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FEMA P-58 Seismic Building Performance Assessment of the New St. Paul's Hospital

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ABSTRACT

The new St. Paul's Hospital, currently under construction in Vancouver's False Creek Flats, is designed as a post-disaster facility in accordance with the 2019 Vancouver Building By-law. As it will play an essential role in the post-disaster response of the community, additional assessments beyond the requirements of the building code were conducted to better predict the post-earthquake performance of the facility. The assessment methodology as outlined in the FEMA P-58: Seismic Performance Assessment of Buildings was utilized to assess the facility's performance based on its specific site characteristics, structural and non-structural components, medical equipment, and occupancy. This paper presents an overview of two methods that were used to present and summarize the FEMA P-58 assessment's outputs to various stakeholders: 1) floor-by-floor breakdown of repair costs and repair times for various component groups with emphasis on equipment crucial to post-earthquake functionality of the facility 2) component-by-component damage state data breakdown translated from numbers into written statements. This information helped various technical and non-technical stakeholders including the design professionals understand the impact of seismic damage and confirm/improve design decisions.

Keywords: FEMA P-58: Seismic Performance Assessment, Post-earthquake functionality, FEMA P-58 results breakdown, Damage state breakdown and interpretation, Seismic performance measures

INTRODUCTION

The new St. Paul's Hospital, currently under construction in Vancouver's False Creek Flats, is designed as a post-disaster facility in accordance with the 2019 Vancouver Building By-law (VBBL). As it will play an essential role in the post-disaster response of the community, additional assessments beyond the requirements of the building code were conducted to better predict the post-earthquake performance of the facility. The assessment methodology as outlined in the FEMA P-58: Seismic Performance Assessment of Buildings was utilized to assess the facility's performance for several shaking intensities.

This paper provides a brief background of the FEMA P-58 assessment methodology and various inputs used in the analysis. It then focuses on how the outputs of the assessment were summarized and presented to various stakeholders and design professionals in a manner to inform them of the potential impacts of seismic events on the functionality of building.

BACKGROUND

The seismic performance assessment methodology as outlined in FEMA P-58 Vol. 1 [1] evaluates the likelihood of a building, including structural and non-structural components, being damaged by earthquake ground shaking and estimates the potential consequences of such damage. There are four main parameters that comprise the methodology: site hazard characteristic, structural responses, assembling building model including structural and non-structural components, and developing consequence fragilities. The information acquired through these four parameters will then go through Monte Carlo simulation to generate building specific performance measures. Figure 1 is a flowchart of this process.

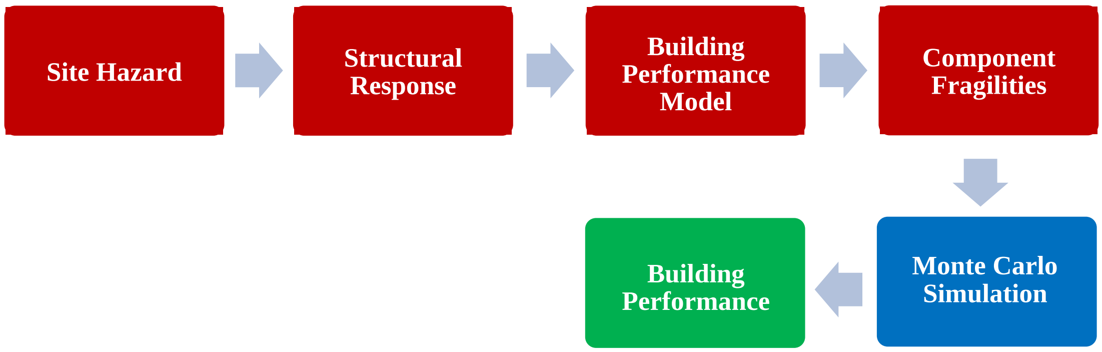

Figure 1: FEMA P-58 Assessment Methodology Flowchart

The assessment outlined in this paper is the intensity-based type as described in FEMA P-58 Vol.1 Section 2.5 [1]. It evaluates the performance for a specified shaking intensity defined by a user-selected acceleration response spectrum. This assessment is often used for buildings that are designed for shaking intensities consistent with code-based response spectrum.

The assessment tool used for the purpose of this project was the SP3-RiskModel Advanced analysis module of the Seismic Performance Prediction Program (SP3) software platform developed by Haselton Baker Risk Group (HBR). The FEMA P-58 damage and loss assessment methodology is implemented in SP3-RiskModel Advanced using their in-house developed analytical engine.

Three ground shaking intensities were considered in the assessment as related to probabilities of exceedance of 2% in 50 years, 10% in 50 years, and 40% in 50 years in accordance with VBBL 2019 seismic loading. Figure 2 illustrates the uniform hazard curves for the site.

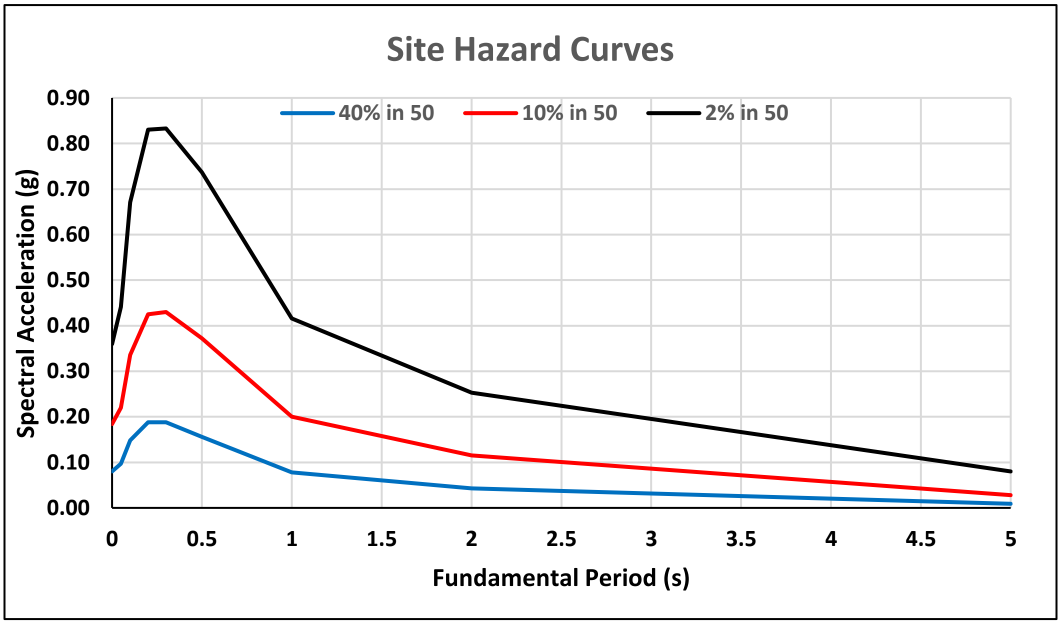

Figure 2: Uniform Hazard Curves for the Site

The assessment included the effects of all structural, non-structural, and medical equipment using data available in the FEMA-P58 database as well as equipment data provided by the owner. The quantities of structural and non-structural components used in developing the performance model were per the design of the facility.

PRESENTATION OF RESULTS

The objective of this assessment was to predict the post-earthquake performance of the facility and inform various stakeholders including the design team of the probabilistic impacts on the functionality of the different systems. Therefore, the outputs of the P-58 analysis had to be presented in a form that is simple to interpret for all disciplines (structural and other) yet effective in confirming/improving design decisions.

The results were provided in two formats: 1) floor-by-floor breakdown of repair costs and repair times for different component groups; 2) component-by-component damage state (DS) breakdown for every single component included in the performance model. An overview and discussion of each set of results is provided below.

Floor-by-Floor Breakdown

The building repair cost, as a percentage of the total building replacement cost, and the building repair time, commonly reported in days, are typical outputs of the FEMA P-58 analysis. However, to better identify areas that may require more attention with regards to their post-earthquake functionality, a floor-by-floor breakdown of repair costs and repair times were provided to the design team.

Table 1 shows the contribution of each component group to the repair cost of a given floor, as well as the contribution of each floor to the total repair cost of the structure (shown in percentages at the bottom of the table) for the 2% in 50 year shaking intensity. The values shown in the far-right column provide the contribution of a component group summed up over all floors to the total mean repair cost of the building for the 2% in 50 year shaking intensity. For example, per Table 1, for the 2% in 50 year intensity, the contribution of Electrical component group is 2% of the total mean repair cost of the structure.

To be able to develop such a breakdown, mean results had to be used as raw data. By using mean results, if the repair costs per storey were added together, it would sum to the total mean repair cost of the building; this would not hold up if median results were used instead. For repair times mean results in series (i.e., repairs carried out one floor at a time; repairs not completed in parallel on all floors) were used to construct a similar floor-by-floor breakdown to that of repair costs. The repair time contributions shown in the far-right column provide the repair time of a given component group if it were the only component group to be repaired in series floor after floor. For example per Table 2, the duration it would take to only repair the Medical Equipment group floor after floor for the 2% in 50 year intensity would be 69% of the total mean repair time of all components of the building in series.

In the following breakdowns, each component group is shown with a different colour: Electrical in green (includes Elevators and Generators), Cladding and Finishes in blue (includes Partitions Walls and Other Non-structural), Plumbing and HVAC in yellow, Medical Equipment in grey, and Structural in orange. Other Non-structural components consist of only concrete stair assemblies in this project. Within each component group, individual losses of certain items are reported such as Elevators and Generators as these items were identified to be of higher importance in the post-earthquake functionality of the facility.

Table 1. Floor by Floor Breakdown of Mean Repair Cost (2% in 50 yr. Shaking Intensity)

Component Group	Storey 1	Storey 2	Storey 3	Storey 4	Storey 5	Storey 6	Storey 7	Storey 8	Storey 9	Storey 10	Storey 11	Component Group Contribution to Total Mean Repair Cost
Electrical	3.1%	0.7%	1.8%	14.0%	1.1%	1.0%	1.1%	2.0%	1.3%	1.1%	0.0%	
Generators	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2%
Elevators	3.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.4%	
Exterior Cladding	0.9%	0.4%	0.1%	0.1%	0.5%	1.7%	2.0%	4.3%	2.5%	1.0%	0.9%	
Interior Finishes	0.4%	0.0%	0.0%	0.1%	0.0%	0.1%	0.1%	0.2%	0.2%	0.2%	0.0%	12%
Partition Walls	12.3%	7.6%	2.9%	19.0%	15.1%	18.1%	21.9%	20.5%	20.9%	11.3%	8.9%	
Other Non-structural	1.2%	0.7%	0.3%	3.9%	1.8%	1.1%	1.8%	2.2%	1.0%	0.8%	0.2%	
Plumbing and HVAC	1.5%	0.3%	3.8%	7.4%	0.4%	0.4%	0.5%	0.8%	0.8%	11.5%	0.0%	3%
Medical Equipment	37.8%	69.1%	85.4%	1.1%	50.4%	20.1%	38.2%	24.7%	35.0%	25.0%	21.8%	
1.5T MRI	0.0%	2.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
3.0T MRI	0.0%	5.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	56%
Angio	0.0%	0.0%	1.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
CT Scanner	0.6%	5.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
Structural - Coupling Beams	0.5%	0.2%	0.1%	1.0%	1.0%	2.6%	3.3%	4.1%	4.5%	2.7%	2.7%	
Structural - Shear Walls	23.6%	0.6%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	26%
Structural - Slab/Col. Joints	14.7%	6.8%	3.1%	53.3%	29.7%	54.8%	31.2%	41.2%	33.5%	21.7%	22.9%	
Structural - Steel	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	24.7%	42.1%	
% Total Mean Repair Cost	**10.8%**	**11.9%**	**34.2%**	**3.8%**	**8.0%**	**5.6%**	**5.0%**	**3.7%**	**4.8%**	**5.9%**	**6.4%**	**100%**

Table 2. Floor by Floor Breakdown of Mean Repair Time in Series (2% in 50 yr. Shaking Intensity)

Component Group	Storey 1	Storey 2	Storey 3	Storey 4	Storey 5	Storey 6	Storey 7	Storey 8	Storey 9	Storey 10	Storey 11	Component Group Contribution to Total Mean Repair Time
Electrical	0.6%	0.2%	0.4%	2.5%	0.4%	0.1%	0.1%	0.2%	0.1%	0.1%	0.0%	
Generators	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1%
Elevators	2.6%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	
Exterior Cladding	0.4%	0.2%	0.1%	0.0%	0.4%	0.5%	0.4%	1.1%	0.5%	0.3%	0.3%	
Interior Finishes	0.3%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.0%	9%
Partition Walls	8.7%	8.1%	4.0%	20.1%	20.5%	9.3%	7.2%	9.1%	7.7%	5.8%	4.5%	
Other Non-structural	1.2%	1.1%	0.5%	5.8%	3.4%	0.8%	0.8%	1.3%	0.5%	0.6%	0.2%	
Plumbing and HVAC	1.2%	0.4%	0.8%	2.1%	0.7%	0.3%	0.2%	0.5%	0.5%	0.8%	0.0%	1%
Medical Equipment	56.8%	71.9%	87.2%	6.0%	29.2%	56.7%	79.1%	65.8%	75.1%	67.6%	62.4%	
1.5T MRI	0.0%	1.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
3.0T MRI	0.0%	3.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	69%
Angio	0.0%	0.0%	1.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
CT Scanner	0.3%	4.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
Structural - Coupling Beams	0.4%	0.2%	0.1%	1.1%	1.5%	1.4%	1.2%	2.0%	1.8%	1.5%	1.5%	
Structural - Shear Walls	16.4%	0.6%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	21%
Structural - Slab/Col. Joints	11.3%	7.4%	4.7%	62.0%	43.9%	30.8%	11.0%	19.8%	13.5%	12.2%	12.7%	
Structural - Steel	0.0%	0.0%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	10.9%	18.2%	
% Total Mean Repair Time	**0.7%**	**4.1%**	**8.3%**	**0.2%**	**1.2%**	**6.9%**	**16.7%**	**8.9%**	**18.8%**	**15.8%**	**18.4%**	**100%**

Component-by-Component Damage State (DS) Breakdown

In collaboration with HBR's technical staff, a more refined breakdown of all possible DSs of any given component for various shaking intensities was developed and reported to the design team. The main challenge with this level of refinement is the very significant amount of numerical data that needs to be translated by the design disciplines into concise and informative information for the benefit of the owner and other stakeholders.

A sample of DS data for a Distribution Panel (fragility label: D5012.033c) is shown in Figure 3. These DS data provide the following information about this component:

- Each column corresponds to one of the three shaking intensities considered for the project: 40%, 10%, and 2% in 50 year probability of exceedance earthquake events.

- Each row provides the data corresponding to the various DSs of a component. There are four values for each DS for a given shaking intensity:

    1. From left to right, the first number is the average quantity of the components in a given DS reported as the percentage of total quantity of that component (highlighted in orange). This is the average of the components in a DS over all the possible realizations. For this component the value is 0.1% for the 40% in 50 year shaking intensity.

    2. The second number is the percentage of realizations that are damaged (highlighted in red). This value can be considered the probability of occurrence for a given DS subject to a given shaking intensity. For this component the value is 20% for the 40% in 50 year shaking intensity.

    3. The third value is the percentage of total quantity conditioned on being damaged (highlighted in blue). In other words, it is the quantity of components (reported as percentage of total quantity) in each DS averaged over only the realizations that have damage in them. Note that some realizations will have no damage in them. For this component the value is 0.6% for the 40% in 50 year shaking intensity.

    4. The fourth value is the quantity of components conditioned on being damaged (highlighted in green). In other words, it is the quantity of components averaged over only the realizations with damage in them. For this component the value is 3.26 panels which may be rounded to 3 panels for the 40% in 50 year shaking intensity.

- For convenience, the total quantity of a component used in the performance model is also provided. It is the last number on the last line labelled *Total* (highlighted in pink). For this component the value is 555 units. Notice that this value remains unchanged for all shaking intensities.

	40% in 50 years	10% in 50 years	2% in 50 years
D5012.033c #1 (D5012.033c: Distribution Panel - Capacity: 100 to <350 Amp - Equipment that is either...)			
DS1a	0.1 (20) 0.6 (3.26)	1.1 (61) 1.7 (9.60)	5.0 (91) 5.4 (30.2)
DS1b	0.0 (13) 0.4 (2.14)	0.5 (48) 0.9 (5.25)	2.1 (85) 2.5 (13.8)
DS1c	0.2 (23) 0.7 (3.96)	1.5 (66) 2.3 (12.9)	7.1 (93) 7.6 (42.1)
Total	**0.3** (31) , 1.1 (5.90 / 555)	**3.0** (74) , 4.1 (22.8 / 555)	**14** (96) , 15 (82.0 / 555)

Figure 3: Sample DS Data for a Distribution Panel (D5012.033c) – Screenshot Taken from SP3 Outputs

The following simplified example explains how the four values are calculated.

Assume there is a fragility for a component (i.e., a component in the model) with a total quantity of 5. For the purposes of this example, the fragility is assumed to be for a chiller with certain capacity that only has one damage state DS1. The total number of realizations is assumed to be 10 in this example. Out of the 10 realizations, 5 of them are randomly selected to be damaged. For example, the first, fourth, sixth, and seventh realizations are assumed to have 2,1,1, and 3 chillers damaged respectively. The rest of the realizations have no damage. The table below summarizes the values used in this example. The calculations presented in Figure 4 and the colour coding show how each of the values highlighted in Figure 3 would be calculated for the simple example demonstrated here.

Total Quantity of Chillers **5 units**

Realization #	1	2	3	4	5	6	7	8	9	10	SUM
Quantity Damaged (DS1)	2	0	0	1	0	1	3	0	0	0	7

Avg Quantity Damaged	= 7/10	0.7 units
Avg Quantity Damaged Normalized by Total Quantity	= 0.7/5	14%
% Realization Damaged	= 4/10	40%
% Quantity if Damaged	= 0.14/0.4	35%
Quantity of Chillers if Damaged	= 35%*5	1.75 units
Total Quantity of Chillers in the Model	= 5	5 units

Figure 4: Data Corresponding to the Simple Example

To be able to present the DS data in a more meaningful manner to the design team and various stakeholders, the values had to be accompanied by the description of each DS for any component. For the Distribution Panel with data shown in Figure 3, the accompanying DS description is provided in Table 3.

Table 3.Component Damage State Description Provided in FEMA P-58

Damage State	Description	Repair Description
DS1a	Anchorage failure.	Repair anchorage and concrete pad (if floor mounted and wall if wall mounted) and remount equipment.
DS1b	Anchorage failure and Equipment damaged beyond repair.	Replace equipment in addition to repairing anchorage and concrete pad if floor mounted or wall if wall mounted.
DS1c	Damaged, Inoperative but anchorage OK.	Replace equipment.

The total quantity of this component (i.e., the Distribution Panel) is 555 units (value in pink in Figure 3).

The DS data shows that conditioned on being damaged, on average 3 panels (value in green, 3.26 rounded to 3) out of the 555 would be in DS1a when subject to an earthquake with the 40% in 50 year shaking intensity. In other words, 3 panels on average may have anchorage failure only. The probability of such a damage state occurring would be 20% (value in red in Figure 3).

Similarly, when subject to an earthquake with the 40% in 50 year shaking intensity, there would be 2 (2.14 rounded to 2) panels that would have anchorage and equipment damage beyond repair (i.e., they would be in DS1b) with a 13% probability of such a damage state, and there would be 4 panels (3.96 rounded to 4) that would have equipment damage – inoperative only (DS1c) with a 23% probability of such a damage state.

Each design discipline on the project utilized component-by-component DS breakdown to provide a letter to the appropriate stakeholders regarding the ability for the hospital to remain functional after an earthquake with a given shaking intensity. The goal of using these breakdowns is to enable the design professionals to provide comments such as "unlikely to disrupt hospital operations for any significant period of time" or "will not significantly prevent functionality while waiting for proper repairs to be made after an event" as it relates to the post-earthquake functionality of the facility.

CONCLUSIONS

Performance-based seismic assessments including the procedure outlined in FEMA P-58 can be used to better predict the performance of buildings in the event of an earthquake. One of the main challenges with performance-based assessments is the large amount of data that is generated. It is crucial to be able to develop and present the performance data in a manner that is simple yet useful to all stakeholders and design professionals involved in a project. An overview of two methods that were used to summarize and interpret the FEMA P-58 assessment outputs of the new St. Paul's Hospital were presented in this paper: 1) floor-by-floor breakdown of repair costs and repair times for various component groups with emphasis on equipment crucial to post-earthquake functionality of the facility 2) component-by-component DS data breakdown translated from numerical value into written statements about damage states. These two methods helped various stakeholders and the design consultants better understand the impact of seismic damage and confirm/improve design decisions.

ACKNOWLEDGMENTS

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REFERENCES

[1] FEMA, 2018, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology, Second Edition*, FEMA P-58-1, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.