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MODEL UPDATING OF A 4-STOREY PARKING GARAGE USING AMBIENT VIBRATION MEASUREMENTS

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ABSTRACT: The study reported in this paper fits within a large-scale project of seismic upgrading of some facilities at The University of British Columbia in Vancouver. The structure under consideration is the Health Sciences Parkade, which can be generally described as a combination of two main 4-storey buildings connected by sets of three parking ramps for each level. This particular configuration and the presence of many ramps are distinctive features of the Parkade and require careful assumptions, which make the modelling process quite challenging. Series of ambient vibration tests were conducted at the Parkade in March 2014 with the purpose of evaluating the natural frequencies, damping and mode shapes. A finite element model of the structure was built using computer program SAP2000 V15. Due to the complexity of the structure, the calibration of the FE Model to the test data was necessary. A sensitivity analysis and model updating of the Parkade was performed and used to correct the inaccuracies of the modeling assumptions and the discrepancies between the model and the modal analysis results. The updated model will be used with much more confidence for structural analysis and seismic retrofit purposes.

1. Introduction

Since the Health Sciences Parkade was constructed in the 1979, it was necessary to undertake an investigation of its dynamic properties in order to determine whether seismic retrofit is necessary.

The structure under consideration is a combination of two 4-storey reinforced concrete buildings connected by sets of three parking ramps at each level. The Lateral Force Resisting System (LFRS) is composed mainly of shear walls working together with a moment resisting frame system. The north building has also a basement level which was temporarily inaccessible because used as storage area by UBC Parking Services (Capraro, Pan, Rollins, & Gao, 2014). Moreover, at basement level, additional internal and external shear walls provide additional stiffness to the storey and introduce stiffness irregularity in elevation and short column phenomena. Figure 1 shows the north elevation view of the Parkade at the intersection between East Mall and Hospital Lane street.

Figure 1: North Elevation of the Parkade.

2. Ambient Vibration Testing

The Ambient Vibration Test was conducted in March 14th 2014 by a group of graduate students at UBC when the Parkade was experiencing high levels of traffic, typical of normal operational conditions. A total of nine Tromino sensors were used to perform the test: one sensor was kept at the second floor as reference sensors and the remaining eight sensors were shifted floor by floor for a total of five setups. The duration of the recording was set to 40 minutes for each setup and the sampling frequency was 256 Hz. Figure 2 shows the setups configuration with location and orientation of the sensors.

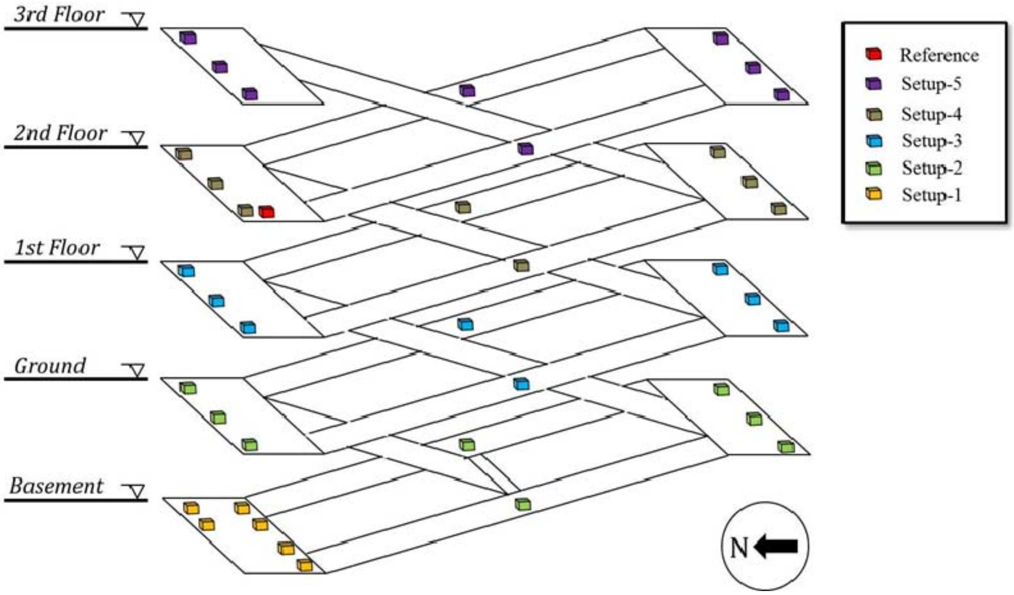

Figure 2: Setups configuration.

The data was processed with ARTeMIS Modal V3.0 computer program. The modal analysis was performed in the frequency domain with the Frequency Domain Decomposition (FDD) technique. The natural frequencies were identified with the peak picking method on the spectral density matrices plot as provided in Figure 3.

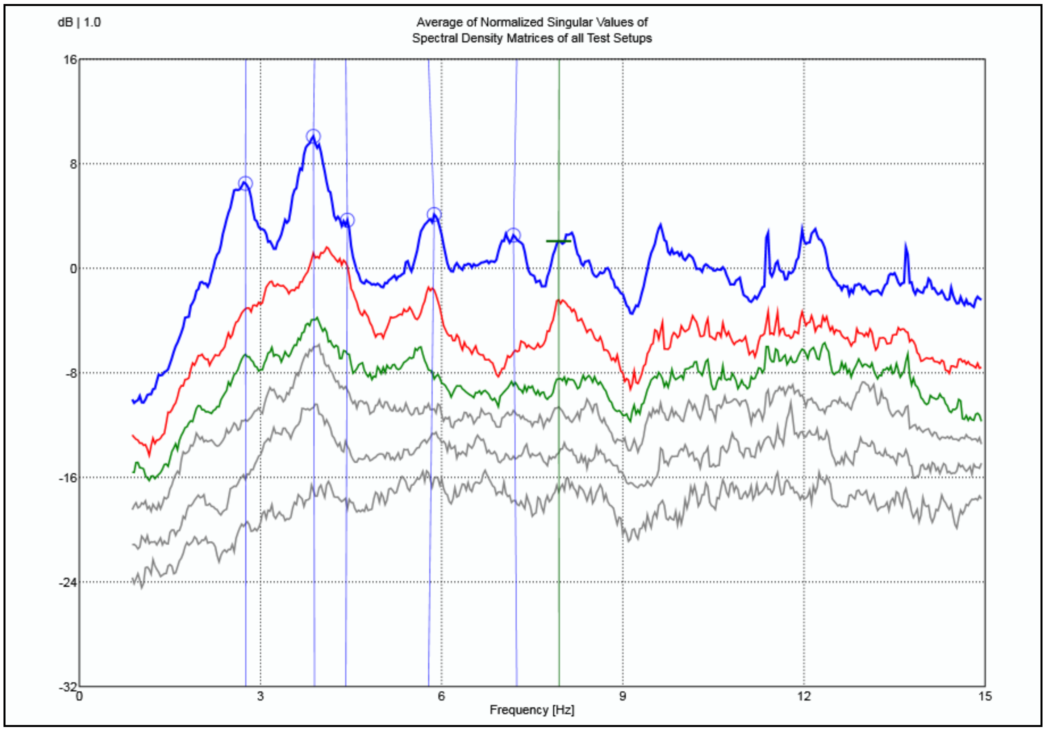

Figure 3: Average of the Normalized Singular Values of the Spectral Density Matrices plot.

The fundamental frequency of the building has been identified at 2.756 Hz and corresponded to a first longitudinal mode shape in the N-S direction. The first torsional mode has been recognized at 3.875 Hz while the second torsional mode has been identified at 4.413 Hz. The results obtained via ambient vibration testing showed a significant tridimensional response and a clear influence of the ramps system on the overall behaviour of the structure.

Figure 4, Figure 5, Figure 6 and Figure 6 7 show the first four mode shapes identified with the FDD technique developed in ARTeMIS Modal computer program (Structural Vibration Solutions A/S).

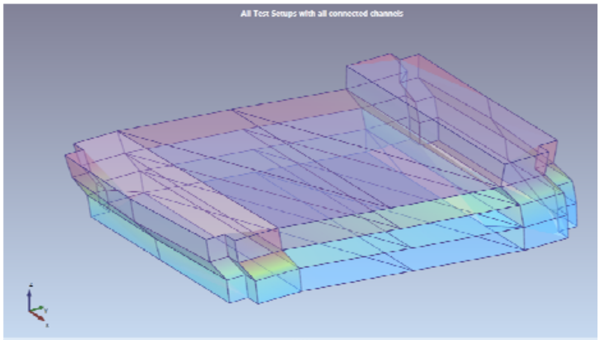

Figure 4. 1st Mode in longitudinal (N-S) direction.

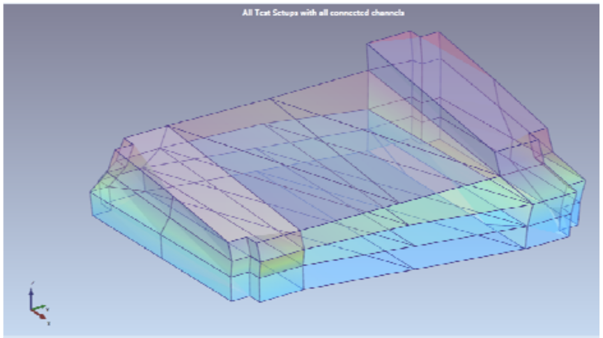

Figure 5. 2nd Mode in Torsion (1T).

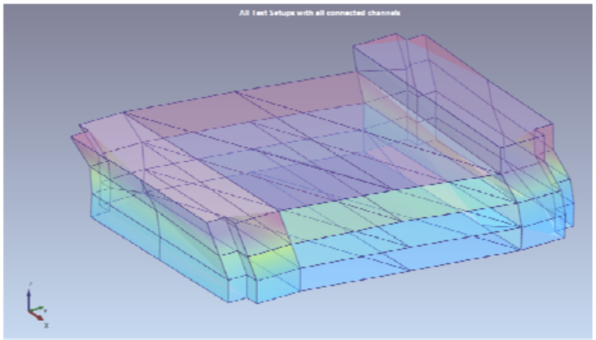

Figure 6. 3rd Mode in transversal (E-W) direction.

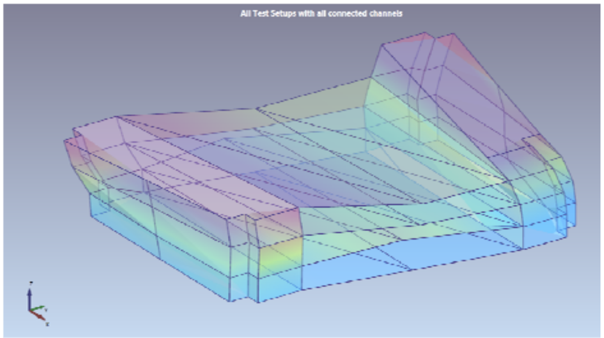

Figure 7. 4th Mode in Torsion (2T).

3. Finite Element Modelling

A Finite Element Model was developed with SAP2000 V15 computer program. Beams and columns of the moment resisting frame were modelled as frame elements, with uncracked cross sectional area and elastic Young modulus. Shear walls were modeled as shell elements and slabs were modelled as plate elements. Figure 8 shows the resulting FE Model built with SAP2000.

Stairwells were present at each corner and at mid span of the parking ramps. Although they were built as separate precast structures, they are well connected to the main structure and therefore they cannot be neglected in the FE modelling as they provide additional stiffness and they behave as a constraint through the height of the two main buildings. With this in mind, the stairwells were modelled as shell elements fixed to the corners of the Parkade.

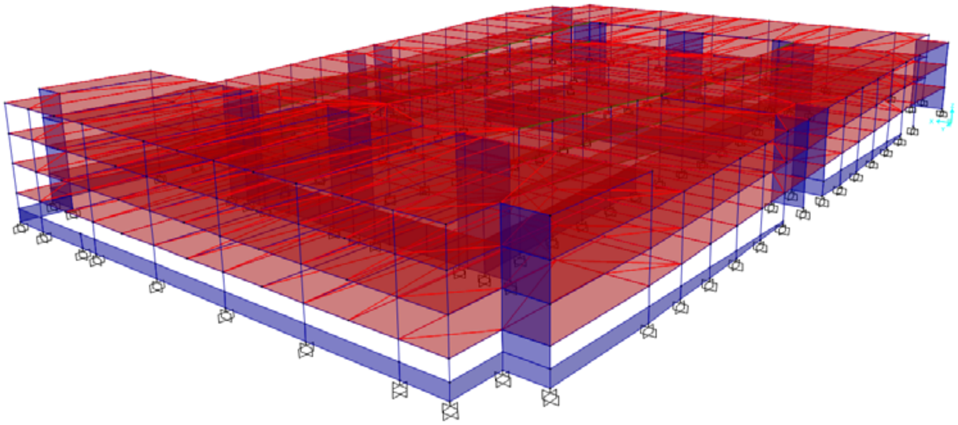

Figure 8: FE Model built with SAP2000.

Preliminary values of the natural frequencies have been obtained with the modal analysis via SAP2000. In addition to the global modes, local modes of vibration have been identified at low frequency range with the FEM modal analysis. These local modes of vibration are mainly related to the local dynamic behaviour of the slabs. Therefore, they cannot be defined as global mode shapes for the structure and they need separate consideration.

Given the extremely complex configuration of the Parkade, few assumptions have been made during the modelling process. Features such as the flexibility of the ramps system or the partial embedment of the bottom level are aspects difficult to model and require careful assumptions.

As a consequence, it was necessary to calibrate the FE Model to the results of the data acquired from the experimental tests. The differences and inaccuracies between the model and the ambient vibration results have been corrected through a sensitivity analysis performed with FEMtools and the FE model was updated with FEMtools computer program.

4. Sensitivity Analysis

The SAP2000 FE Model was imported into FEMtools V3.8 to perform the model updating process. Four points per floor were selected as representative during the FE Model calibration to the test data for a total of 18 node-point pairs. Figure 9 shows the imported FEModel and the node-point pairs selection in FEMtools.

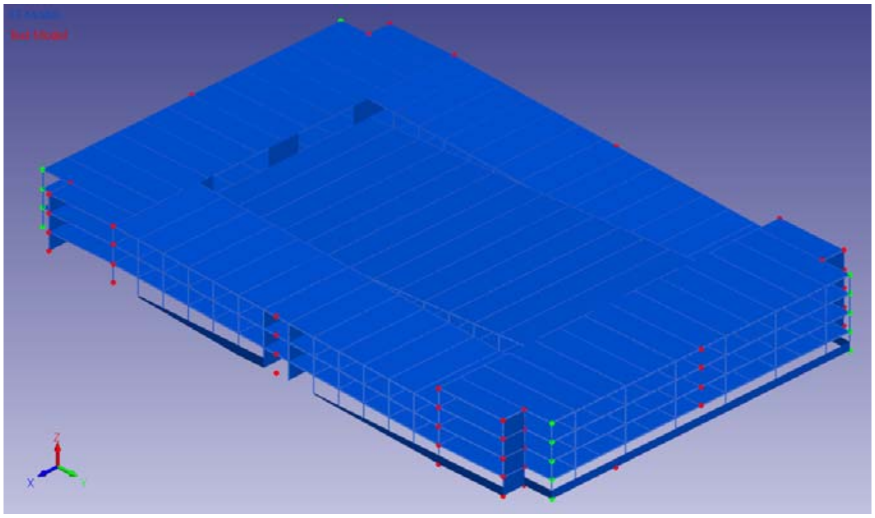

Figure 9: Node-Point Pair with FEMtools 3.8

A sensitivity analysis was performed to assess whether selected responses are sensitive to changes of selected parameters. A preliminary sensitivity analysis was carried out considering the parameters as global characteristics of the structure. As a results, it was found that the shear areas and cross sectional modulus of inertia did not affect significantly the change in responses so they were removed for the refined sensitivity analysis.

The responses selected for the calibration of the model were the natural frequencies. In general, good match was found for the longitudinal and transversal modes. As for the torsional modes, the correspondence showed not good correlation, with MAC values between 3 and 11%. With this in mind, lower scatter values were assigned to longitudinal and transversal modes to express the higher level of confidence on these modes with respect to the torsional modes.

The parameters selected for the final sensitivity analysis were:

- Material density, Rho;
- Elastic Modulus, E;
- Cross sectional area of elements, Ax;
- Thickness of shell elements, H.

The change in mass due to the presence of cars during the test was accounted simulating the mass of the vehicles as an increase in the mass of the slabs. This was possible allowing the material density Rho to increase up to 50% of its initial value.

Due to the complexity of the structure, these parameters were selected globally for each set of elements to allow the system more freedom to adjust and predict the new updated responses. Figure 10 shows a 3D representation of the sensitivity matrix between the responses and the selected parameters.

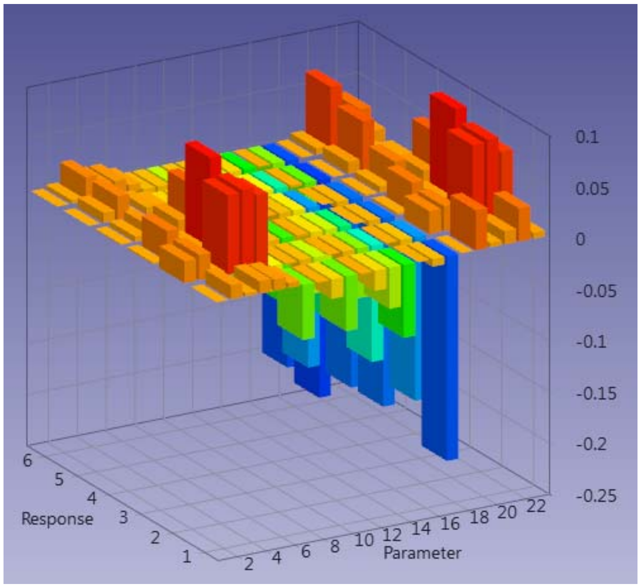

Figure 10: Sensitivity Matrix.

Table 1 shows the summary of the results after the model updating process. The frequencies for N-S longitudinal modes and E-W transversal modes improved with an average difference from the test results of about 9%. The MAC values increased sensitively, indicating a better match with respect to the AVT results. In particular, for the 1st mode in the E-W direction than MAC values increased from about 31% to 72%.

As for the torsional modes, it was not possible to obtain a good match between the FEMtools model and the ARTeMIS results and there was not a significant improvement either on the MAC values.

Table 1: Model updating summary of the results.

Mode	AVT	SAP2000			FEMtools updated			Description
	Frequency [Hz]	Frequency [Hz]	Difference	MAC	Frequency [Hz]	Difference	MAC	
1	2.756	2.58	6.82%	94.40%	2.74	0.58%	94.00%	1st N-S Longitudinal
2	3.875	3.56	8.85%	11.00%	3.68	5.30%	11.80%	1st Torsional
3	4.413	4.58	-3.65%	36.10%	4.49	-1.71%	43.80%	1st E-W Transversal
4	5.781	6.72	-13.97%	2.70%	6.87	-15.85%	3.60%	2nd Torsional
5	7.25	8.17	-11.26%	39.90%	8.25	-12.12%	58.80%	2nd N-S Longitudinal
6	7.931	7.98	-0.61%	55.00%	8.08	-1.84%	58.80%	3rd N-S Longitudinal

The most significant change after the model was updated, was the increase of the material density values between 10 and 50% of the initial values. A general decrease was observed in the cross section areas of elements and on the shear wall thickness indicating that a cracked cross section should be preferred in the FE modelling process.

No important difference could be recognized in the change in values of Young Modulus. The E values oscillate between -70% and 50%. The cross sectional area Ax showed as a general trend decreased values indicating that cracked section should be considered in the modelling process. The average decrease was found to be about -50%.

5. Conclusions

Six mode shapes have been identified up to a frequency of 8 Hz, with the fundamental frequency at 2.756 Hz corresponding to a first longitudinal mode in the NS direction. The first torsional mode was identified at a frequency about 1 Hz higher than the fundamental mode. Therefore, it is likely that the Parkade will experience both strong lateral and torsional responses when excited by a seismic event.

Given the limited number of sensors, only two accelerometers were placed on the lateral ramps, leading to relatively poor definition of the ramps deflection shapes. Moreover, due to practical limitations, no sensor was placed on the central ramps, so no consideration can be done a priori on their contribution on the global behaviour.

However, it can be recognized that the presence of the ramps system greatly contributes to the overall dynamic behaviour of the structure as they link and constrain the two buildings to work together. With this in mind, further tests with multiple sensors on each ramp would be needed to have a more refined definition of their mode shapes and their contribution to the Parkade dynamic behaviour.

Thanks to the modelling updating process, the resulting updated model can be used with much more confidence for structural analysis and seismic retrofit purposes. The shear walls are the main lateral force resisting system of the Parkade and they contribute for the most part to the longitudinal and transversal stiffness of the whole structure. This was confirmed during the model updating process as an important change within the range of selected parameters was found in the shear wall thickness.

The most significant change in the parameters was proved to be the material density of the slabs, indicating how the mass of the cars affect significantly the dynamic properties of the Parkade.

It was not possible to reach a good match for the first and second torsional mode, probably due to assumptions made during the FE modelling process and the low level of confidence at these torsional responses.

Further studies including a more refined representation of the stairwell should be needed to get a complete and reasonable match for all the mode shapes.

6. Acknowledgements

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7. References

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