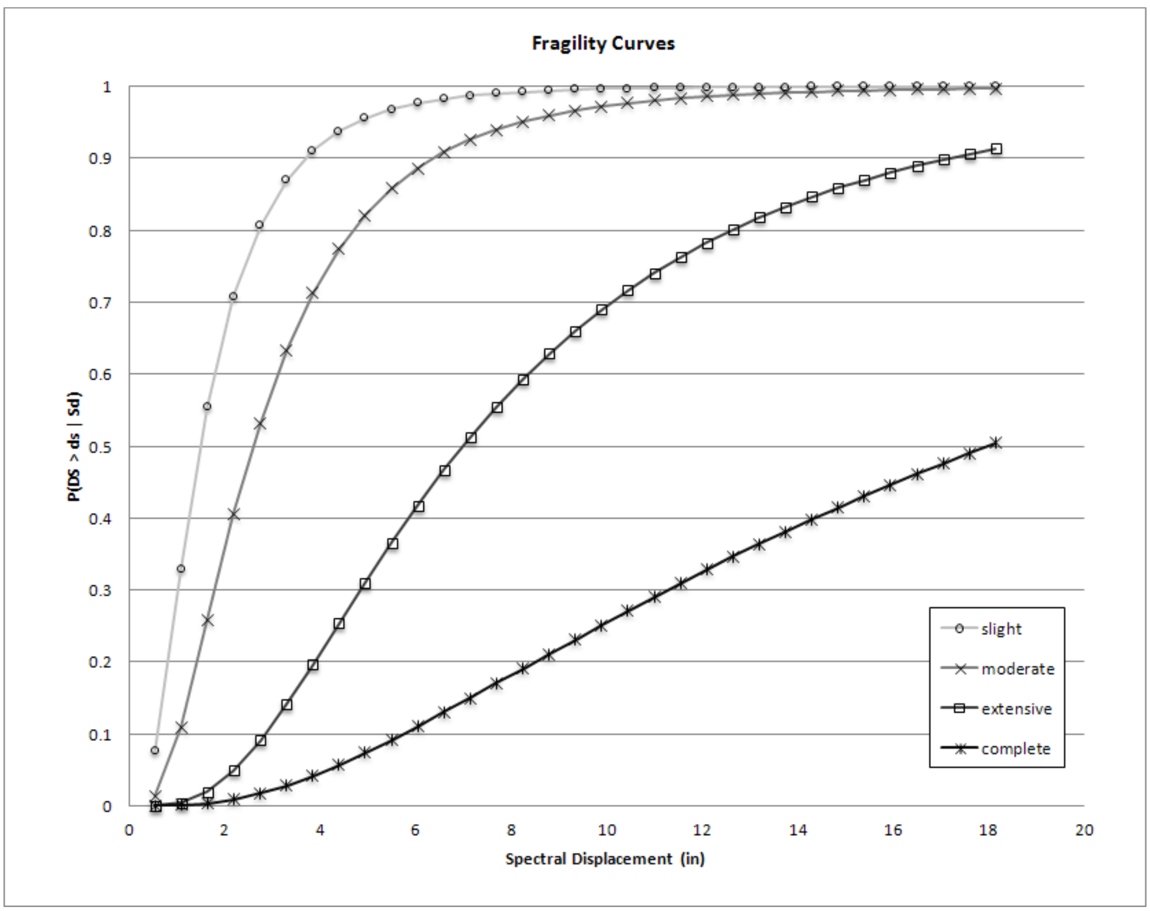

Figure 11. Fragility functions for different damage states

Table 13. Probabilities of damage states, expected damage state & standard deviation

P[None]	P[Slight]	P[Moderate]	P[Extensive]	P[Complete]
0.7526	0.1260	0.0958	0.0188	0.0067
Expected damage state:			1.4008	
Variance of the damage state:			0.624715476	
Standard deviation of the damage state:			0.790389446	

Table 14. Expected loss

E[Loss], $ per ft^2	3.76
Total [$]	529,812.50

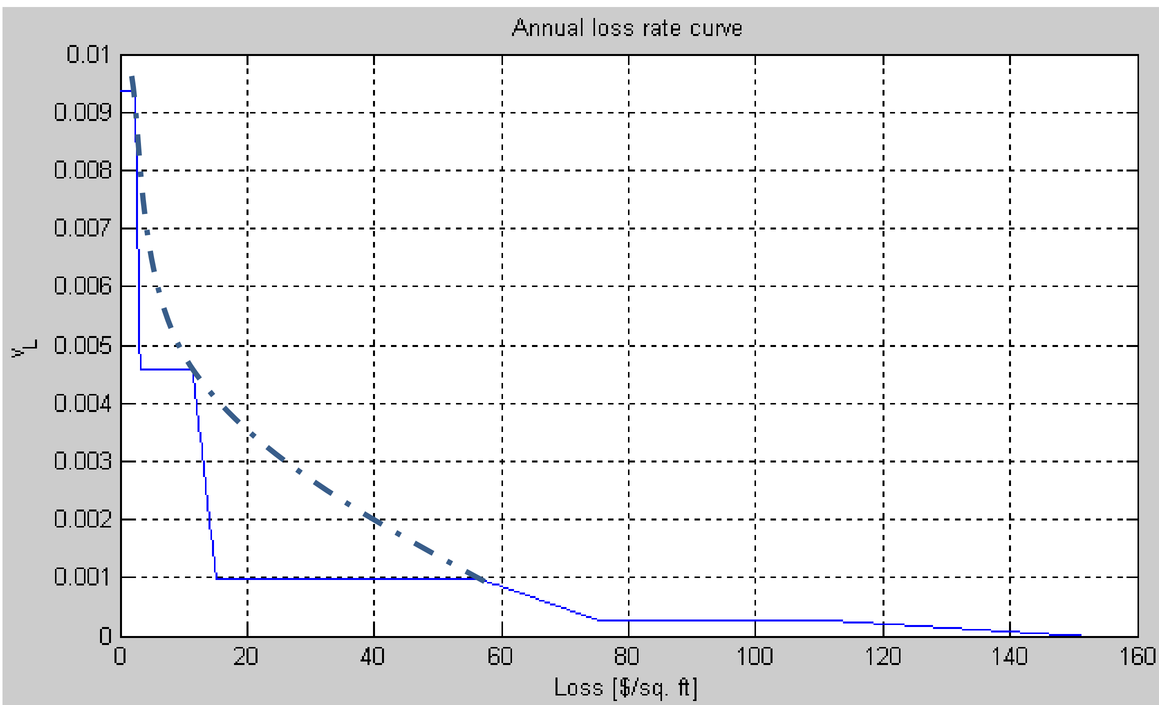

Figure 12. Annual loss rate curve

Table 15. Annual exceedence losses

Annual exceedence rate	Loss [$ per ft^2]	Total loss [$]
10%	~ 0	~ 0
1/475	42.62	6,004,007.26

b) Pre-code design level

Table 16. Structural fragility curve parameters – Pre-code design level

Structural Class	slight		moderate		extensive		complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta
C1M	1.50	0.70	2.40	0.74	6.00	0.86	15.00	0.98

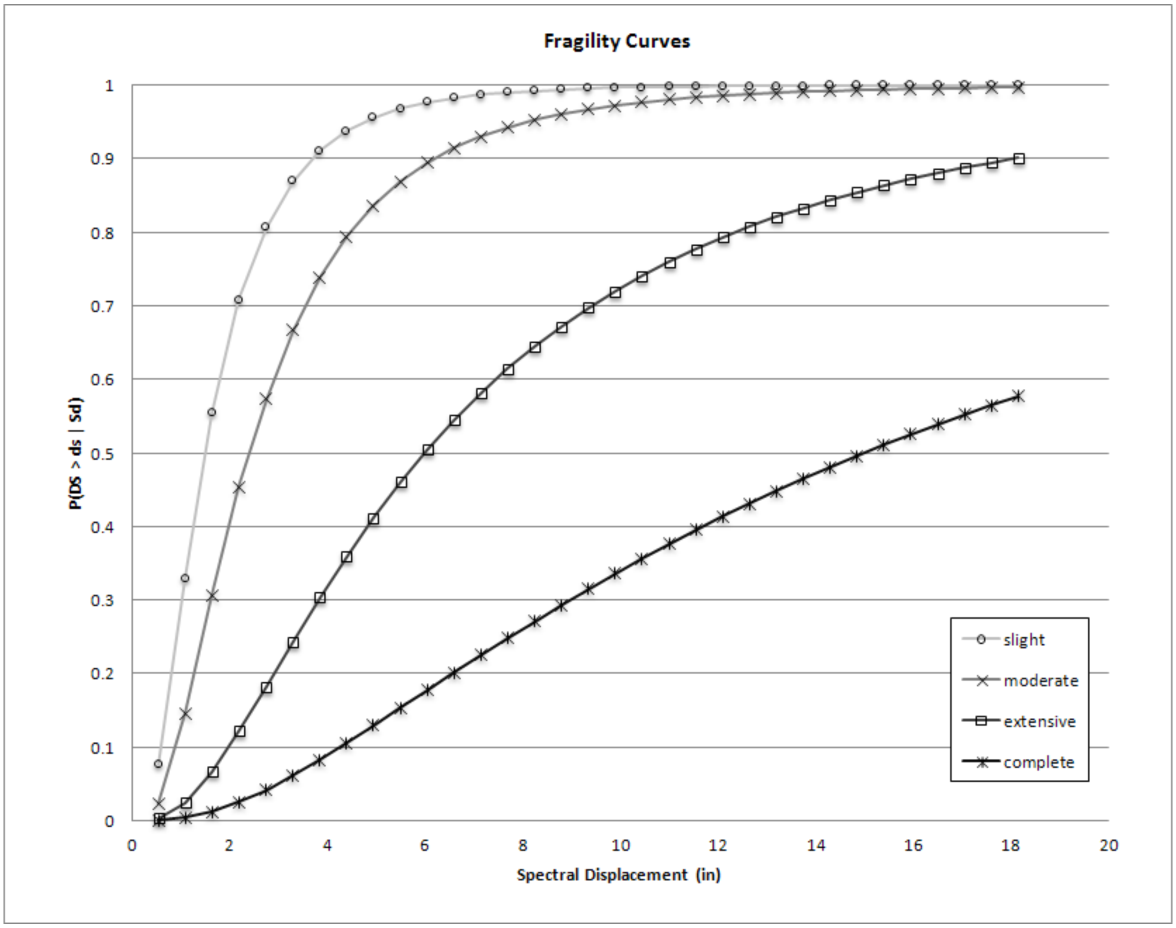

Figure 13. Fragility functions for different damage states

Table 17. Probabilities of damage states, expected damage state & standard deviation

P[None]	P[Slight]	P[Moderate]	P[Extensive]	P[Complete]
0.7526	0.1060	0.0970	0.0320	0.0124

Expected damage state:	1.4454
Variance of the damage state:	0.781192304
Standard deviation of the damage state:	0.883850838

Table 18. Expected loss

E[Loss], $ per ft^2	5.35
Total [$]	753,524.47

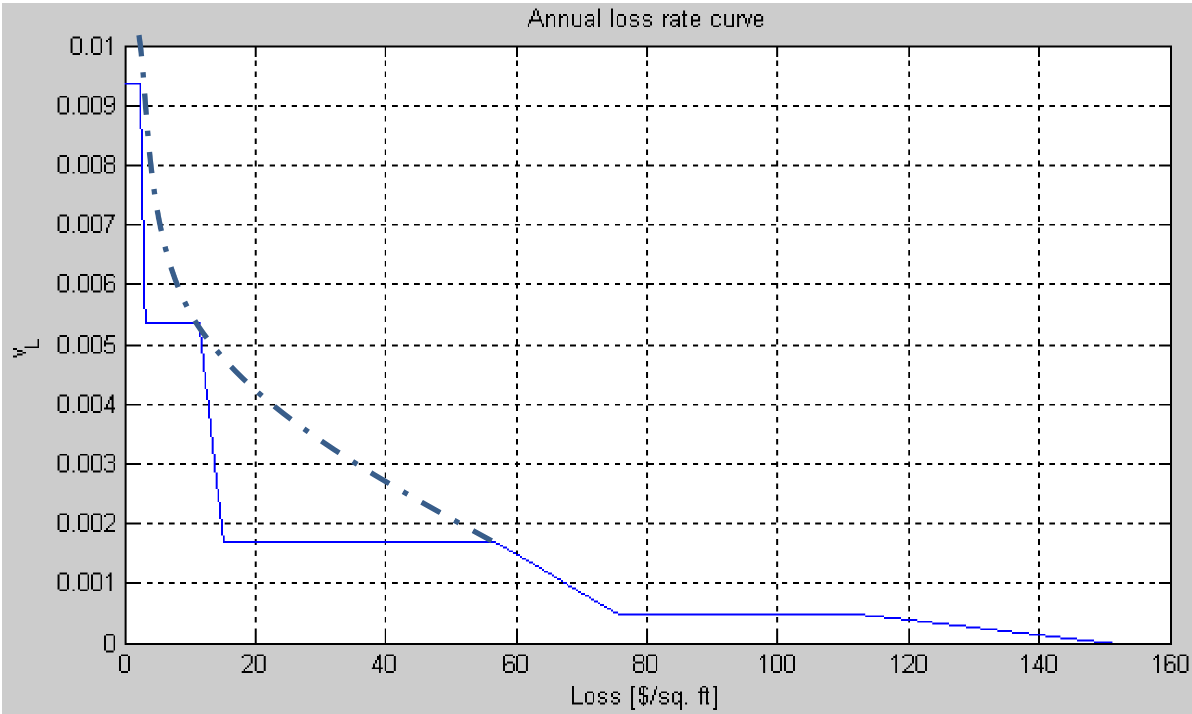

Figure 14. Annual loss rate curve

Table 19. Annual exceedence losses

Annual exceedence rate	Loss [$ per ft^2]	Total loss [$]
10%	~ 0	~ 0
1/475	51.70	7,283,134.10

Comparison with part A, comments and recommendations

By comparing the results obtained by the ATC-13 and HAZUS it can be seen that the two methodologies yield different results. In terms of expected loss, the results of ATC-13 analysis and HAZUS for pre-code level are pretty similar. However, the obtained loss values for considered loss exceedence rates are significantly different between the two methodologies. We are uncertain about why this is the case.

Table 20. Comparison between ATC-13 and HAZUS for un-retrofitted structure

	ATC-13 (un-retrofitted)	HAZUS (moderate-code level)	HAZUS (pre-code level)
Expected loss [$]	814,700.00	529,812.50	753,524.47
10% annual exceedence [$]	2,333,333.33	~ 0.00	~ 0.00
1/475 annual exceedence [$]	48,882,931.00	6,004,007.26	7,283,134.10

In order to provide a recommendation about the maximum amount of money that the University should spend to increase the structural capacity (based on the results from HAZUS) a following approach will be used. The difference between the expected loss of the retrofitted structure and the expected loss of the un-retrofitted structure will be used as a measure of annual savings that can be achieved by such retrofit scheme. By assuming that the retrofit is to increase the lifespan of the structure by 50 years, the savings over that period can be calculated and compared to the cost of the retrofit scheme. The results of this analysis are presented in the following table:

Table 21. Potential savings from retrofit (HAZUS)

	Expected loss [annual in $]	Savings [annual in $]	Savings over 50 year lifespan
un-retrofitted (pre-code design level)	753,523.47	-	-
retro 1 (moderate-code design level)	529,812.50	223,711.97	11,185,598.30
retro 2 (high-code design level)	376,129.07	377,395.40	18,869,769.94

From the table 21 it can be seen that the savings due to retrofit options that were considered are smaller than the cost of retrofit which is around $40 million to $60 million as discussed in part A. The savings over a 50 year period from retrofit option 2 (which would correspond to combination of adding shear walls and also increasing ductility of columns) amount to around a third of the retrofit cost. Savings due to retrofit option 1, which would include addition of shear walls only, would amount to around a quarter of retrofit costs. Therefore, it seems that the potential savings that would be achieved from undertaking a retrofit do not justify the cost of retrofit. Moreover, the annual return that Stanford University has on its investments would suggest that undertaking a retrofit is not the best option. In this sense both HAZUS and ATC-13 methodologies, although yielding substantially different values for losses, would support the same conclusion.

As a final note, it has to be stated that the cost of a retrofit option depends on the type of a retrofit that will be undertaken; the maximum amount that should be spent on increasing the structural capacity should be such that the savings due to retrofit 'balance' the loss in the optimal way. In case of Meyer Library, the results of HAZUS and ATC-13 methodologies would lead us to believe that such optimum cannot be achieved through retrofit when considering structural losses only. Since losses due to structural damage are predominant in the total losses (part A), one thing that Stanford University might consider for final decision is whether or not Meyer library is of historical significance for the University. If this is not the case, our opinion/recommendation based on the performed analysis is that an investment in a new building that will meet current code requirements is a better option than investing in the retrofit of the existing structure.