

# Next-Generation Performance-Based Earthquake Engineering

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4<sup>TH</sup> INTERNATIONAL CONFERENCE ON EARTHQUAKE  
ENGINEERING AND DISASTER MITIGATION  
PADANG, INDONESIA



# 1906 San Francisco Earthquake, USA

- Destroyed 80% of the “golden” city.
- Over 3,000 died and half of the population homeless.



# 2011 Christchurch earthquake, New Zealand



**Financial loss: \$35 Billion USD**



# 2011 Tohoku earthquake, Japan

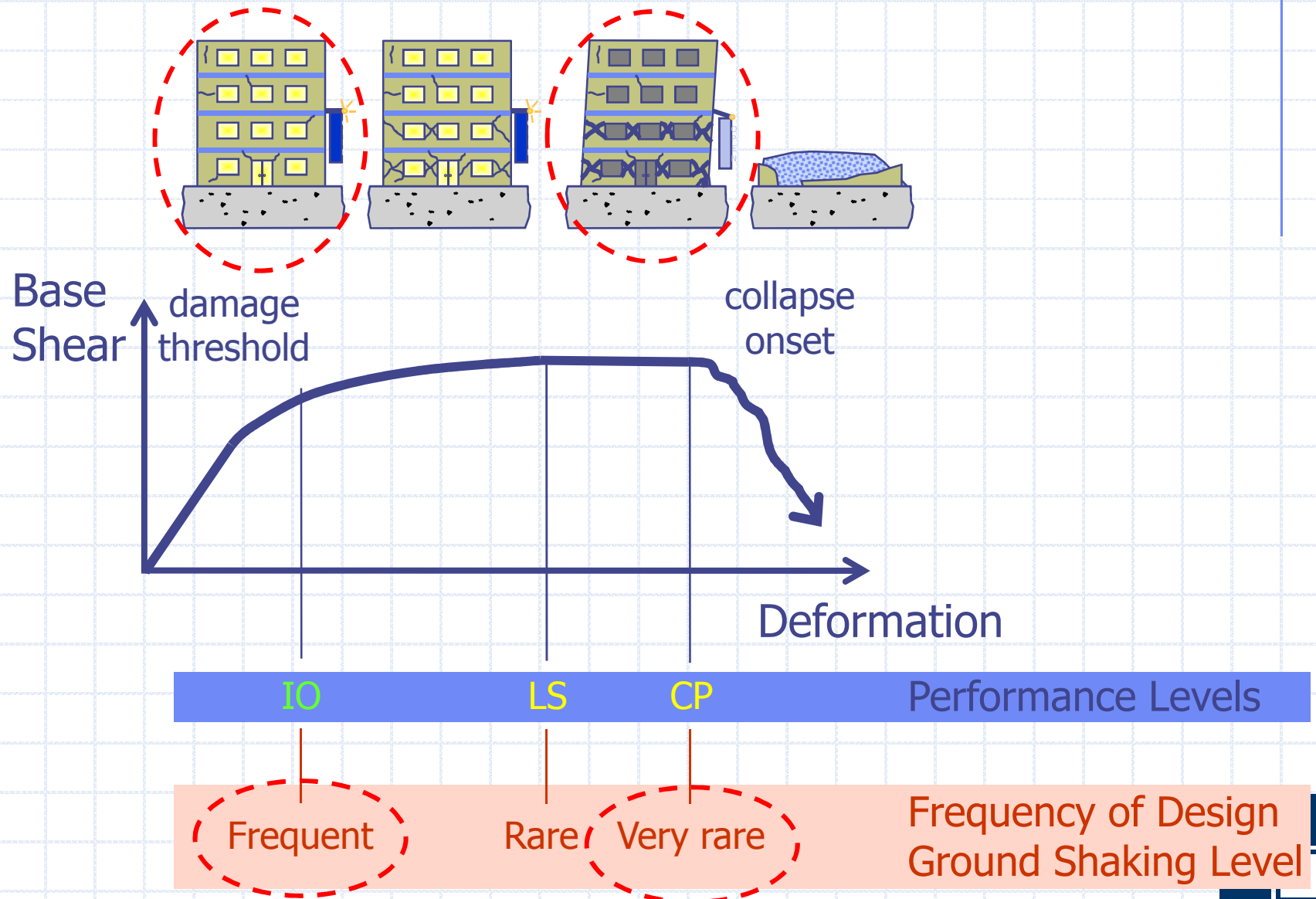


**Financial loss: \$235 Billion USD**

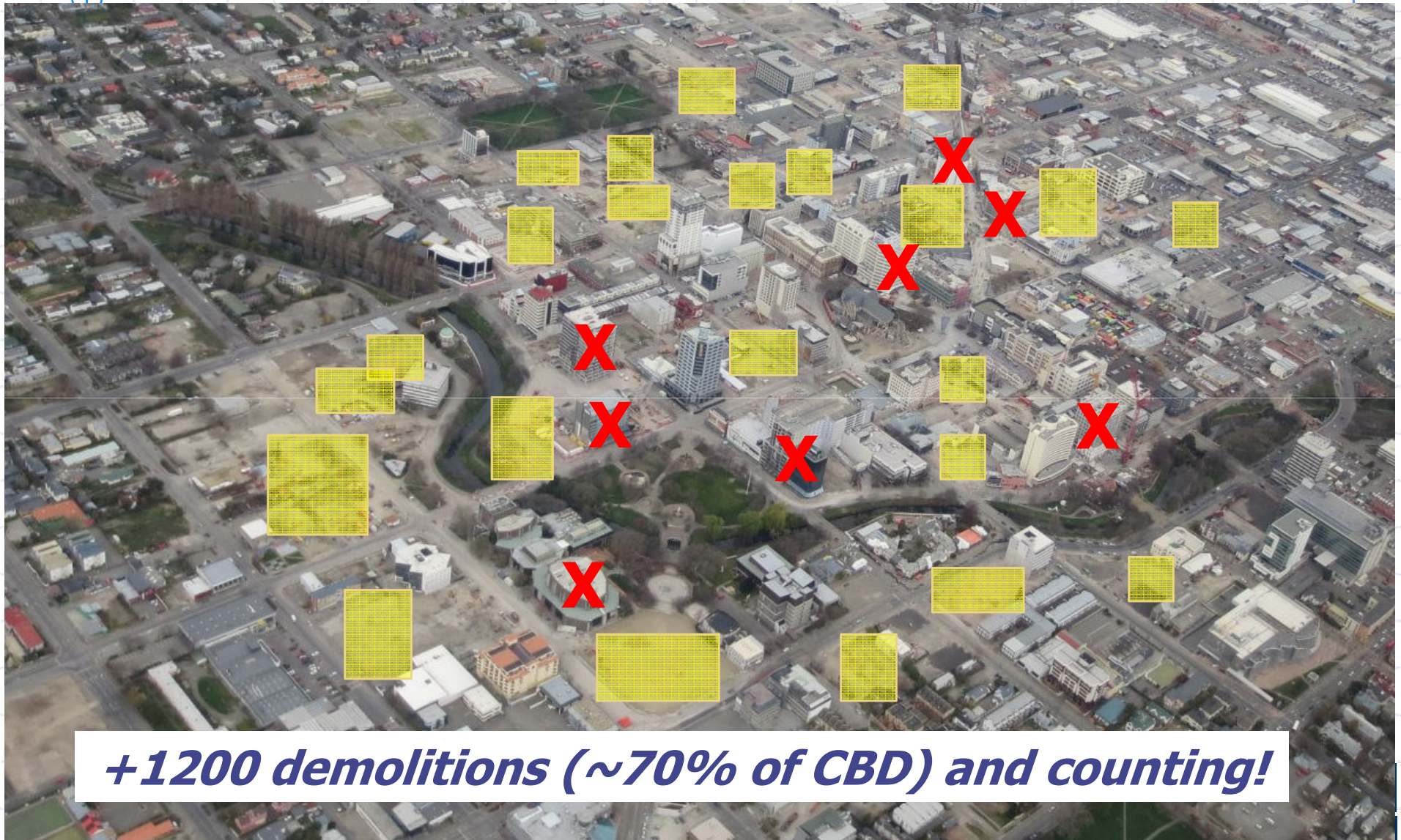
# Earthquake engineering



# Performance-based design approach

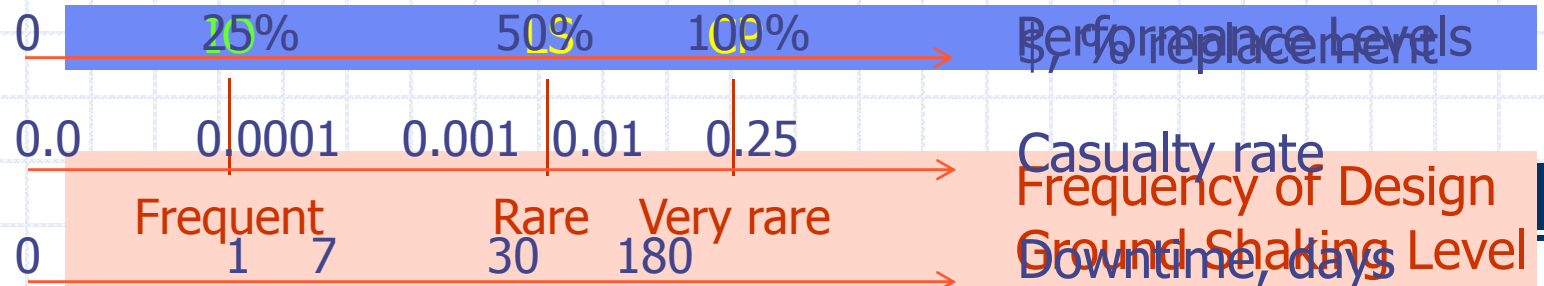
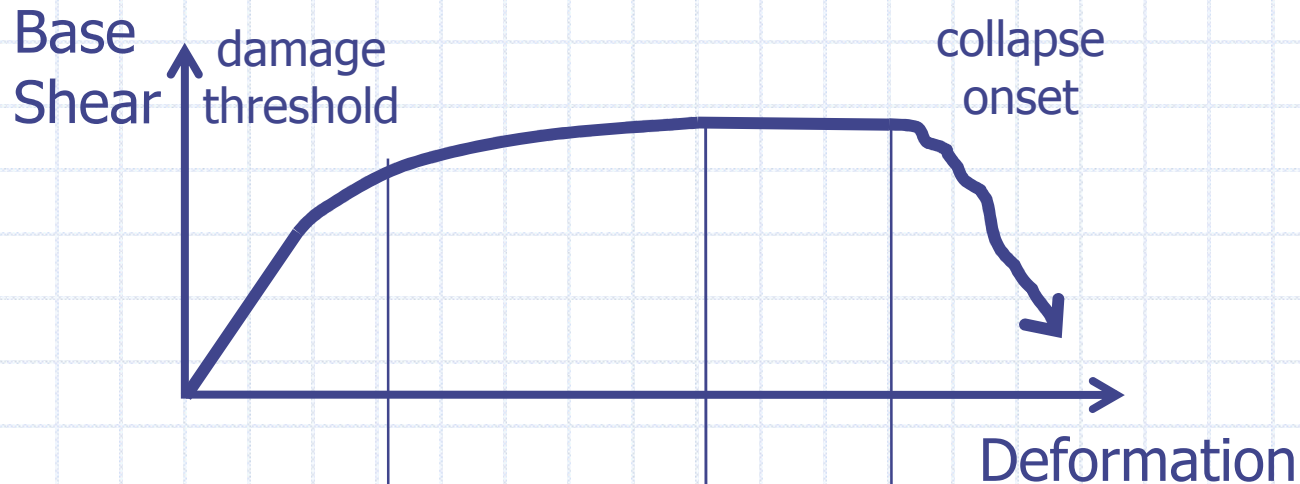
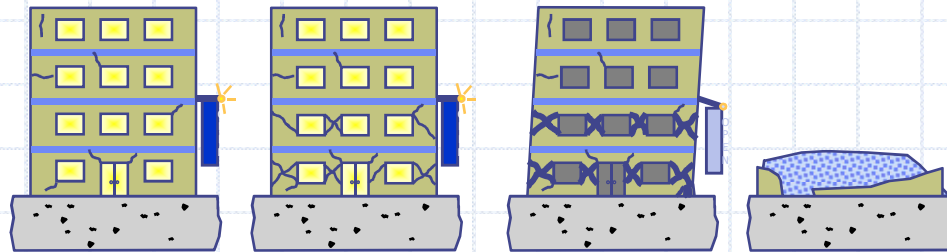


# 2011 Christchurch earthquake, New Zealand



***+1200 demolitions (~70% of CBD) and counting!***

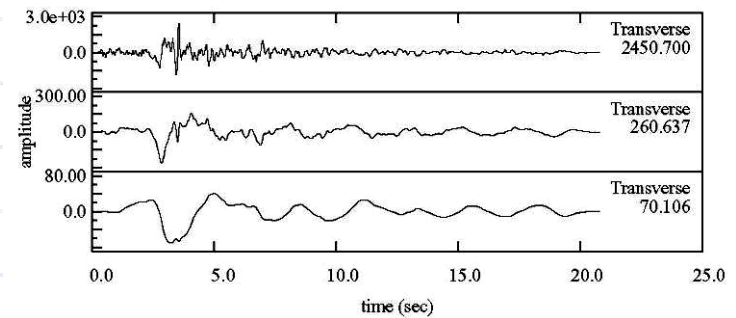
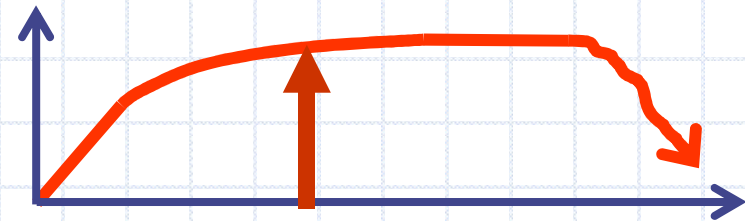
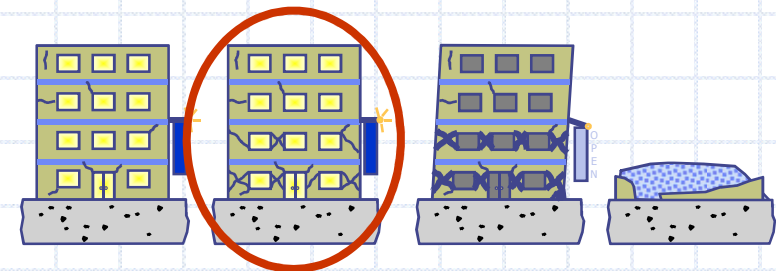
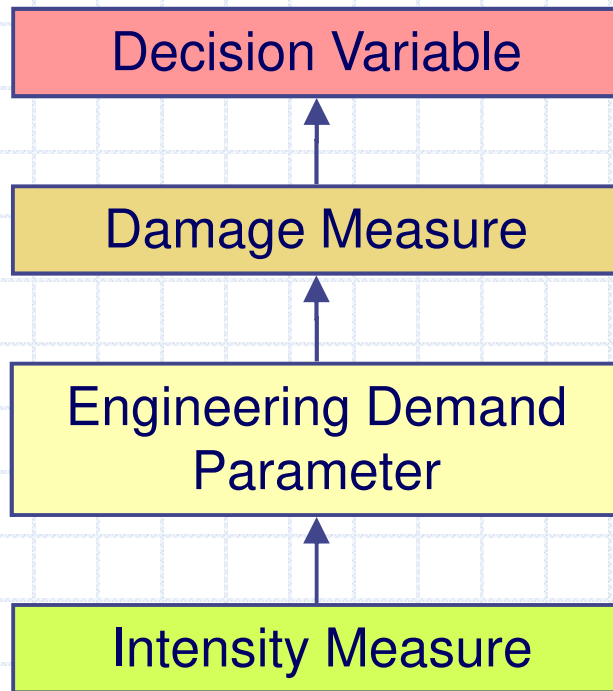
# Performance-based design approach



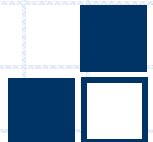


# PBEE framework

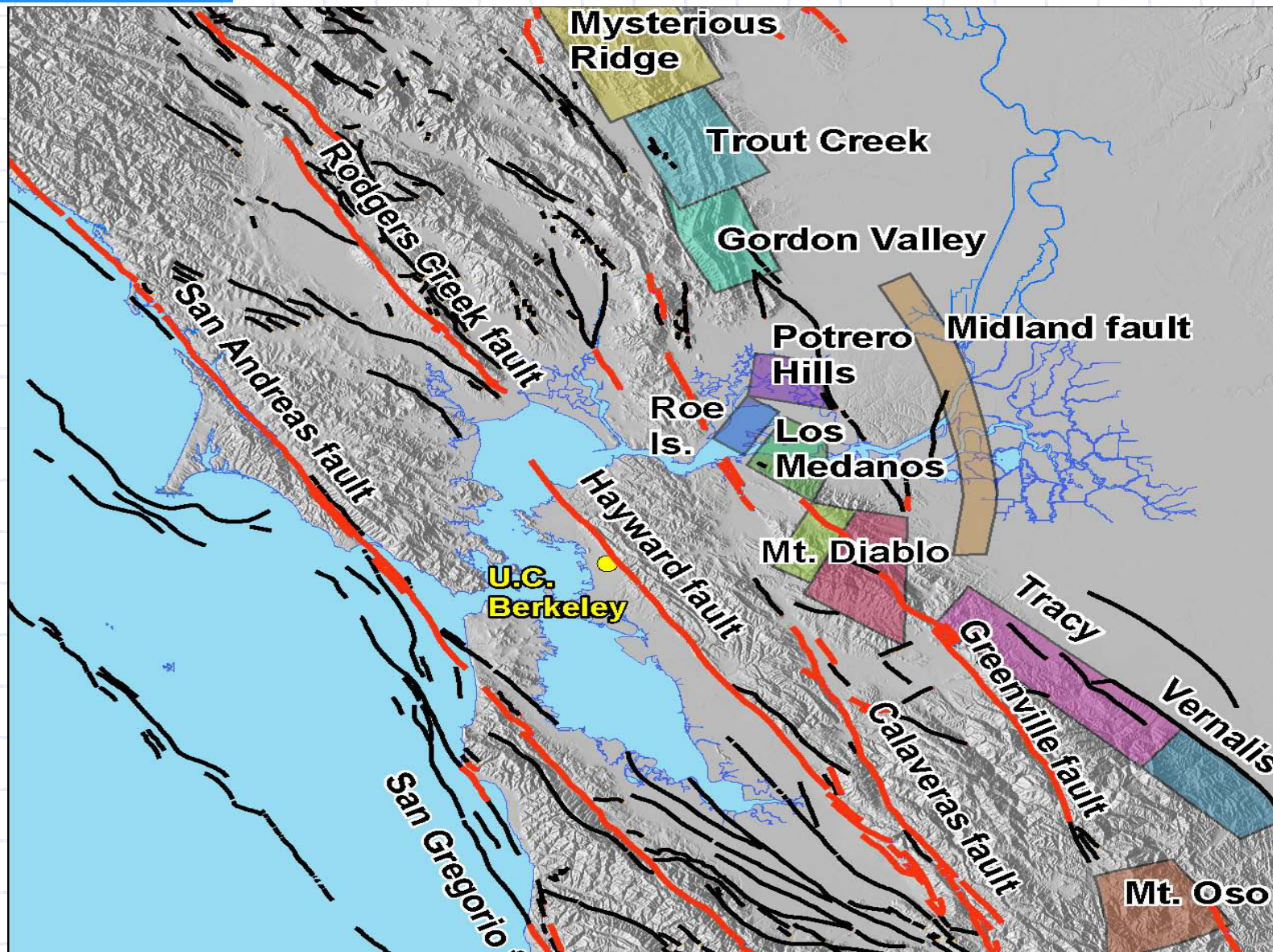
$$\lambda(dv < DV) = \iiint G(dv | dm) dG(dm | edp) dG(edp | im) |d\lambda(im)|$$



# Implementation of PBEE

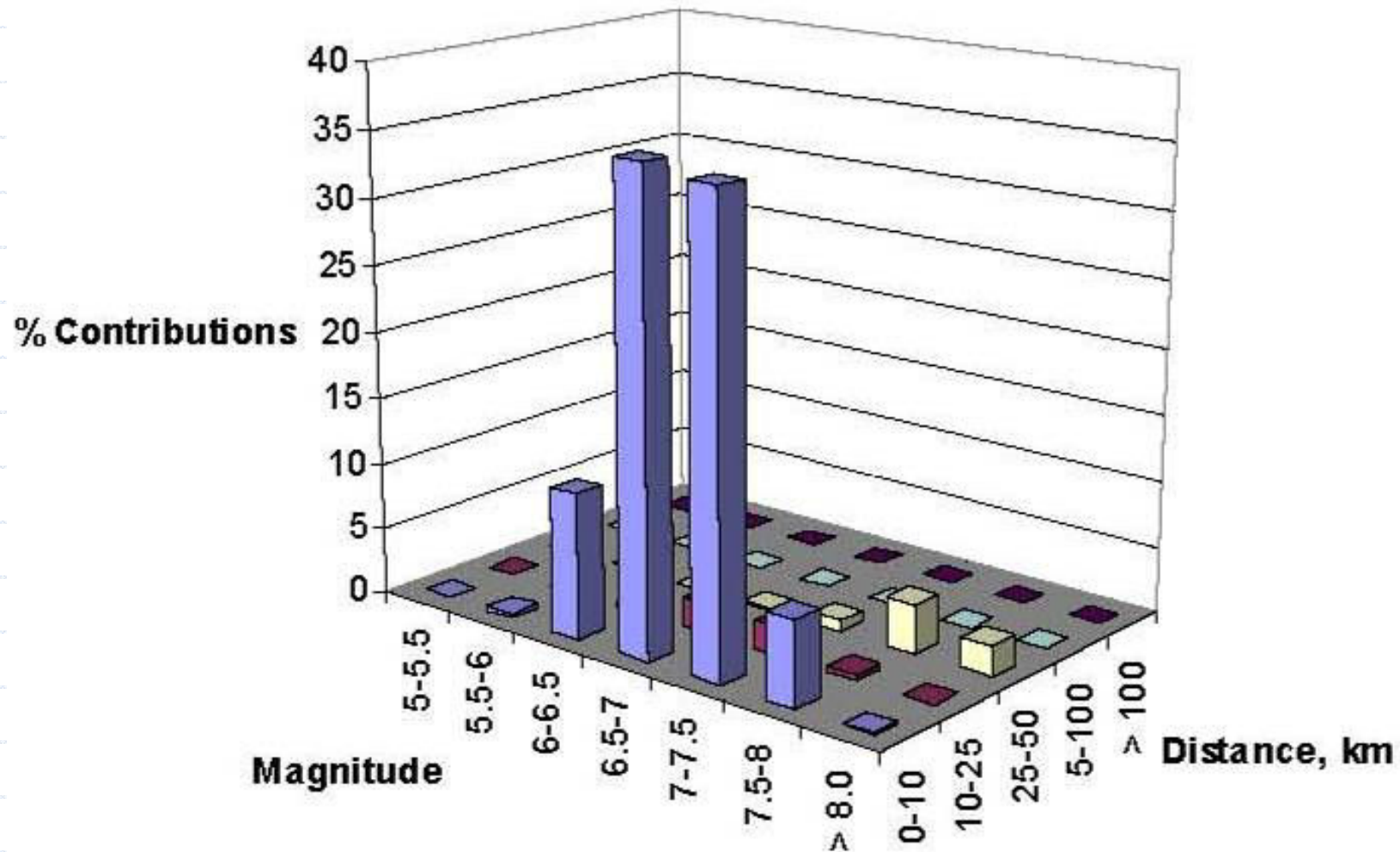


# Earthquake Engineering



# Probabilistic seismic hazard analysis

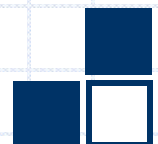
Seismic hazard level: 10% in 50 years



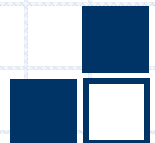
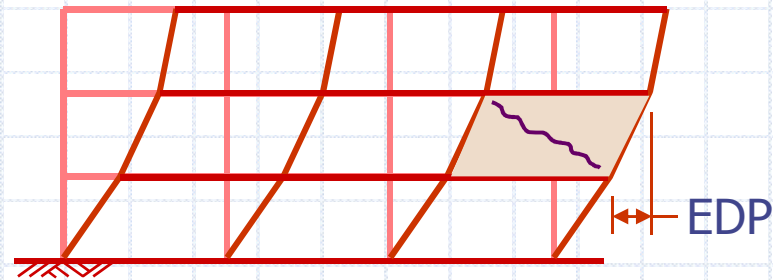
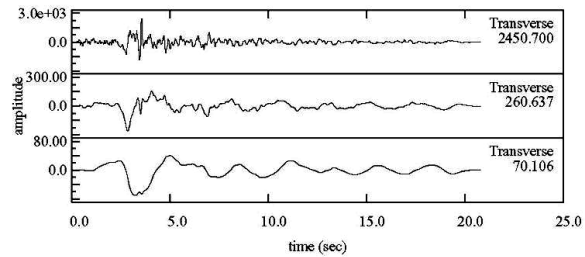
# Suites of ground motions

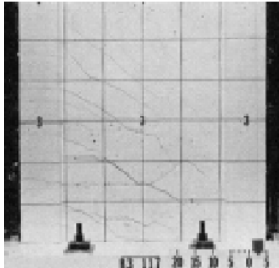
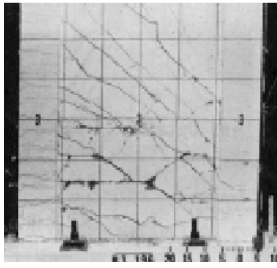
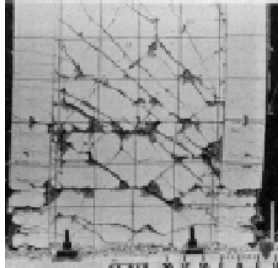
Seismic hazard level: 10% in 50 years

Earthquake	Mw	Station	Distance	Site	Record
Loma Prieta, 1989/10/17	7.0	Los Gatos Present Center	3.5	C	LP_lgpc
		Saratoga Aloha Ave	8.3	C	LP_srtg
		Corralitos	3.4	C	LP_cor
		Gavilan College	9.5	C	LP_gav
		Gilroy Historic Building		C	LP_gilb
		Lexington Dam Abutment	6.3	C	LP_lex1
Kobe, Japan 1995/1/17	6.9	Kobe JM A	4.4	C	KB_kobj
Tottori, Japan 2000/10/6	6.6	Hino	1	C	TO_hino
Erzincan, Turkey 1992/3/13	6.7	Erzincan	1.8	C*	EZ_erzi



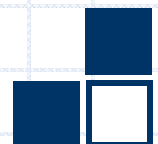
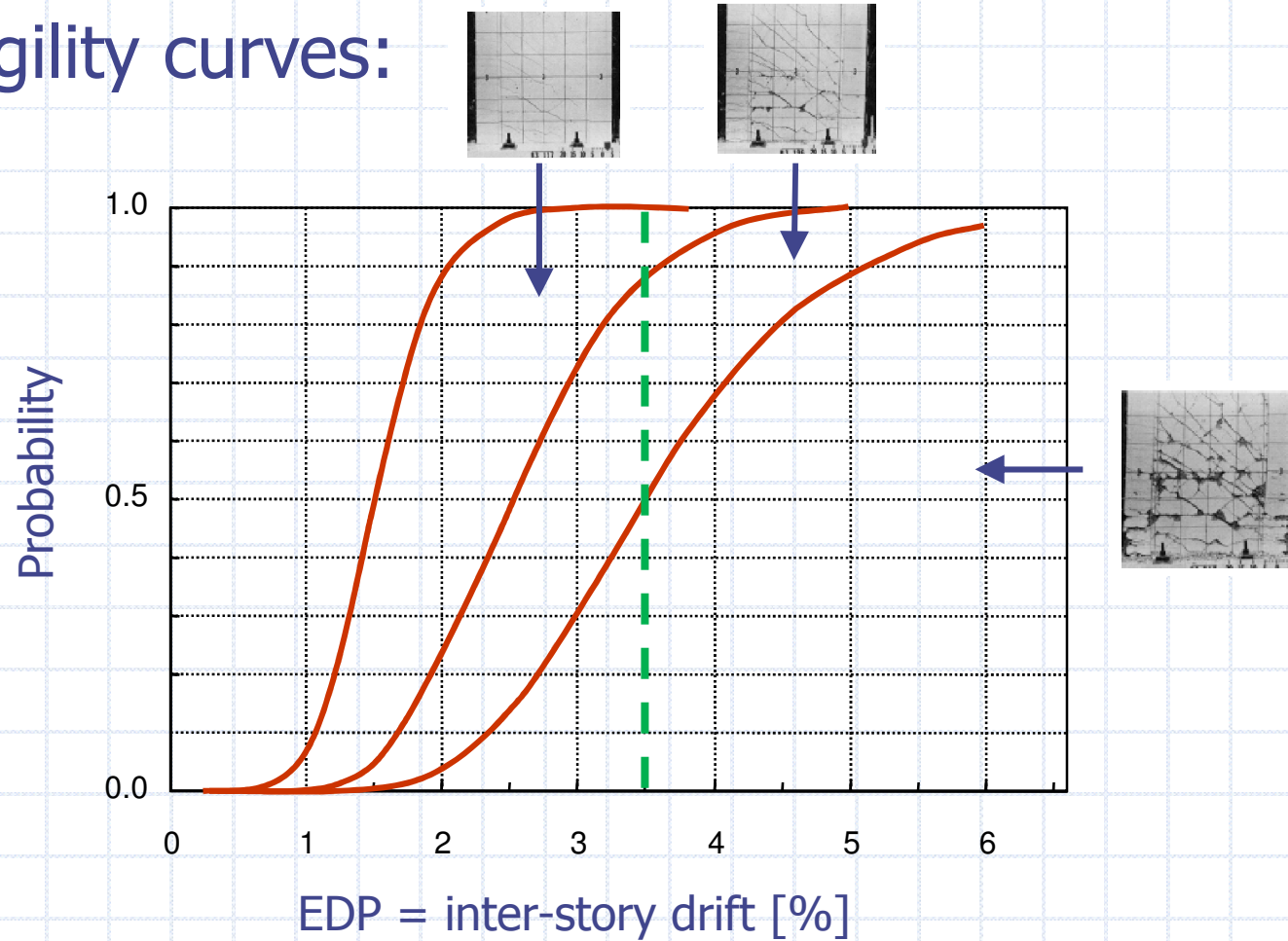
# Response analysis



<b><u>BASIC COMPOSITION</u></b>	<b>DAMAGES STATES</b>		
	<b>DS2</b>	<b>DS3</b>	<b>DS4</b>
No of square feet of flexurally controlled RC concrete shear walls in each direction			
<b><u>DESCRIPTION</u></b>	Flexural cracks < 3/16" Shear (diagonal) cracks < 1/16" No significant spalling No fracture or buckling of r/f Not structurally significant	Flexural cracks > 1/4" Shear (diagonal) cracks > 1/8" Moderate spalling/ loose cover No fracture or buckling of r/f Insignificant residual drift/shortening	Max. crack widths >3/8" Significant spalling/ loose cover Fracture or buckling some r/f Significant residual drift/shortening Repair in place impractical
<b><u>ILLUSTRATION</u></b> (example photo or drawing)			
<b><u>MEDIAN EDP</u></b> (interstory drift)	1.25%	2.5%	3.5%
<b><u>BETA</u></b>	0.2	0.3	0.4
<b><u>CORRELATION (%)</u></b>	70%		
<b><u>REPAIR MEASURES</u></b>	Patch cracks each side with caulk Paint each side	Remove loose concrete Patch spalls with NS grout Patch cracks each side with caulk Paint each side	Shore Demo existing wall Replace Patch and paint
<b><u>CONSEQUENCE FUNCTION</u></b> <b><u>Cost per sq ft of wall for repair</u></b>			
Max. cost up to lower quantity	\$4.00 per sq ft up to 800 sq ft	\$10.00 per sq ft up to 800 sq ft	\$50.00 per sq ft up to 200 sq ft
Min cost over upper quantity	\$2.00 per sq ft over 4000 sq ft	\$5.00 per sq ft over to 4000 sq ft	\$30.00 per sq ft over 2000 sq ft
Beta (cost)	0.2	0.3	0.3

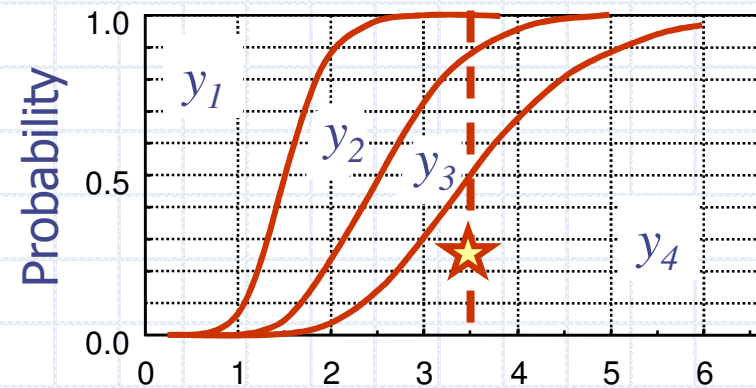
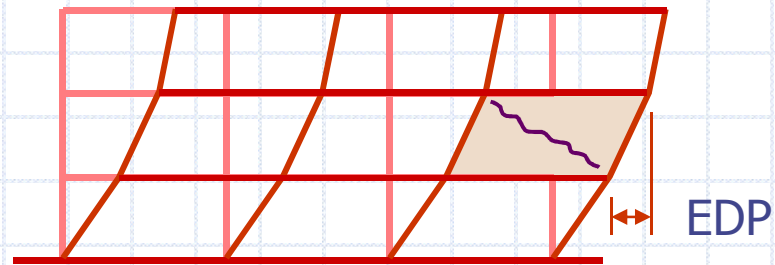
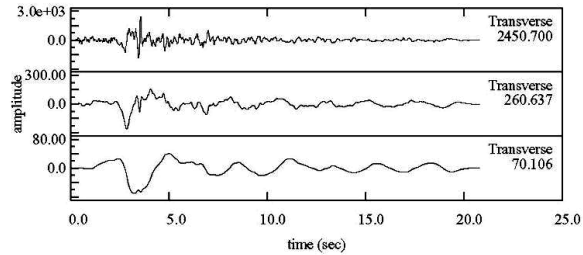
# Damage analysis

Fragility curves:





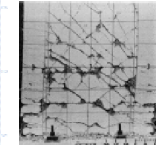
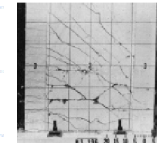
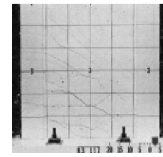
# Damage analysis



EDP = inter-story drift [%]

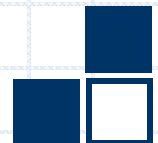
# Repair quantity calculation

Performance group  $i$



Damage state

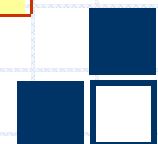
Quantities	Damage state			
	$y_1$	$y_2$	$y_3$	$y_4$
concrete	0	0	0	10
steel	0	0	0	20
wallboard	0	0	100	10,000
paint	0	100	1000	10,000
electrical	0	0	0	0
...				



# Repair quantity calculation

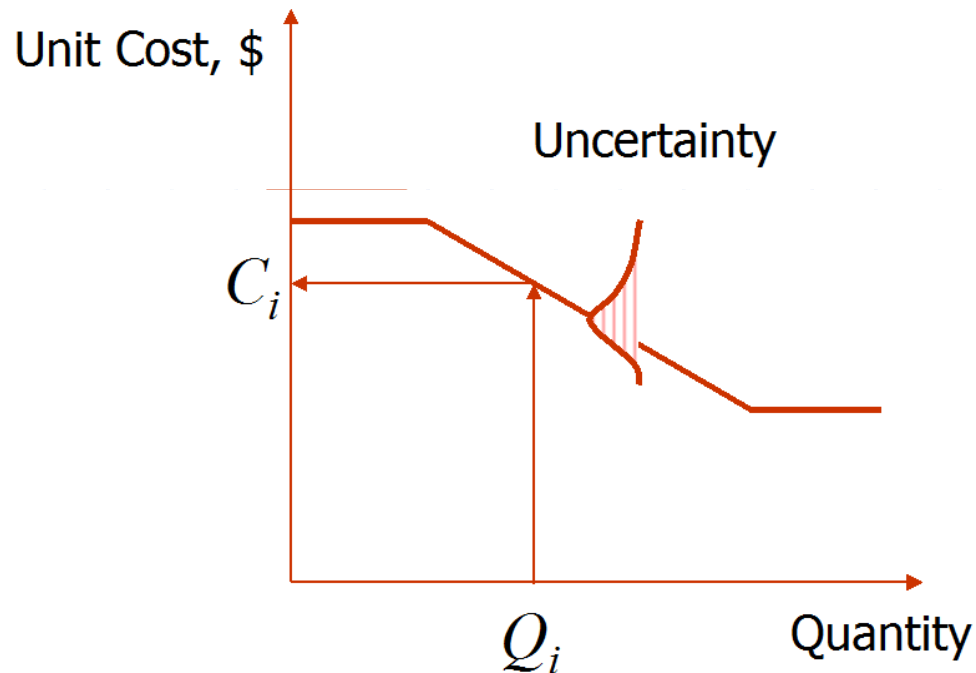
## All performance groups

Quantities	Performance group			<i>Totals</i>
	<i>1</i>	<i>2</i>	...	
concrete	10	0	...	30
steel	20	0	...	20
wallboard	10,000	100	...	10,100
paint	10,000	1000	...	11,000
electrical	0	0	...	0
...				



# Repair quantity calculation

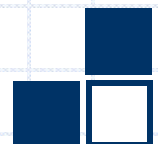
Quantity  $i$  (e.g., sq ft of the concrete shear wall)



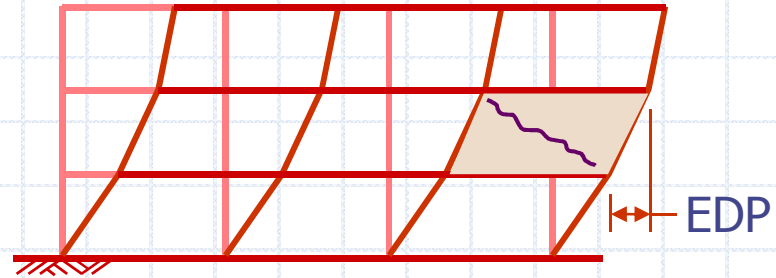
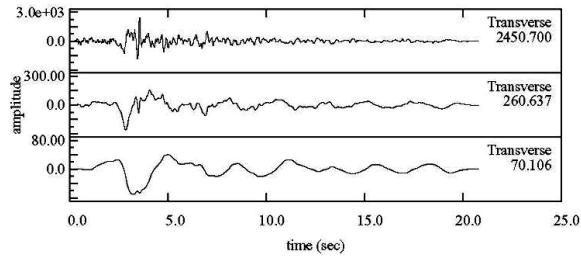
Total repair cost

$$\text{Total cost} = \sum C_i Q_i$$

(plus contractor's OH and profit (~12%) and general project costs (design, admin etc, at 20-50%).



# EDP matrix



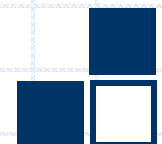
	$\Delta 1$ [%]	$\Delta 2$ [%]	$\Delta 3$ [%]	$A_g$ [%]	$A_1$ [%]	$A_2$ [%]	$A_3$ [%]
GM 1	1.26	1.45	1.71	0.54	0.87	0.88	0.65

→ Cost<sub>1</sub>

→ Cost<sub>2</sub>

⋮

→ Cost<sub>n</sub>



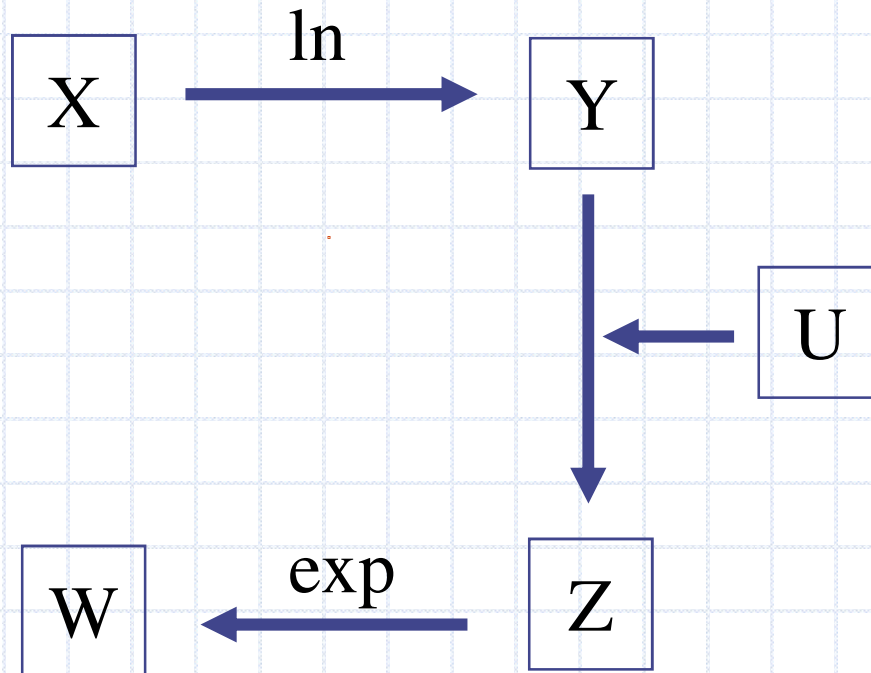
# Generate correlated EDP matrix

Filename	$\Delta u_1$ (%)	$\Delta u_2$ (%)	$\Delta u_3$ (%)	$a_g$ (g)	$a_2$ (g)	$a_3$ (g)	$a_R$ (g)
LPlgpc	1.40	1.83	1.79	0.51	1.02	0.65	0.64
LPsrtg	1.31	1.47	1.63	0.46	0.94	0.99	0.64
LPcor	1.53	2.56	3.10	0.81	0.97	1.01	0.85
LPgav	1.84	1.89	2.79	1.11	1.64	1.45	1.04
LPgilb	2.14	2.63	2.94	0.66	0.77	0.74	0.72
LPlex1	1.26	1.90	1.89	0.21	0.36	0.40	0.48
KBkobj	0.77	1.69	2.29	0.42	0.76	0.72	0.64
TOhino	1.38	1.76	2.07	0.59	0.69	0.58	0.61
EZerzi	1.66	2.23	2.35	0.59	0.77	0.77	0.61

$$\Rightarrow M_Z = B$$

$$\Rightarrow \Sigma_{ZZ} = AA^T$$

# Generate correlated EDP matrix



$$Z = A U + B$$

If U is a vector of uncorrelated standard normal RVs.

$$\Rightarrow M_Z = B$$

$$\Rightarrow \Sigma_{ZZ} = A A^T$$

$$M_Z = M_Y = B$$

$$\Sigma_{ZZ} = \Sigma_{YY} = A A^T$$

$$Z = \text{chol}(\Sigma_{YY}) U + M_Y$$

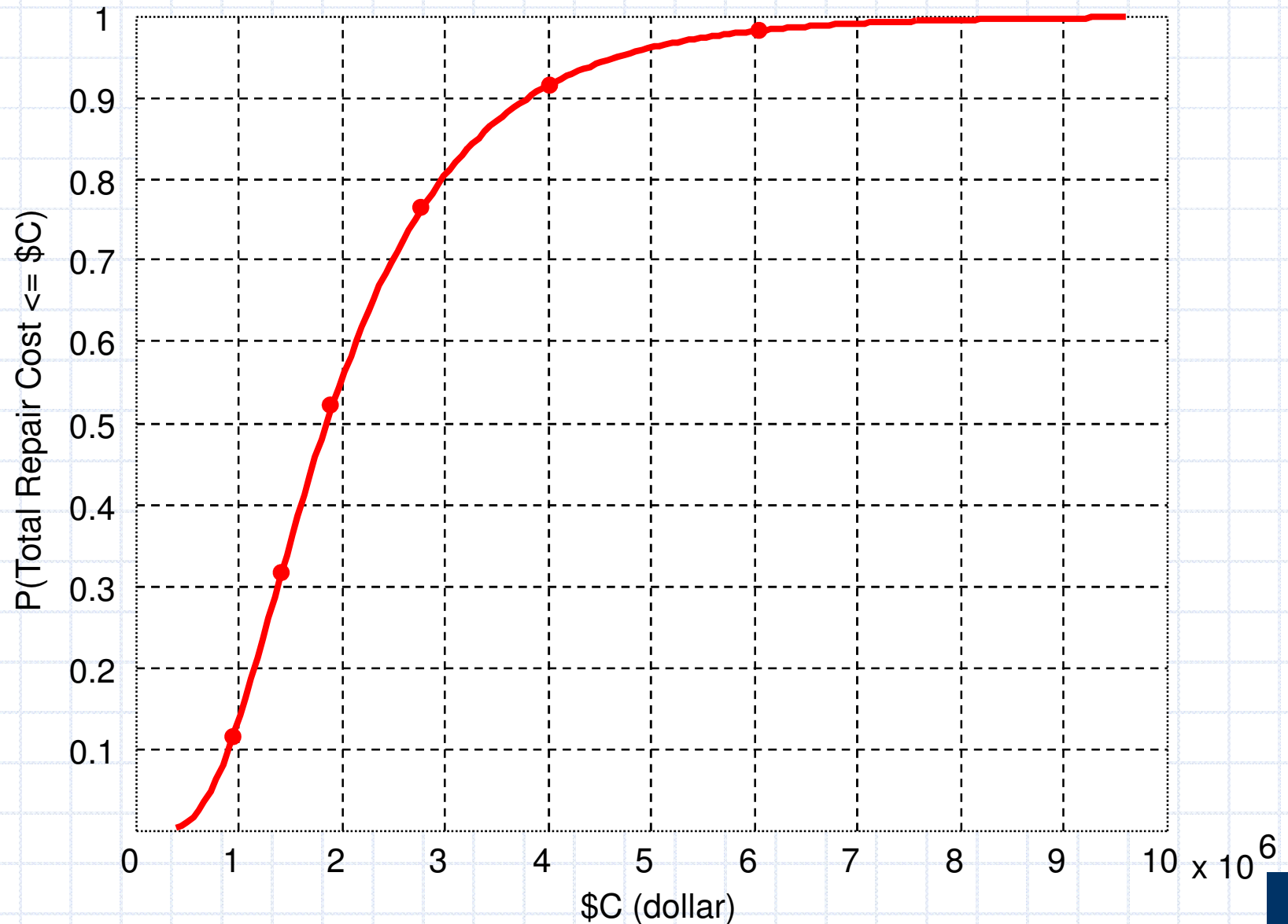
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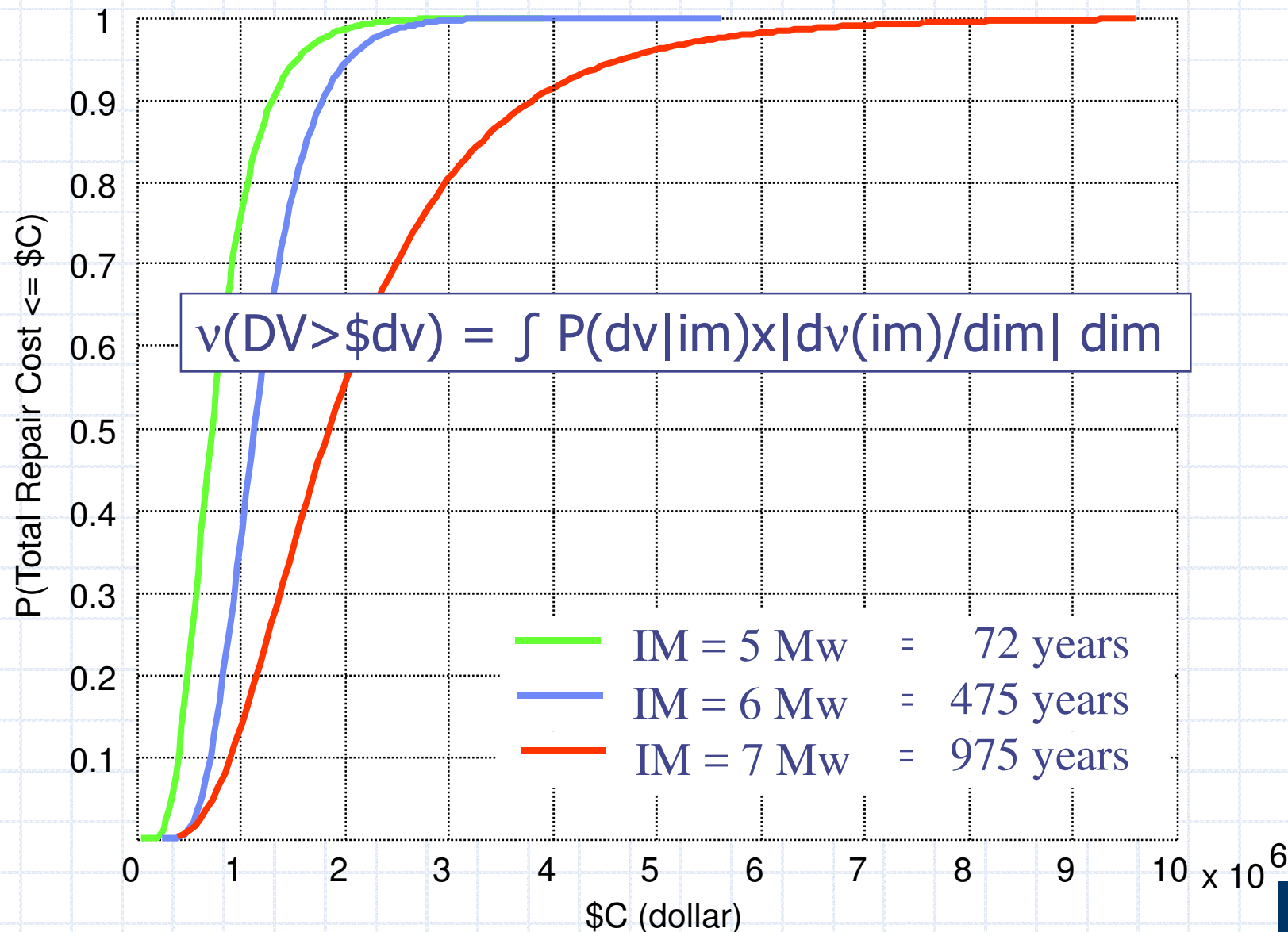
...	...	...	...	...	...	...	...
....	...	...	...	...	...	...	...
GM M	...	...	...	...	...	...	...



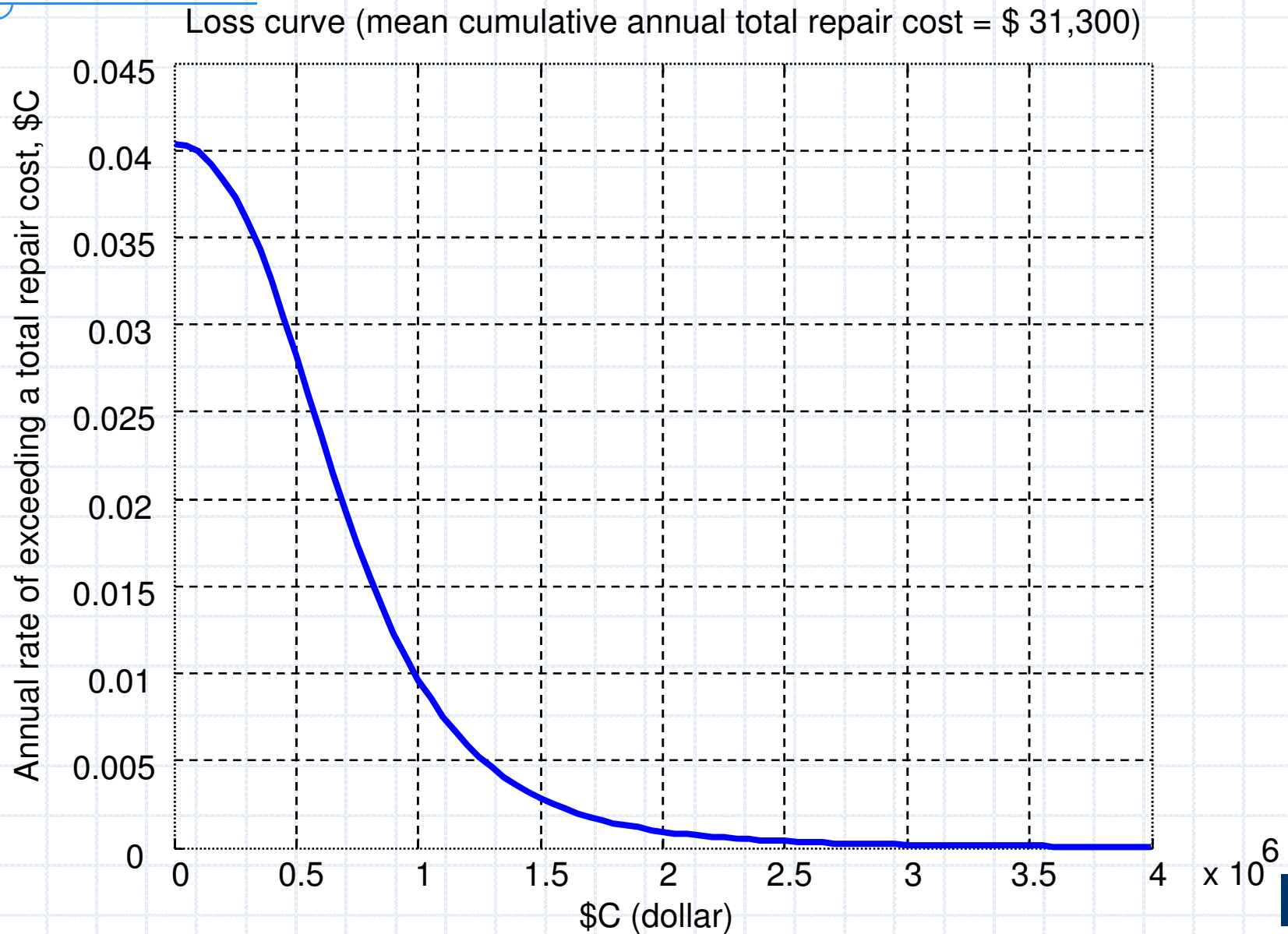
# Conceptual repair cost calculation



# Distribution of repair costs



# Annual rate of exceedance



# Various expression of costs

\$1.2M

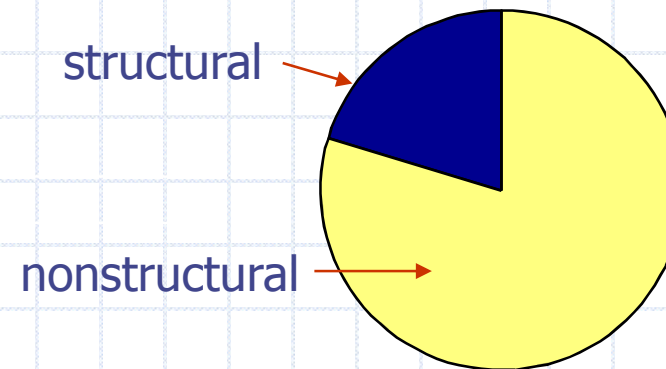
(a) Expected cost  
for M7 scenario

\$3.8M

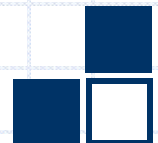
(b) 90% confidence cost does not exceed  
threshold for 975-yr return period hazard level

\$31,000

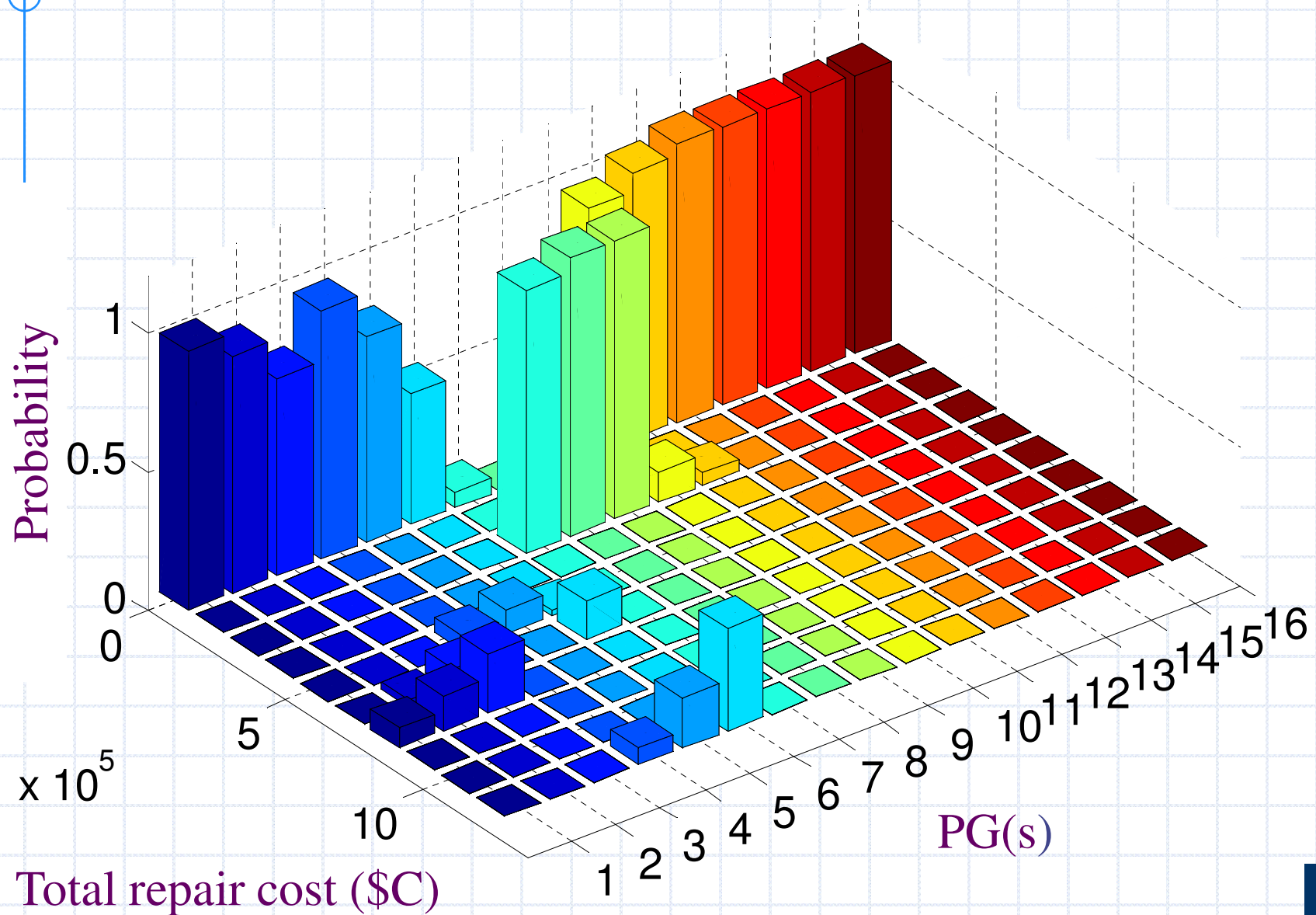
(c) Mean cumulative annual  
total cost of damage



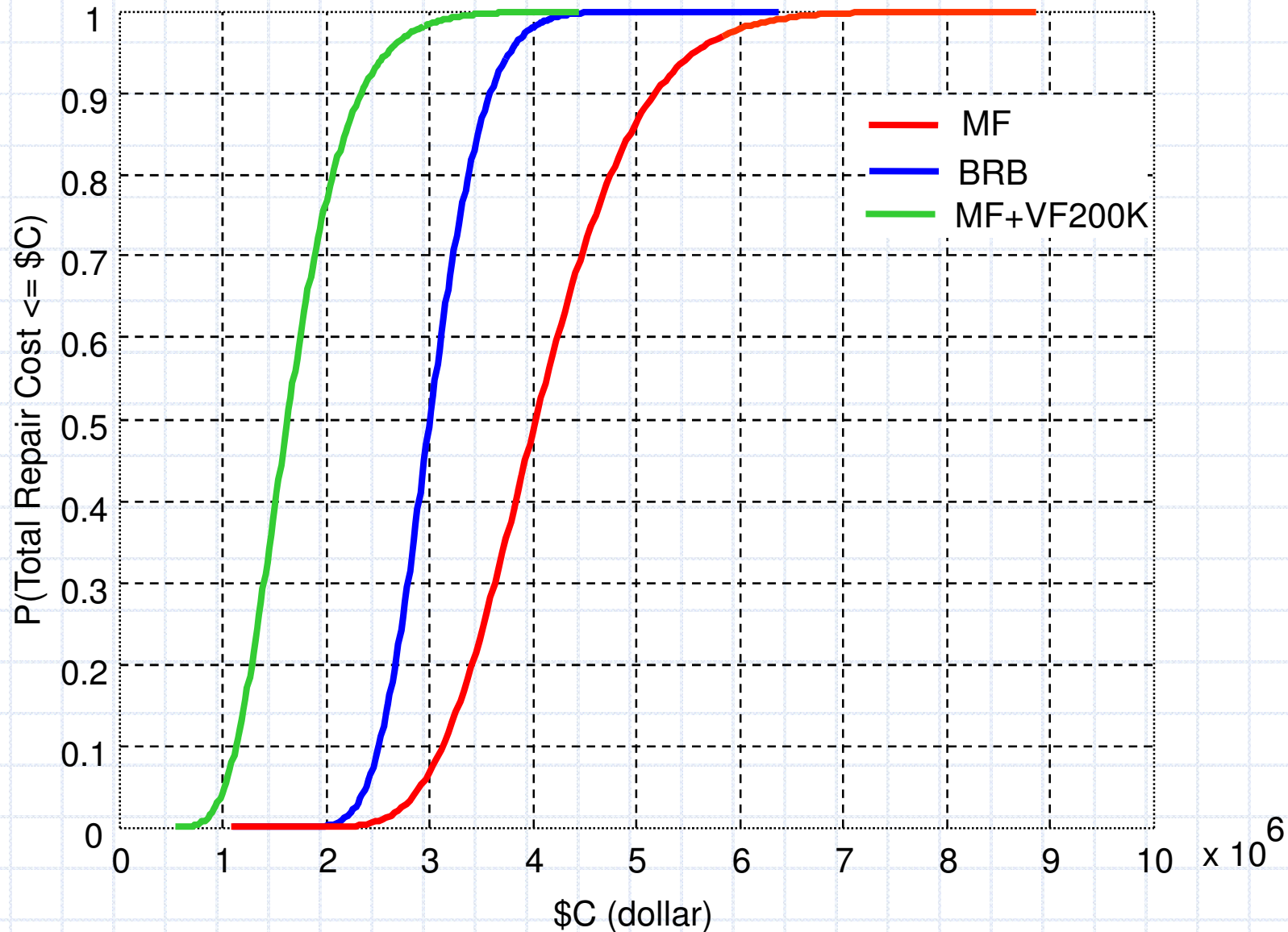
(d) Contributions to total  
cost for scenario



# Deaggregation of repair cost

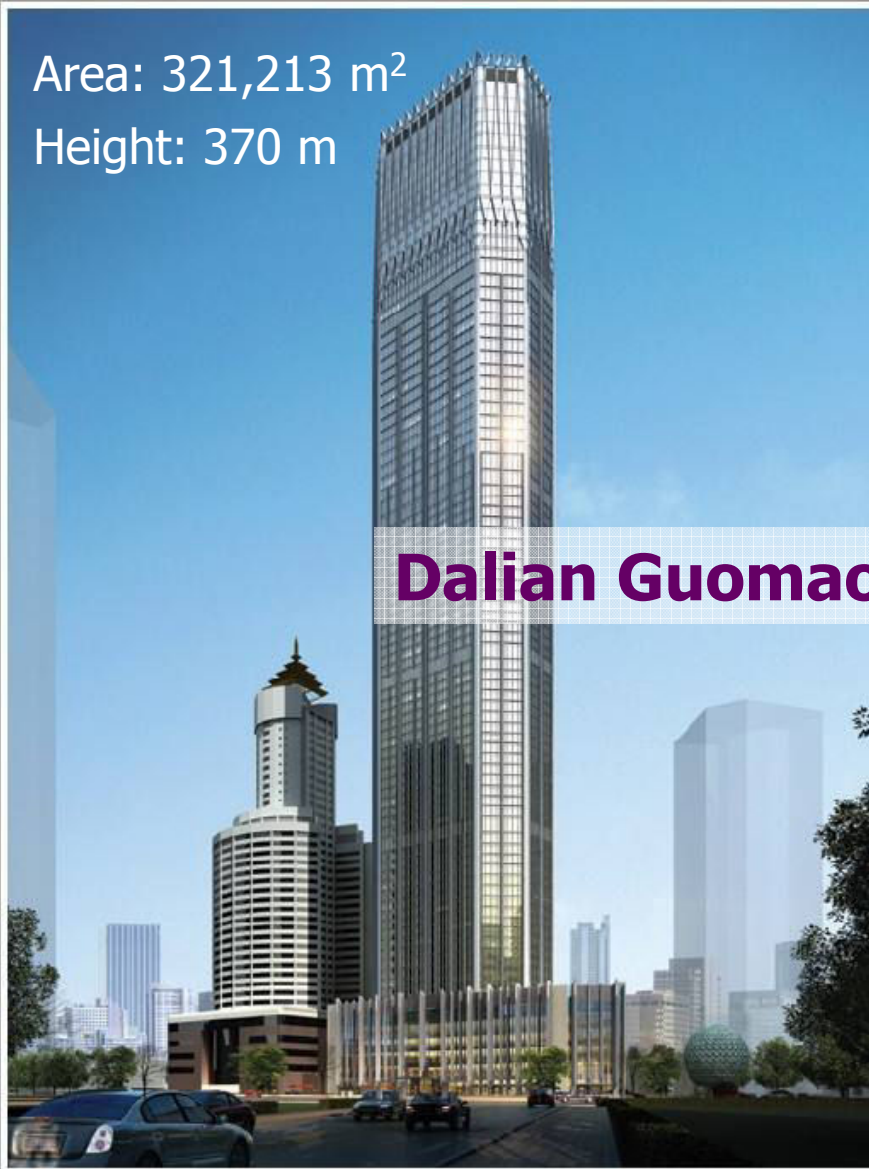


# PE and new structural systems

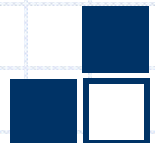


# Application of PBEE

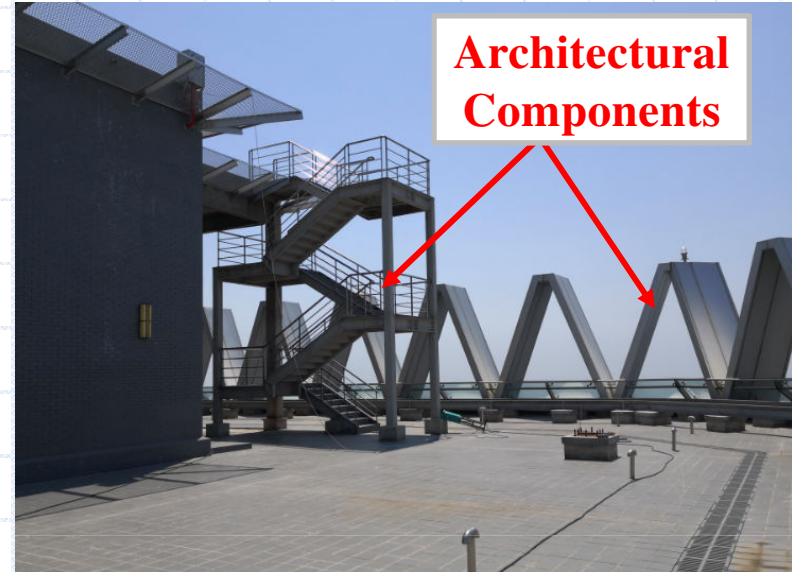
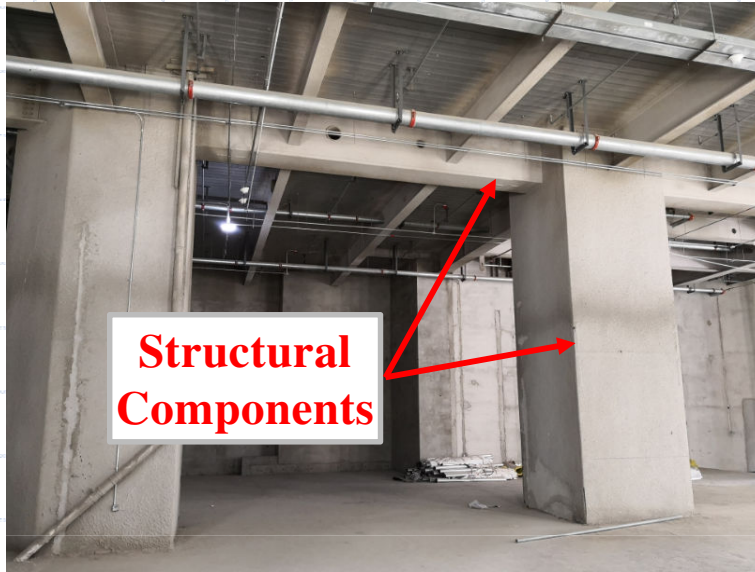
Area: 321,213 m<sup>2</sup>  
Height: 370 m



**Dalian Guomao Building**



# Application of PBEE





# Application of PBEE

$$\lambda(dv < DV) = \iiint G(dv | dm) dG(dm | edp) dG(edp | im) |d\lambda(im)|$$

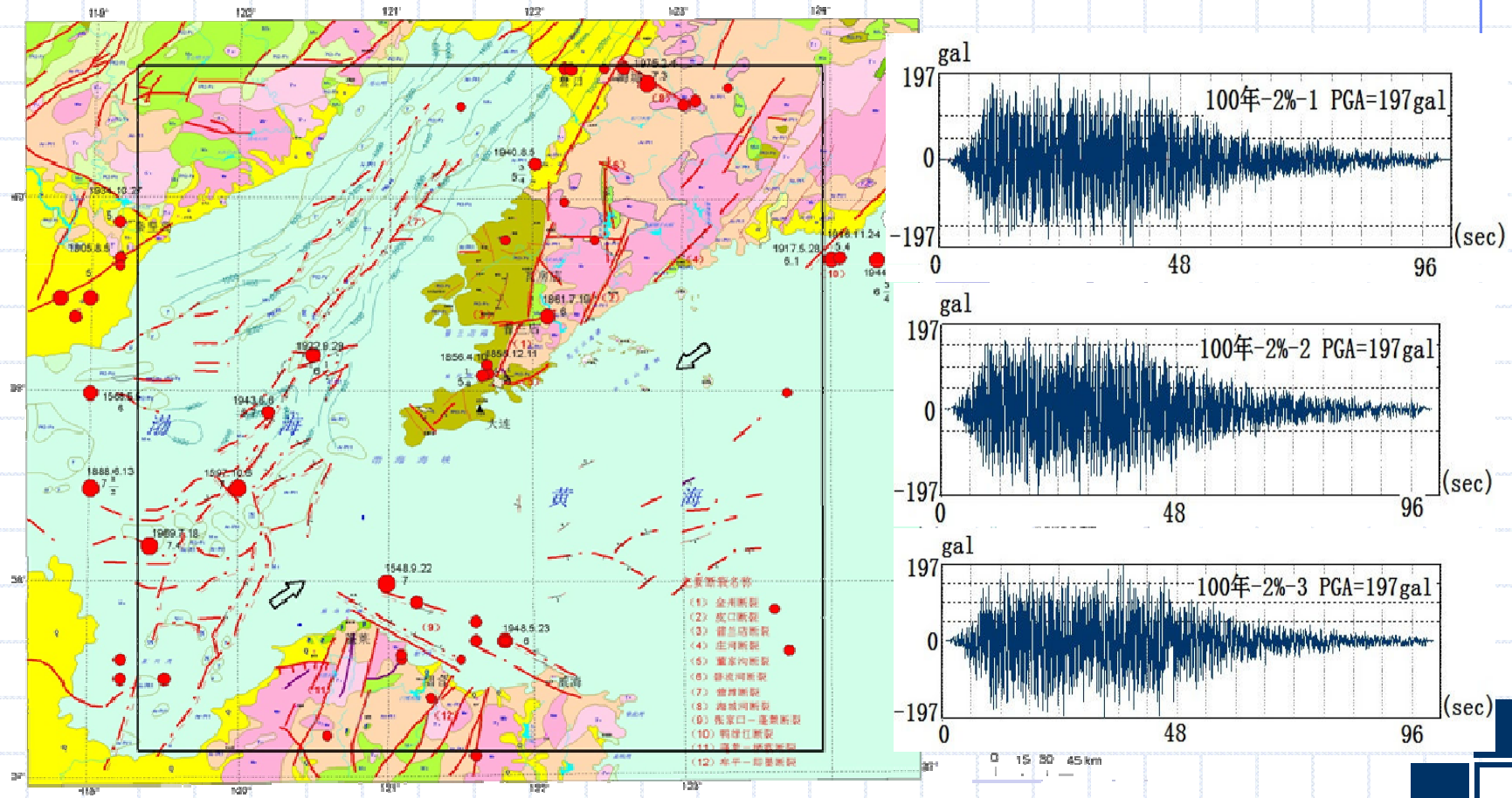
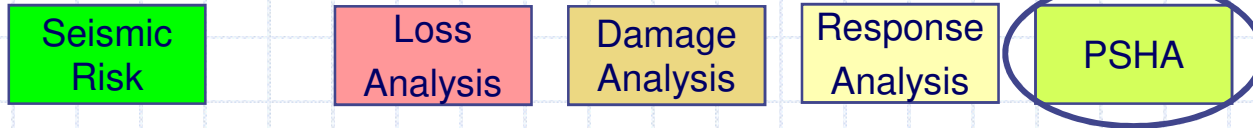


图 3.1-3 渤海湾地震图

# Application of PBEE

$$\lambda(dv < DV) = \iiint G(dv | dm) dG(dm | edp) dG(edp | im) | d\lambda(im)$$

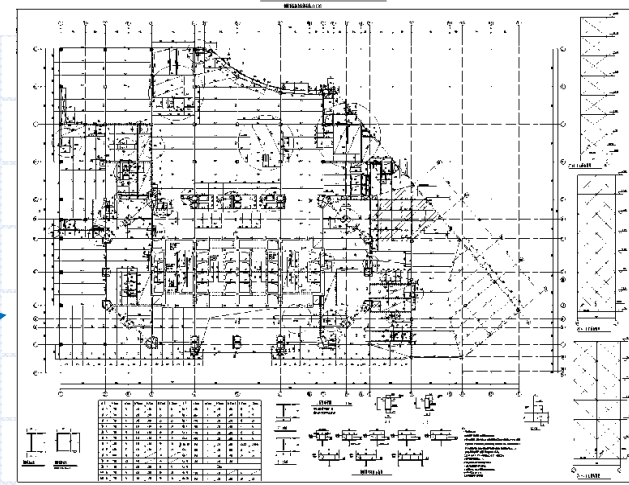
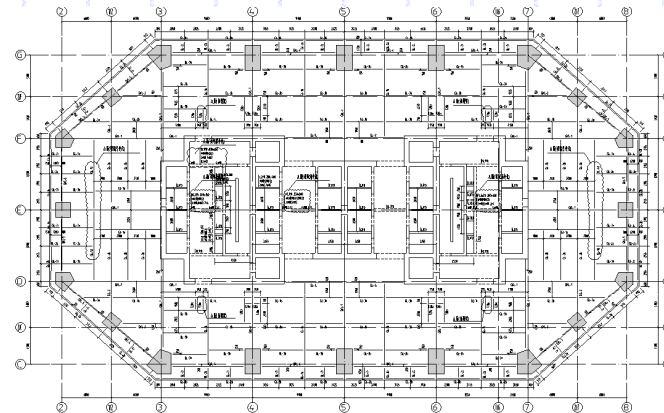
Seismic Risk

Loss Analysis

Damage Analysis

Response Analysis

PSHA



# Application of PBEE

$$\lambda(dv < DV) = \iiint G(dv | dm) dG(dm | edp) dG(edp | im) |d\lambda(im)|$$

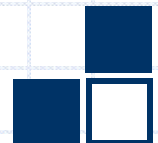
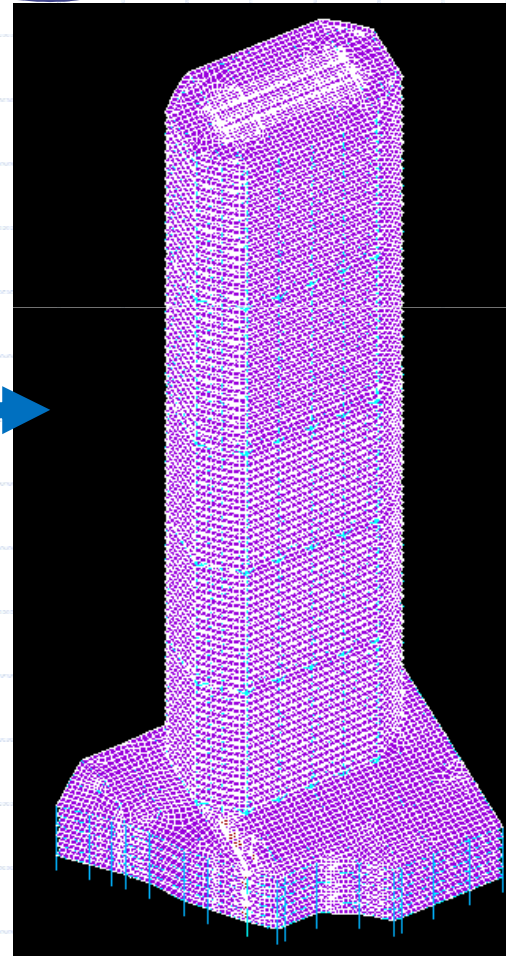
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# Application of PBEE

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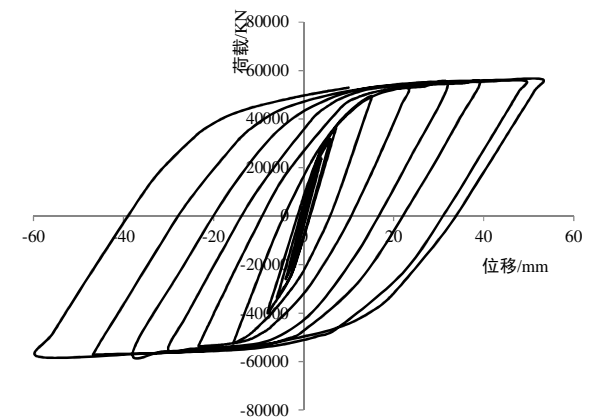
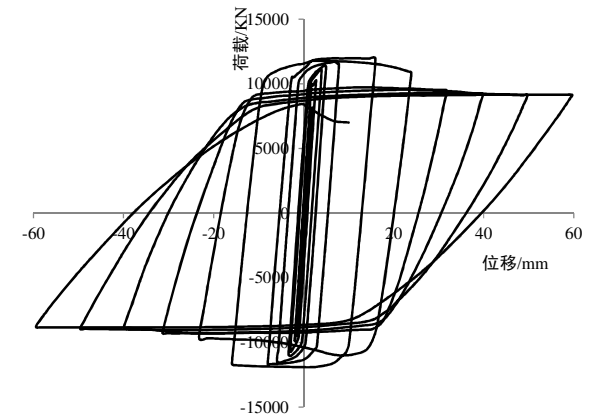
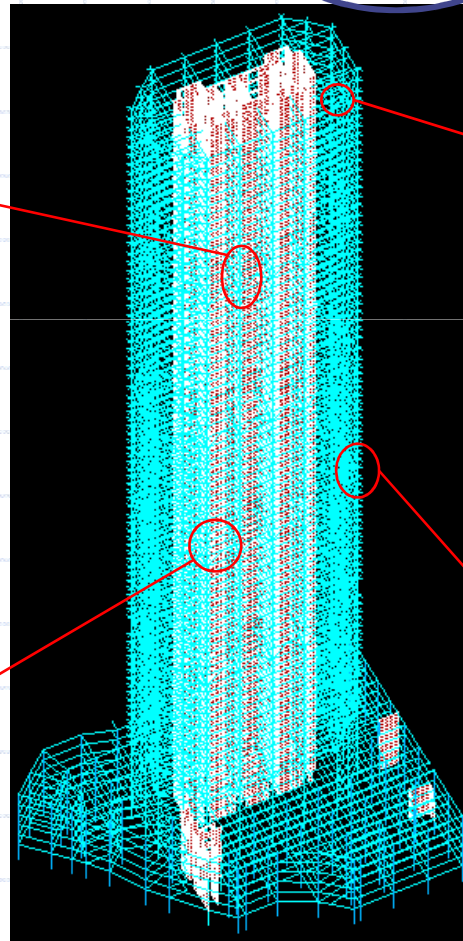
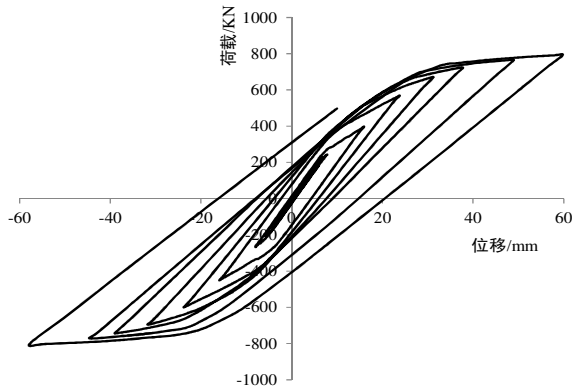
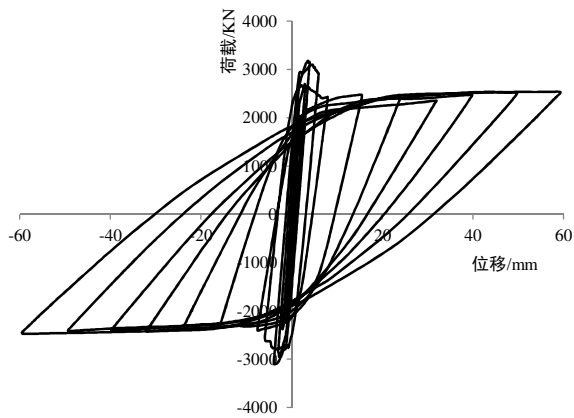
Seismic Risk

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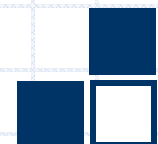
PSHA





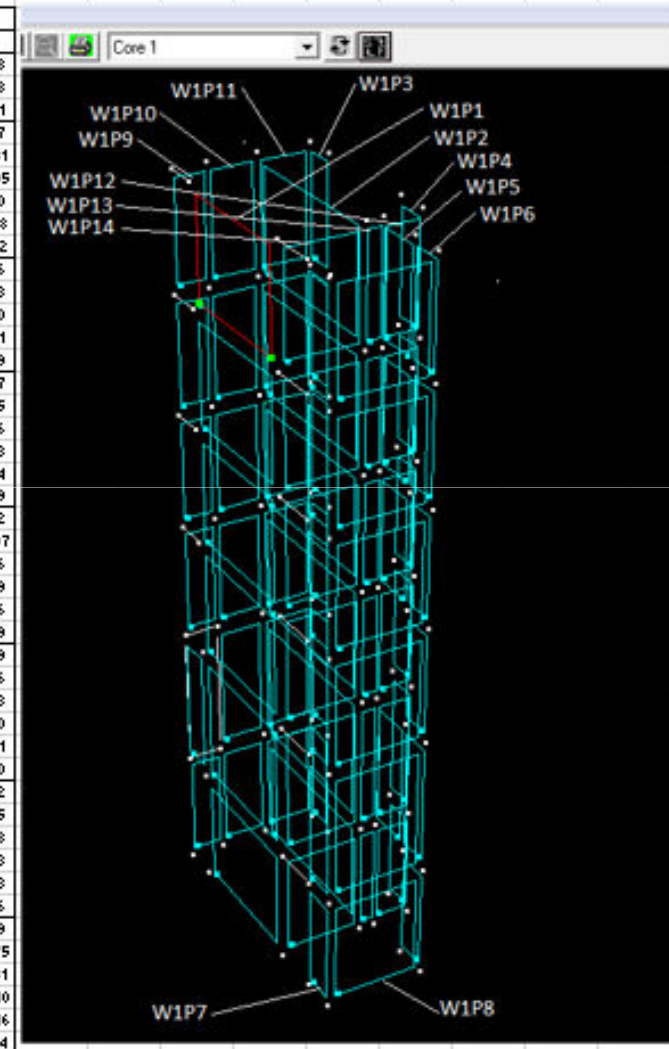
# Application of QuakeProof<sup>®</sup>

<i>Non-structural Component Name:</i>	<i>Location</i>	<i>Type</i>
<b>Interior Glazing</b>	All floors	Architectural
<b>Exterior Glazing</b>	All floors	Architectural
<b>Stone Wall Panels</b>	First floor	Architectural
<b>Partition Walls</b>	All floors	Architectural
<b>Suspended Ceilings</b>	All floors	Architectural
<b>Elevators</b>	All floors	Building Services
<b>Cold Water Piping</b>	All floors	Building Services
<b>Natural Gas Piping</b>	Labs, Floors B1,2,3,4	Building Services
<b>Compressed Air Piping</b>	Labs, Floors B1,2,3,4	Building Services
<b>Fire Suppression Piping</b>	All floors	Building Services
<b>Sanitary Piping</b>	All floors	Building Services
<b>HVAC Chiller</b>	Roof	Building Services
<b>Heat Pump</b>	Basement Floor	Building Services
<b>HVAC Cooling Tower</b>	Roof	Building Services
<b>Non-medical Air Compressor</b>	Roof	Building Services
<b>HVAC ductwork</b>	All floors	Building Services
<b>Air Handling Units</b>	Basement Floor	Building Services
<b>Pump Control System</b>	Basement Floor	Building Services
<b>Electrical Transformer</b>	Basement Floor	Building Services
<b>Electrical Switch Gear</b>	Basement Floor	Building Services
<b>Electrical Distribution Panel</b>	All floors	Building Services
<b>Suspended LAN cable trays</b>	All floors	Building Services
<b>Office Shelving/Cabinets</b>	All floors	Contents
<b>Computer Labs</b>	Floor 1,3,4	Contents
<b>Document Cameras</b>	Theatres - Floors B1,1,2	Contents
<b>AV control module</b>	Theatres - Floors B1,1,2	Contents
<b>Lecture Projectors</b>	Theatres - Floors B1,1,2	Contents
<b>Theatre Speakers</b>	Theatres - Floors B1,1,2	Contents
<b>Wireless Network Routers</b>	All floors	Contents
<b>Lab Equipment</b>	Labs, Floors B1,2,3,4	Contents
<b>Computer servers</b>	Basement Floor	Contents
<b>Office Electronics</b>	All floors	Contents
<b>Office Bookshelves</b>	All floors	Contents



# Application of PBEE

Shear Demand for Different Hazards and Groundmotions																							
250									1050									5050					
131	67	96	61	104	130	93	91	41	85	44	66	63	85	47	38	17	25	27	15	19	19	18	18
117	126	71	63	79	82	104	92	48	52	54	52	51	51	56	48	22	21	26	22	16	21	27	18
72	83	49	55	72	69	70	52	34	42	34	30	44	43	34	53	21	26	21	19	21	23	19	21
936	825	937	931	931	660	749	939	701	921	912	763	365	659	910	305	228	179	423	207	156	142	439	87
925	939	995	842	947	913	917	935	567	853	477	681	634	621	563	421	218	236	334	244	187	223	274	181
851	865	928	791	817	873	623	803	463	680	374	596	513	616	503	346	291	221	245	201	158	127	187	105
537	328	617	423	486	478	411	376	317	404	309	355	311	448	334	230	176	134	198	140	115	110	184	80
921	654	783	644	825	854	762	522	437	567	344	545	465	617	502	382	196	137	210	139	111	118	198	118
389	503	292	327	475	447	408	336	197	241	200	183	252	247	200	293	111	140	118	94	105	123	93	112
331	294	325	316	312	266	240	325	297	318	239	272	175	196	244	134	67	63	115	76	51	50	138	46
327	344	263	326	358	324	309	331	311	331	326	307	221	333	316	228	146	98	230	138	83	100	210	63
213	176	275	228	234	113	114	183	51	167	80	66	55	87	91	51	20	20	22	18	20	17	25	20
262	150	203	219	203	234	185	201	112	145	120	113	106	124	117	100	49	51	70	38	30	38	67	31
178	183	142	123	143	181	180	147	89	72	70	64	108	127	96	128	35	44	29	28	37	41	27	29
454	454	470	464	467	327	404	462	419	461	453	428	268	385	455	171	158	110	250	112	79	66	265	47
463	447	403	413	470	438	456	448	257	320	287	307	284	358	307	250	133	130	195	133	85	100	158	85
482	425	465	457	453	330	367	461	376	406	247	344	222	346	258	236	120	92	144	133	74	81	146	66
296	252	322	296	243	225	229	292	188	229	222	194	130	167	195	149	81	79	112	87	62	62	126	53
458	310	329	290	301	460	348	303	204	264	166	206	218	253	200	166	63	90	96	75	52	73	72	64
286	347	231	206	250	303	302	241	157	117	124	140	180	209	157	216	78	83	69	68	78	85	68	69
606	605	617	614	620	431	600	614	600	616	607	602	397	541	603	269	249	178	364	180	143	118	380	62
602	491	604	536	606	492	598	601	385	513	442	396	347	322	416	329	128	140	212	153	103	99	228	107
512	490	511	488	497	318	300	472	293	501	401	245	214	351	374	256	134	77	192	125	95	72	195	66
368	392	502	467	485	440	394	454	327	486	337	286	214	355	315	288	124	74	183	127	66	55	185	49
488	298	420	249	285	380	271	300	177	259	217	195	147	193	195	175	70	61	99	72	52	52	117	56
265	510	290	259	422	384	447	259	205	212	196	211	233	216	176	271	96	104	71	88	78	91	66	69
395	340	425	422	421	292	289	421	369	422	422	354	166	281	416	185	113	77	208	106	63	56	225	39
361	316	413	336	416	290	248	318	166	260	234	242	162	192	282	119	83	67	129	93	70	60	153	66
221	246	345	338	344	191	234	328	189	345	284	218	115	155	251	91	83	60	127	75	54	49	135	33
289	203	339	333	333	185	196	296	197	342	233	206	113	191	244	103	87	70	134	68	52	50	127	30
180	207	266	197	238	132	138	248	111	186	153	137	83	110	164	84	47	38	70	38	34	35	72	31
155	183	161	170	173	159	124	175	55	135	89	87	73	119	106	71	35	34	44	35	36	35	32	30
168	162	278	231	233	143	158	244	160	233	219	156	77	132	184	99	66	50	95	60	45	41	98	32
202	193	222	186	233	197	164	169	132	209	128	138	119	204	132	106	64	52	76	61	47	49	70	35
128	170	213	154	220	141	161	213	122	232	123	149	104	184	130	84	74	58	80	64	50	43	65	28
136	105	154	119	110	114	109	116	78	111	68	77	86	99	79	63	43	40	47	40	38	42	39	33
116	124	149	100	111	101	93	131	84	117	73	78	76	106	87	64	42	36	48	44	35	38	49	33
83	86	94	70	95	81	74	88	43	66	40	61	56	65	50	50	30	31	30	30	29	30	25	26
765	769	788	782	781	606	602	782	690	780	774	709	315	580	771	388	221	152	389	178	116	104	420	79
768	793	785	776	786	613	783	765	412	612	733	525	356	570	566	301	219	194	299	225	178	190	331	175
767	781	792	795	782	564	564	782	463	768	642	561	335	484	754	263	229	186	339	222	184	180	355	131
601	461	756	706	508	449	391	697	504	505	487	490	262	362	522	295	228	178	309	224	166	185	344	140
581	576	619	604	455	337	415	641	422	479	420	435	235	275	493	267	192	141	278	189	140	156	306	146
401	410	547	481	438	340	344	526	306	384	341	300	213	338	390	295	146	125	193	158	133	123	208	114



# Application of PBEE

$$\lambda(dv < DV) = \iiint G(dv | dm) dG(dm | edp) dG(edp | im) |d\lambda(im)|$$

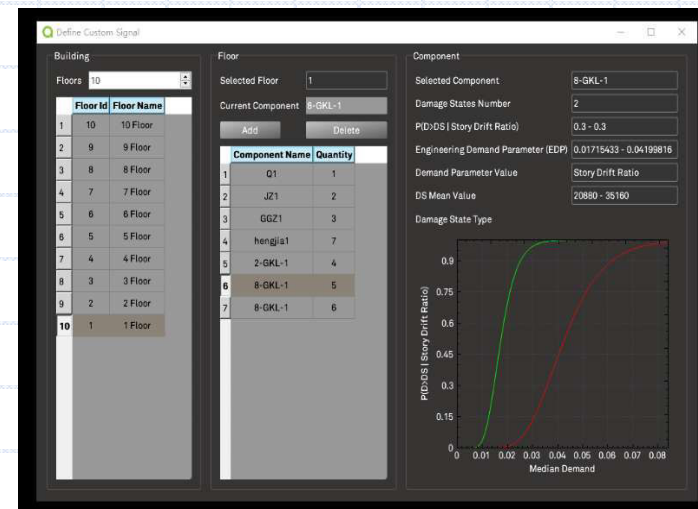
Seismic Risk

Loss Analysis

Damage Analysis






Response Analysis

PSHA





# Application of PBEE

Seismic Risk Assessment of OFCs - Building Walkthrough Report																	
Project Name: NSERC Project Field Test			Building Type: Concrete Shear Wall							Sa (0.2): 1.1		Data Collector: Jeremy Atkinson					
Client: Test			Soil Class: D - Stiff Soil							Sa (0.2): 0.95		Assessment Date: 20-Jan-13					
Location: UBC Vancouver			Period: 0.47		RB: 1.3		RG: 0.836										
Name:	QC:	PO:	Photo:	Location	height	depth	Restraint	Impact	Overturning	Flexibility	Life Safety	Downtime	Vulnerability Index	Consequence Index	Risk Index	Retrofit Index	
breaker panel sp. 1 - 1 x 1	1	15		room 1012	1500	150	Full	Adequate Gap	Fully restrained	On/below ground floor	R <= 1	more than 1 week	0.9	1.1	0.9	0.0	
BSMT cable trays (LXN)	1	15		BSMT	1200	450	Full	Adequate Gap	Fully restrained	On/below ground floor	1-0N<10	more than 1 week	0.9	5.1	4.3	0.0	
compressed air tanks	1	15		BSMT lab	1500	400	Partial	Adequate Gap	Fully restrained	On/below ground floor	R <= 1	more than 1 week	2.6	1.1	2.6	17.4	
display lights	11	15		lobby	0.1	1.5	Full	Adequate Gap	Fully restrained	On/below ground floor	R <= 1	more than 1 week	0.9	1.1	0.9	0.0	
document camera 1 per theater	15	15		room 1012	150	350	Full	Adequate Gap	Fully restrained	On/below ground floor	R <= 1	more than 1 week	0.9	1.1	0.9	0.0	

# Application of PBEE

$$\lambda(dv < DV) = \iiint G(dv | dm) dG(dm | edp) dG(edp | im) | d\lambda(im)$$

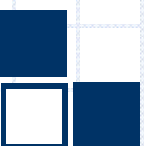
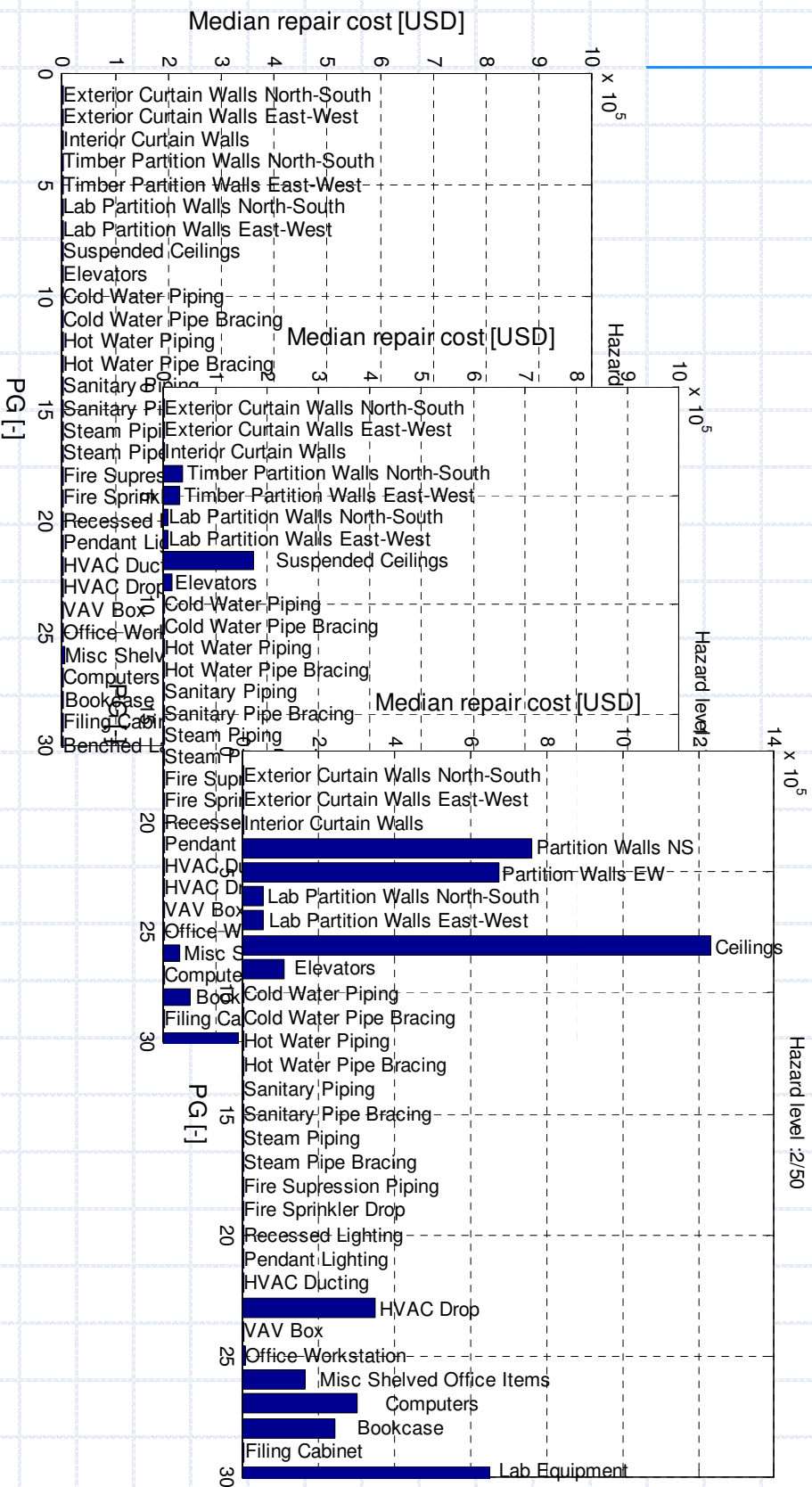
Seismic Risk

Loss Analysis

Damage Analysis

Response Analysis

PSHA



# Application of PBEE

$$\lambda(dv < DV) = \iiint G(dv | dm) dG(dm | edp) dG(edp | im) |d\lambda(im)|$$

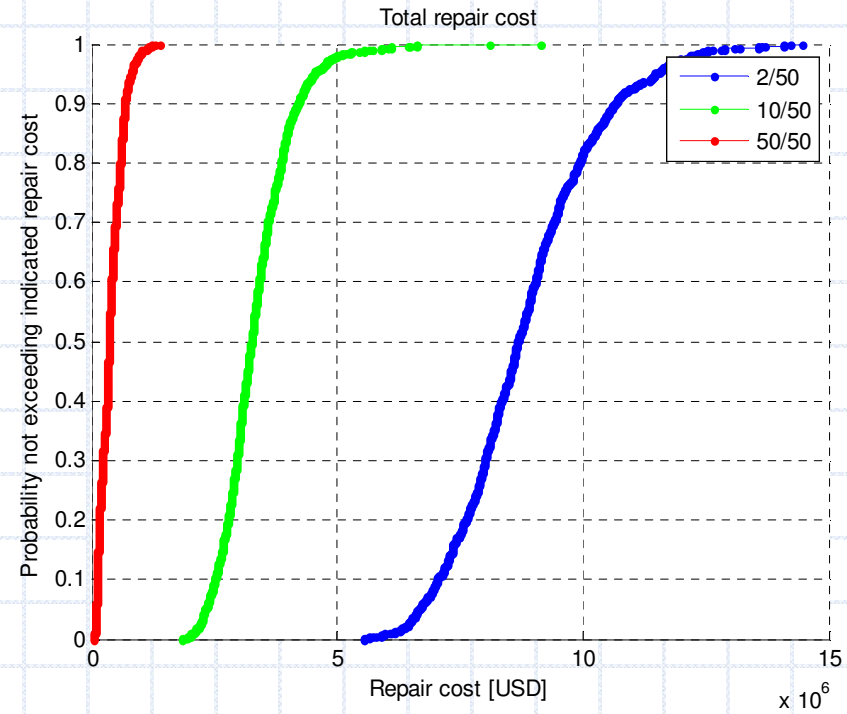
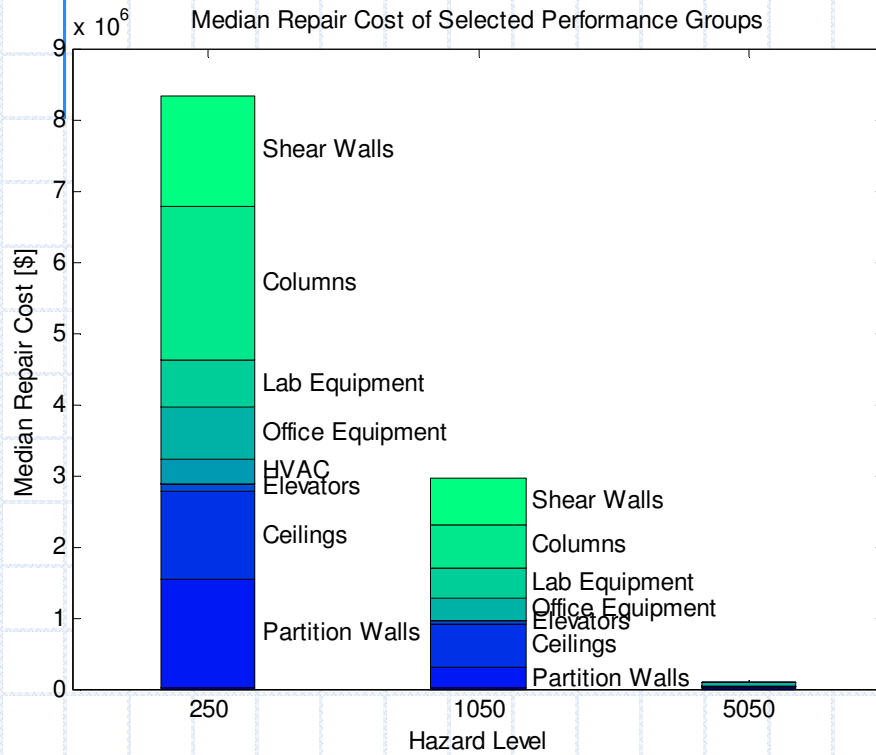
Seismic Risk

Loss Analysis

Damage Analysis

Response Analysis

PSHA



# Application of PBEE

ApowerEdit



Dalian Guomao Building

# AI vision-based technology for PBEE

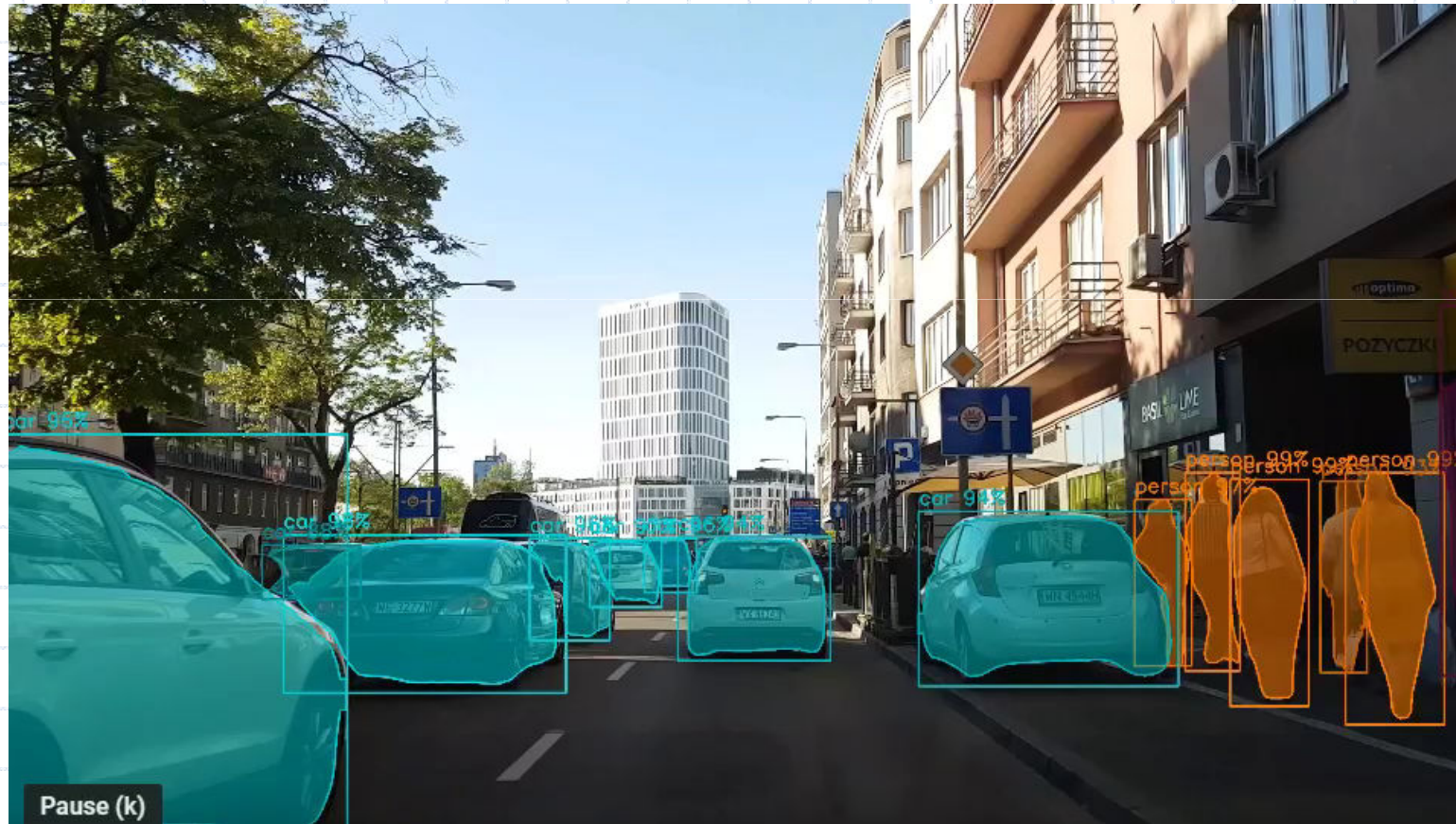


Source: <https://software.intel.com>

# AI vision-based technology for PBEE

## Visual sensing technology

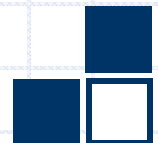
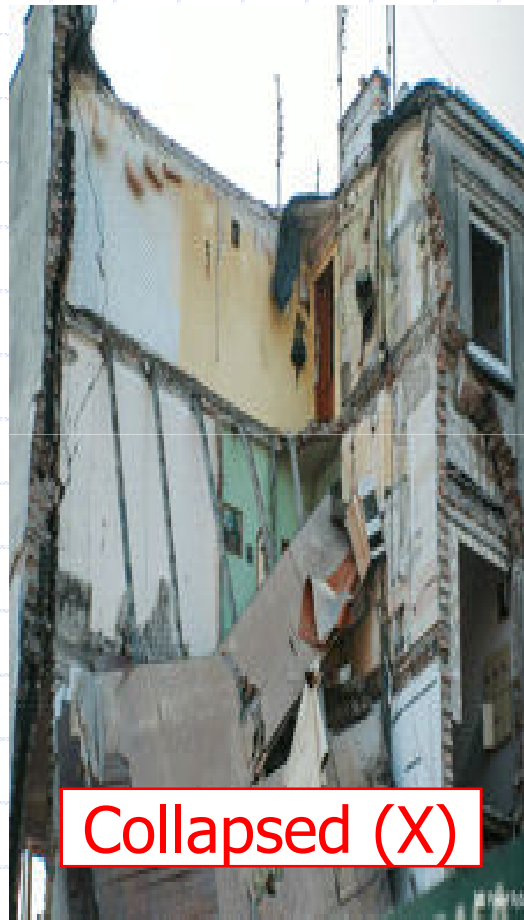
Advancement of deep-learning-based computer vision technology brought breakthroughs in the image processing tasks



Source: [https://github.com/karolmajek/Mask\\_RCNN](https://github.com/karolmajek/Mask_RCNN)

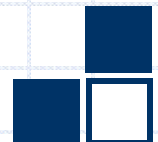
# AI vision-based technology for PBEE

## ◆ Classification



# AI vision-based technology for PBEE

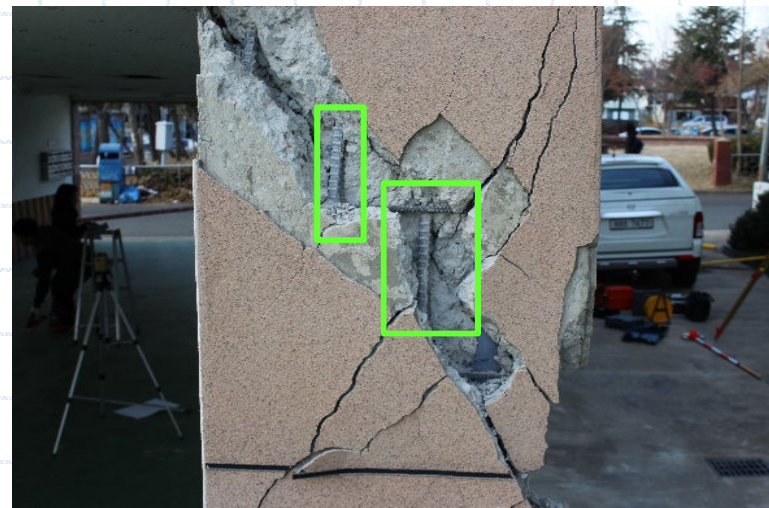
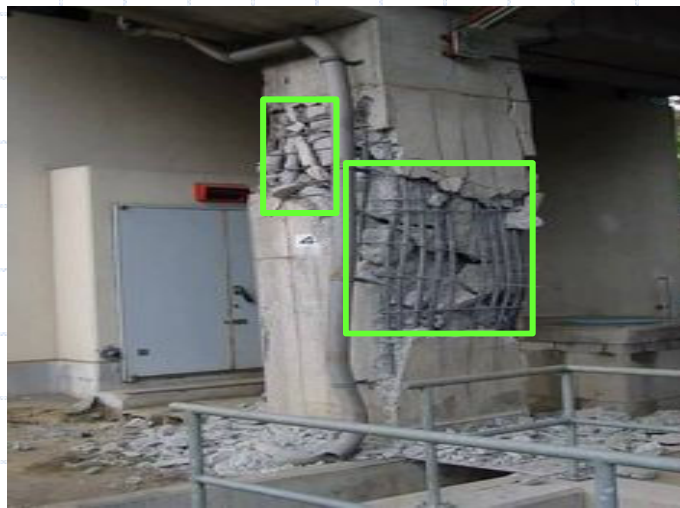
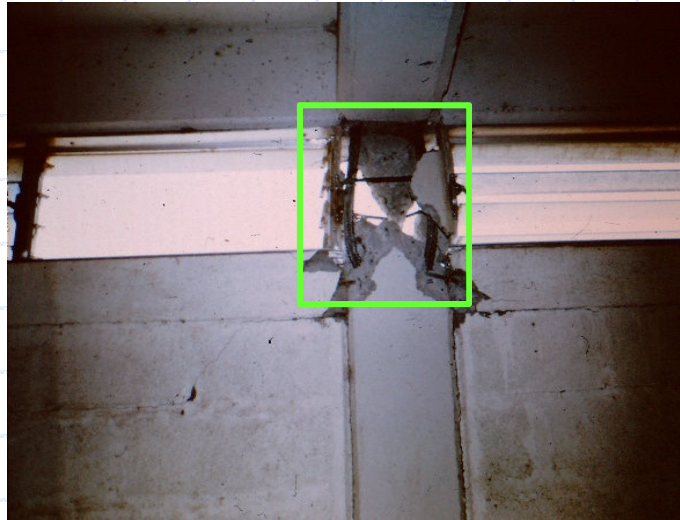
## ◆ Classification





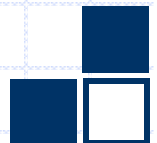
# AI vision-based technology for PBEE

## ◆ Detection



# Summary and conclusions

- ◆ Earthquake is one of the most extreme loading condition that a structure will experience during its design lifetime.
- ◆ Advanced analytical tools are being developed to understand the seismic risk of the structures.
- ◆ PBEE incorporates the state-of-the-art seismic assessment research outcome to allow engineers to share resources to quantify the performance of the structure.
- ◆ Hence, structures can be designed to be more economical and resilient toward future earthquakes.
- ◆ Together, we can make a difference!



Thank you for your attention!

Tony T.Y. Yang, Ph.D., P.Eng.

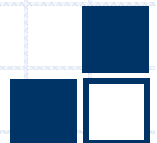
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<http://www.civil.ubc.ca/people/faculty/faculty-yang.php>

<http://smartstructures.civil.ubc.ca/>



# Vancouver, Canada

- ◆ I look forward to welcoming you to beautiful British Columbia
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