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1965 PUGET SOUND, WASHINGTON, EARTHQUAKE TALL BUILDING DAMAGE REVIEW

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16. Abstract (Limit: 200 words)

This study describes the damage behavior of buildings in the Puget Sound, Washington region resulting from an earthquake of Richter Magnitude 6.5 which occurred on April 29, 1965. The affected area includes the State of Washington and part of Oregon, Idaho, and British Columbia, Canada. Major cities sustaining building damages from the earthquake are Seattle, Tacoma, and Olympia. Since this study concerns buildings that are five stories and higher, only the damage data from Seattle buildings are used. The report contains an intensity map of the Puget Sound Earthquake, a comparison of earthquake codes, damage data and building information covering about 1400 buildings, and a discussion and charts of the damage matrices based on information obtained from both the Puget Sound and San Fernando earthquakes. Some findings of the study indicate that building store-height seems not to affect damage behavior. Pre-1942 steel buildings suffered more damage than pre-1942 concrete buildings. Post 1943 buildings, built according to earthquake provision codes, suffered no damage, whereas most of the buildings in the San Fernando area suffered light damage. Damage behavior of high-rise buildings in Tacoma and Olympia are discussed.

17. Document Analysis a. Descriptors

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Earthquake Resistant structures	Building codes
Damage assessment	Commercial buildings
Dynamic structural analysis	Residential buildings

b. Identifiers/Open-Ended Terms

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San Fernando Earthquake of 1971	Tacoma, Washington
Seattle, Washington	Olympia, Washington

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1965 Puget Sound Earthquake

I. Introduction

On April 29, at 8:29 a.m. Pacific Daylight time, the Puget Sound, Washington region was shaken by an earthquake of Richter magnitude 6.5. The epicenter was located between Seattle and Tacoma, and the focal depth was about 36 miles. The strong ground motion lasted for about 20 seconds. The earthquake was characterized by a relatively large area of intensity VII as compared with other earthquakes occurring on the West Coast of the United States. The affected area included the State of Washington and part of Oregon, Idaho and British Columbia, Canada. The Modified Mercalli Intensities in the affected area are shown in Fig. 1. (1)

Seattle, Tacoma and Olympia are the three major cities sustaining building damages from this earthquake. Property loss due to the 1965 shock was estimated at $12,500,000, with much of this loss being in Seattle and King County (1). A preliminary survey of damages, immediately after the earthquake, was reported by Steinbrugge and Cloud (1).

This study describes the damage behavior of the high-rise buildings, 5 stories and higher, in the affected area. Since the number of high-rise buildings located in Tacoma and Olympia is very small, only the damage data from Seattle provides meaningful damage statistics.

II. The Damage Behavior of High-Rise Buildings in Seattle

Seismicity

The seismicity in the Seattle area was classified as MMI VII. The recorded maximum horizontal acceleration was about 0.09g (1).

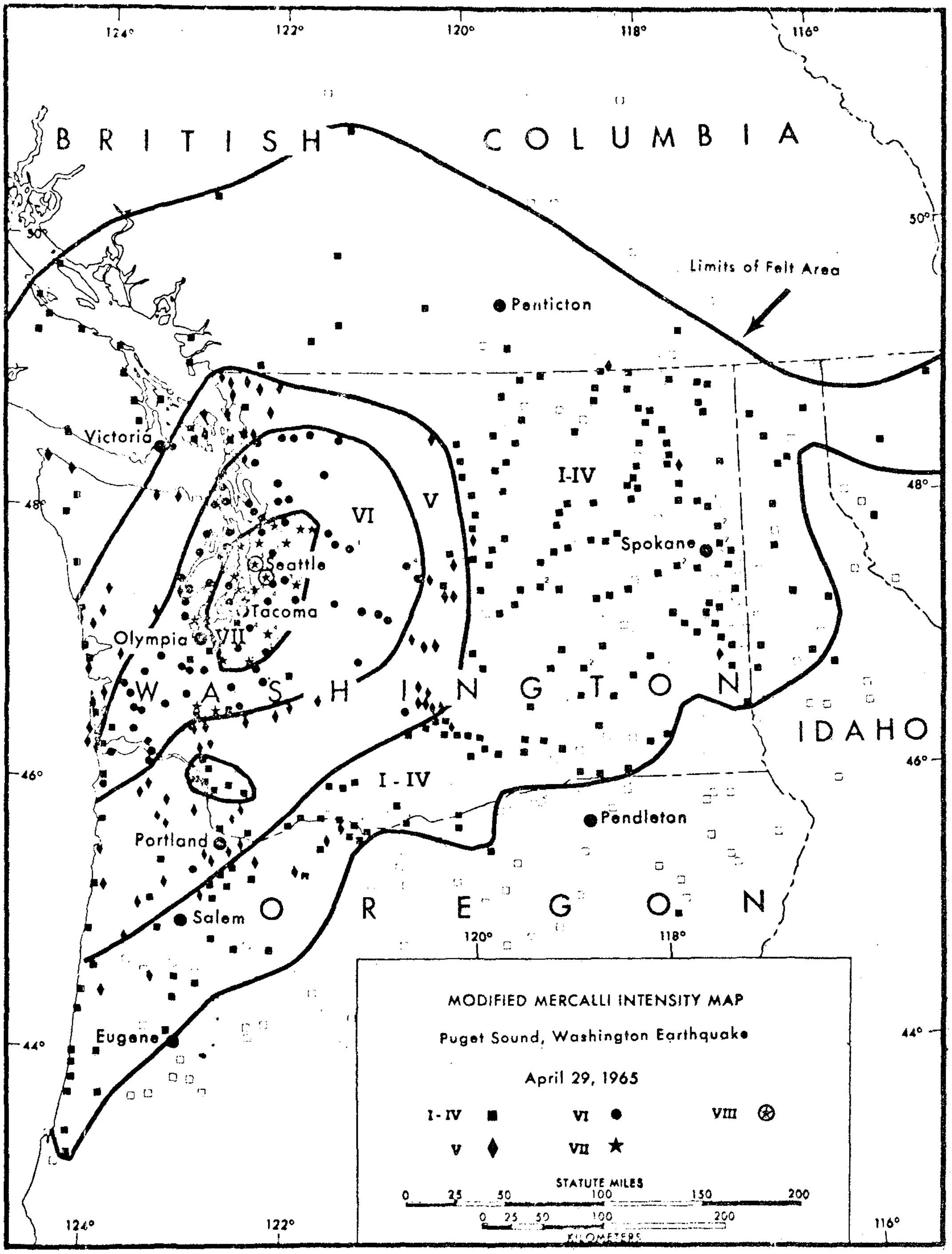

Fig. 1. Intensity Map of the Puget Sound, Washington, Earthquake of April 29, 1965 (1).

Even though some small pocket areas were reported to have MMI VIII seismicity, the maximum horizontal acceleration may suggest that the whole area was subjected to only a weak MMI VII.

Earthquake Code

Before proceeding to the damage data analysis, it is desirable to have a general understanding of earthquake-resisting capability of the Seattle buildings. The first CODE PROVISIONS FOR EARTHQUAKES in Seattle appeared in 1942, with subsequent major modifications being made in 1956 and 1967. A comparison of the base shear coefficients used in the Seattle Code and in the UBC code is shown in Fig. 2.

Base Shear Force = C_e W

Seattle Code			UBC Code k=1 T=0.1n		
Years/ Zone	1942* to 1956	1957 to 1967	1	2	3
W	D.L.+$\frac{1}{2}$ L.L.	D.L.+ $\frac{1}{4}$ L.L.		D.L.	
5	0.02	0.043	0.016	0.031	0.062
10	0.02	0.032	0.013	0.025	0.050
15	0.02	0.025	0.011	0.022	0.044
20	0.02	0.021	0.010	0.020	0.040

* Coefficient shown in this column are applicable only to soil with a bearing capacity higher than 2000 psf.

Fig. 2. Comparison of Base Shear Coefficient (C_e) of the Seattle Code and the UBC Code

From the figure, it is seen that the high-rise buildings constrected after 1942 have the lateral strength roughly corresponding to the Zone 2 design of UBC Code. The pre-1942 buildings have no earthquake provisions.

Damage Data and Building Information

A damage survey covering about 1400 buildings in the Seattle business and high-rise residential districts was conducted jointly by the Seattle Fire Department and the Seattle Building Department. A list of 367 damaged private buildings was obtained from Mr. G. Battson of the Seattle Building Department. This list is considered to include all damaged private high-rise buildings in Seattle at the time of the 1965 earthquake (a total of at least 86 high-rise buildings). The damage states of these buildings were classified as heavy, moderate or light. The number of buildings falling into each damage state are shown in Table 1. The characteristics of the damaged buildings were obtained from the Sanborn maps.

Table 1. Number of Damaged Private Buildings in Seattle Business and High-Rise Residential Districts

Damage State	All Buildings	High-Rise Buildings
Light	155	43
Moderate	120	24
Heavy	92	19
Total	367	86

The damage information of the public high-rise buildings in Seattle area which were not covered in the damage list mentioned above, was obtained from various governmental agencies, notably the City of Seattle and the General Service Administration (G.S.A.), of Auburn, Washington. As a result, 8 high-rise buildings were added to the damage data pool.

Since most of the high-rise buildings are located in downtown

Seattle and the nearby districts, the area shown in Fig. 3 in hatched lines, which corresponds to Vol. 1, 2, and 4 of the Sanborn maps, has been selected as the area on which to base the construction of the damage matrices.

The pertinent information for all high-rise buildings in the selected area (including the address, structural type, date of construction, story height, and building function) was extracted from the Sanborn maps and documented. The buildings were categorized according to the date of construction, story height, structural type, and extent of damage as shown in Fig. 4. The number of buildings in each category and the damage matrices are given in Fig. 5 and Fig. 6, respectively.

Date of Construction	Story Height	Structural Type	Damage State
pre 1942	5-7	Concrete (C)	No damage (N)
1942 - 1965	8-13	Steel (X)	Moderate (M)
Unknown	14-19	Other (O)	Heavy (H)
All	19+	Unknown (U)	All
	All	All	

Fig. 4. Building Categorization

Discussion of the Damage Matrices

In order to facilitate a comparison of the damage matrices obtained from the 1965 Puget Sound earthquake and the 1971 San Fernando earthquake, it is necessary to correlate the damage states used in the study of the Puget Sound earthquake with those used in the San

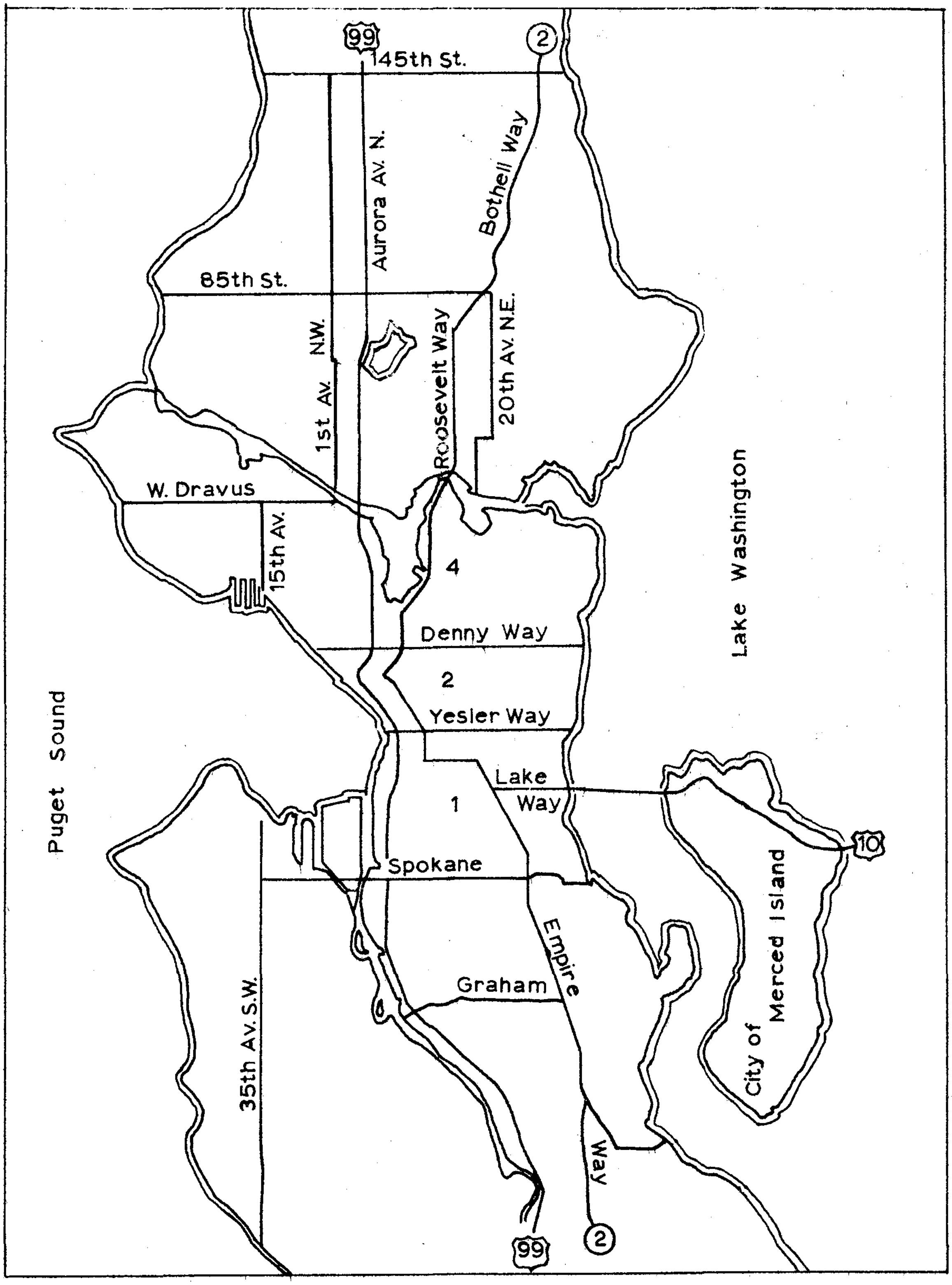

Fig. 3. Areas Used for the Construction of Damage Matrices

Fig.5 Number of Buildings in each Building Category.

Height	Damage state \ Struct. Type \ Date of Const.	UNKNOWN S	UNKNOWN C	UNKNOWN OT	UNKNOWN UN	UNKNOWN All	PRE 1942 S	PRE 1942 C	PRE 1942 OT	PRE 1942 UN	PRE 1942 All	1943-1964 S	1943-1964 C	1943-1964 OT	1943-1964 UN	1943-1964 All	UNKNOWN + PRE 1942 S	UNKNOWN + PRE 1942 C	UNKNOWN + PRE 1942 OT	UNKNOWN + PRE 1942 UN	UNKNOWN + PRE 1942 All	All S	All C	All OT	All UN	All All
5-7	N	5	28	20	42	95	5	41	2	1	49	1	31			32	10	69	22	43	144	11	100	22	43	176
	L	5	6	3	6	19	1	7			8	1				1	6	13	3	5	27	7	13	3	5	23
	M	1	2	3	5	11	3	5		1	9		1			1	4	7	3	6	20	4	8	3	6	21
	H	2	2	3	2	9	3	3			6		1			1	5	5	3	2	15	5	6	3	2	16
	All	13	38	29	54	134	12	56	2	2	72	2	33			35	25	94	31	56	206	27	127	31	56	241
8-13	N	4	4			8	9	31	1		41		11	1		12	13	35	1		49	13	46	2		61
	L	2				2	2	7			9		3			3	4	7			11	4	10			14
	M	0		1		1	1	1			2						1	1	1		3	1	1	1		3
	H	1				1	1	2			3						2	2			4	2	2			4
	All	7	4	1		12	13	41	1		55		14	1		15	20	45	2		67	20	59	3		82
14-18	N	1	2			3		3			3		4	1		5	1	5			6	1	9	1		11
	L	1				1		1			1		1			1	1	1			2	1	2			3
	M							2			2							2			2		2			2
	H																									
	All	2	2			4		6			6		5	1		6	2	8			10	2	13	1		16
19+	N												1			1							1			1
	L							2			2							2			2		2			2
	M						1				1										1					1
	H																									
	All						1	2			3		1			1		2			3		3			4
All	N	10	34	20	42	106	14	75	3	1	93	1	47	2		50	24	109	23	43	199	25	156	25	43	249
	L	8	6	3	5	22	3	17			20	1	4			5	11	23	3	5	42	12	27	3	5	47
	M	1	2	4	5	12	5	8		1	14		1			1	6	10	4	6	26	6	11	4	6	27
	H	3	2	3	2	10	4	5			9		1			1	7	7	3	2	19	7	8	3	2	20
	All	22	44	30	54	150	26	105	3	2	136	2	53	2		57	48	149	33	56	286	50	202	35	56	343

Fig. 6 Damage Matrices from Seattle due to the 1965 Puget Sound Earthquake

Height	Date of Const. / Struc. Type / Damage State	UNKNOWN S	UNKNOWN C	UNKNOWN OT	UNKNOWN UN	UNKNOWN All	PRE 1942 S	PRE 1942 C	PRE 1942 OT	PRE 1942 UN	PRE 1942 All	1943-1964 S	1943-1964 C	1943-1964 OT	1943-1964 UN	1943-1964 All	UNKOWN + PRE 1942 S	UNKOWN + PRE 1942 C	UNKOWN + PRE 1942 OT	UNKOWN + PRE 1942 UN	UNKOWN + PRE 1942 All	All S	All C	All OT	All UN	All All
5-7	N	.38	.73	.69	.78	.71	.42	.73	1	.5	.68	.5	.94			.91	.40	.73	.70	.77	.70	.41	.79	.70	.77	.73
	L	.38	.17	.11	.09	.14	.08	.13			.11	.5				.03	.24	.14	.10	.09	.13	.26	.10	.10	.09	.11
	M	.16	.05	.10	.09	.08	.25	.09		.5	.13		.03			.03	.16	.07	.10	.11	.10	.15	.06	.10	.11	.09
	H	.08	.05	.10	.04	.07	.25	.05			.08		.03			.03	.20	.06	.10	.03	.07	.18	.05	.10	.03	.07
	No of bldgs	13	38	29	54	134	12	56	2	2	72	2	33			35	25	94	31	56	206	27	127	31	56	241
8-13	N	.57	1			.67	.69	.76	1		.75		.79	1		.80	.65	.78	.5		.73	.65	.78	.67		.74
	L	.29				.17	.15	.17			.16		.21			.20	.20	.16			.16	.20	.17			.17
	M			1		.08	.08	.02			.04						.05	.02	.5		.04	.05	.02	.33		.04
	H	.14				.08	.08	.05			.05						.10	.04			.06	.10	.03			.05
	No. of bldgs	7	4	1		12	13	41	1		55		14	1		15	20	45	2		67	20	59	3		82
14-18	N	.5	1			.75		.5			.5		.80	1		.83	.5	.62			.60	.5	.69	1		.69
	L	.5				.25		.17			.17		.20			.17	.5	.13			.20	.5	.16			.19
	M							.33			.33							.25			.20		.15			.12
	H																									
	No. of bldgs	2	2			4		6			6		5	1		6	2	8			10	2	13	1		16
19+	N												1			1							.33			.25
	L							1			.67							1			.67		.67			.50
	M						1				.33										.33					.25
	H																									
	No. of bldgs						1	2			3		1			1		2			3		3			4
All	N	.45	.77	.67	.78	.71	.54	.71	1	.5	.68	.5	.89	1		.88	.50	.73	.70	.77	.70	.50	.73	.71	.77	.73
	L	.36	.13	.10	.09	.14	.12	.16			.15	.5	.07			.08	.23	.15	.09	.09	.14	.24	.13	.09	.09	.13
	M	.05	.05	.13	.09	.08	.19	.08		.5	.10		.02			.02	.12	.07	.12	.11	.09	.12	.05	.11	.11	.08
	H	.14	.05	.10	.04	.07	.15	.05			.07		.02			.02	.15	.05	.09	.03	.07	.14	.04	.09	.03	.06
	No of bldgs	22	44	30	54	150	26	105	3	2	136	2	53	2		57	48	149	33	56	286	50	202	35	56	343

Fernando study. The damage scale used for the Seattle earthquake study is divided into four states, namely: no damage, light damage, moderate damage, and heavy damage. The damage scale used for the San Fernando study is classified into 9 damage states as shown in Fig. 7. Since the damage states used for the Seattle study were defined entirely by the inspector's judgement and no damage costs were available, it is very difficult to establish an accurate correlation between the two damage scales. However, based on the conversation with Mr. G. Battson of the Seattle Building Department and the comparison of the photographs of the damaged buildings in the Seattle area and the descriptions of damages for the damage states used in the San Fernando Study, an approximate correlation between the two damage scales was established as shown in Fig. 8 .

Seattle Damage State	San Fernando Damage State
No	0
Light	1.2
Moderate	3.4
Heavy	5.6,7

Fig. 8. Approximate Correlation between Damage States

Based on this approximate correlation, the damage matrices obtained from the MMI VII zone of the 1971 San Fernando earthquake are modified and shown in Fig. 9 , with the Seattle damage scales indicated.

Description of Level of Damage	Ratio to Present Cost: Central Value	Ratio to Present Cost: Range
0. No Damage	0	0-.0005
1. Minor nonstructural damage—a few walls and partitions cracked, incidental mechanical and electrical damage.	.001	.0005-.003
2. Localized nonstructural damage—more extensive cracking (but still not widespread); possibly damage to elevators and/or other mechanical/electrical components.	.005	.003- .0125
3. Widespread nonstructural damage—possibly a few beams and columns cracked, although not noticeable.	.02	.0125-.035
4. Minor structural damage—obvious cracking or yielding in a few structural members; substantial nonstructural damage with widespread cracking.	.05	.035- .075
5. Substantial structural damage requiring repair or replacement of some structural members; associated extensive nonstructural damage.	.10	.075- .20
6. Major structural damage requiring repair or replacement ofmany structural members; associated nonstructural damage requiring repairs to major portion of interior; building vacated during repairs.	.30	.20- .65
7. Building condemned.	1.0	.65- 1.0
8. Collapse.		

Fig. 7. Damage States Description for the San Fernando Study

Fig. 9 The Damage Matrices From the MMI VII Zone of the 1971 San Fernando Earthquake

Height	Damage State	PRE 1933 S	PRE 1933 C	PRE 1933 All	POST 1947 S	POST 1947 C	POST 1947 All	All S	All C	All All
5-7	N (0)	.18	.16	.18	.24	.21	.24	.24	.17	.22
	L (1,2)	.55	.42	.43	.66	.42	.54	.61	.43	.43
	M (3,4)	.27	.32	.33	.10	.37	.22	.15	.35	.27
	H (5,6,7)		.10	.06					.05	.03
	No. of bldgs	11	19	33	21	19	41	33	40	77
8-13	N (0)	.06	.16	.13	.44	.27	.36	.25	.21	.23
	L (1,2)	.66	.40	.49	.37	.65	.51	.51	.52	.50
	M (3,4)	.16	.35	.28	.19	.08	.13	.18	.22	.21
	H (5,6,7)	.12	.09	.10				.06	.05	.06
	No. of bldgs	32	43	78	32	37	70	65	81	150
14-18	N (0)				.43	.80	.53	.37	.80	.47
	L (1,2)	1		1	.43	.20	.37	.50	.20	.43
	M (3,4)				.14		.10	.13		.10
	H (5,6,7)									
	No. of bldgs	2		2	14	5	19	16	5	21
19+	N (0)				.21	1	.27	.20	1	.26
	L (1,2)				.79		.73	.76		.70
	M (3,4)									
	H (5,6,7)	1		1				.04		.04
	No. of bldgs	1		1	24	2	26	25	2	27
All	N (0)	.09	.16	.14	.33	.32	.33	.25	.23	.25
	L (1,2)	.63	.40	.47	.56	.52	.54	.58	.47	.51
	M (3,4)	.17	.34	.29	.11	.16	.13	.14	.25	.20
	H (5,6,7)	.11	.10	.10				.03	.05	.04
	No. of bldgs	46	62	114	91	63	156	139	128	275

It is worth while noting that the soil conditions in the area under consideration are fairly uniform (at least in a gross sense), and, consequently, the soil conditions will probably not affect the building damage pattern significantly.

It appears reasonable to assume that the buildings with no date of construction provided on the Sanborn maps were constructed before 1942. This assumption is substantiated by the fact that the damage matrices of the buildings with no construction date information are very similar to the damage matrices of the pre-1942 buildings. Therefore these two groups of buildings have been lumped together and considered as pre-1942 buildings.

On the examination of Fig. 6 and Fig. 8, several comments may be made as follows:

(1) The story height (up to 18 stories) seems not to affect the damage behavior.

(2) The pre-1942 steel buildings suffered higher damage than the pre-1942 concrete buildings did. This is just opposite to what was found in the San Fernando study, where the steel buildings suffered lighter damage than their concrete counterparts. Reasons for this inconsistency are not evident; however, Mr. Arthur B. Andersen, of Andersen, Bjornstad, Kane, Consulting Engineers, mentioned that concrete structures in the Seattle area have greater earthquake-resisting capability than concrete structures in other areas because of the particular gradation of the aggregates commonly used in concrete mixes in the Seattle area.

Nevertheless, it is not clear at the moment exactly how the gradation of the aggregates affects the behavior of concrete structures under earthquake excitation.

For the post-1943 buildings, there is not enough data to make a comparison of the damage behavior of steel and concrete buildings.

(3) The post-1943 buildings, which were designed and built according to a code containing earthquake provisions, suffered very little damage. The effectiveness of the earthquake provision in reducing the earthquake damage is clearly demonstrated.

(4) The damage distribution pattern resulting from the Seattle earthquake differs from the pattern resulting from the San Fernando earthquake. Most of the buildings suffered no damage during the Seattle quake, whereas most of the buildings suffered light damage in the MMI VII zone of the San Fernando area. However, if the percentages in the nondamage state and light damage state are combined, the damage distribution patterns of the damage matrices are fairly consistent.

(5) Even though the seismicity in Seattle was classified as MMI VII and some small pocket areas are considered to be as high as MMI VIII, the overall building damages were less than that to buildings in the MMI VII zone of the San Fernando area. This may be explained by the fact that the recorded maximum horizontal acceleration was about 0.09g in Seattle, whereas the recorded maximum

horizontal acceleration in the MMI VII zone of the San Francisco earthquake ranged from 0.1 to 0.2g. Therefore the ground motion in Seattle was not as strong as that in the MMI VII zone of the San Fernando area.

III. Damage Behavior of High-Rise Buildings in Tacoma

The seismicity in Tacoma was classified as MMI VII by the Coast and Geodetic survey and the recorded maximum horizontal acceleration was about 0.08g (1).

A comparison of the ground motion time history in Seattle and that in Tacoma reveals that the strength of shaking in Tacoma was weaker than that in Seattle. Therefore, the seismicity may be considered as weak MMI VII or strong MMI VI.

Located in Tacoma at the time of the earthquake were about 20+ buildings 5 stories or higher. Most of the buildings were older brick masonry structures which can be considered as designed with no earthquake provision. Based on a discussion with Mr. H. Birkeland, president of ABAM Engineers, Inc., and Mr. R. Button and Mr. Ben Thompson (both on the engineering staff for the City of Tacoma), it was concluded that only about 5% of the buildings suffered light damage while the other 95% sustained no apparent damage.

IV. Damage Behavior of High-Rise Buildings in Olympia

The seismicity in Olympia was classified as MMI VI by the Coast and Geodetic Survey (1). The maximum horizontal acceleration was about 0.2g. Even though Olympia was not as close as Seattle and Tacoma to the epicenter, the strength of the ground motion was stronger than that in Seattle and Tacoma. It is not evident why the seismicity in Olympia is MMI VI if the maximum horizontal acceleration can be a good indicator of the earthquake strength.

Only 4 buildings in Olympia can be considered as high-rise, at the time of the earthquake. Most of them are old concrete buildings located at the State Capitol.

Based on a discussion with Mr. Del Pepper of the Division of Engineering and Architecture, Department of General Administration, State of Washington, and his associates, and with Mr. H.K. Kim of Victor Gray and Associates, the damage conditions are summarized as follows: The Legislative Building is the only one which suffered extensive damage, especially around the dome ring. The repairs cost more than $300,000 and the damage ratio was about 5%. The Farmer Insurance Building appeared to suffer only light damage, while the other two buildings suffered no apparent damage.

Reference

1. The Puget Sound, Washington, Earthquake of April 29, 1965, U.S. Department of Commerce, Coast and Geodetic Survey, Rockville, Maryland.