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# EXPERIMENTAL INVESTIGATION OF SEISMIC STABILITY OF POWER PLANTS IN CANADA

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## ABSTRACT

Within the frame of Canadian and Macedonian scientific cooperation, several cooperative projects between Hydro-Quebec and the Institute of Earthquake Engineering and Engineering Seismology - IZIIS, Skopje, Republic of Macedonia, have been realized in the last three years: Experimental investigation of seismic stability on masonry walls at Beauharnois Powerhouse; Ambient vibration measurements of Transformer House "Poste le Cedres"; Ambient vibration measurements of machinery buildings of Chute Hemmings; Ambient vibration measurements of a dam "La Tuque" ; Ambient vibration measurements of "Paugan" Powerhouse ; In situ testing of NPP Gentilly-2 by ambient vibration method.

Presented in the paper is the experimental investigations of seismic stability of powerhouse of Beauharnois dam, Qebec, Canada. Besides ambient vibration in situ tests, the shake table laboratory testing of scaled models have been performed on a two-component seismic shaking table at IZIIS Laboratory.

## Introduction

The seismic stability of mixed steel structures with masonry walls, as are the historical buildings, has not been sufficiently investigated in the current practice. Very few experimental investigations as well as numerical analyses have been performed until today. In the period of construction of these structures (beginning of the 20$^{th}$ century, USA, Canada, etc.), the seismic aspects were not considered in the design process. Friedman (2005) performed a study of high rise buildings of a mixed system (steel frames and masonry facade curtain walls) built in New York and Chicago in the period of 1900-1930. He investigated the effects of temperature change, differential stiffness as well as rust-jacking. The existing analysis and repair techniques are mostly empirical, without consideration of steel and masonry as a composite structure.

There is a similar situation in Canada. This type of composite structures was built in the period 1916-1974. After this period, the Canadian seismic codes didn't permit construction of non-reinforced brick walls. Instead, the walls were constructed of reinforced concrete hollow

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bricks. The powerhouse of the Beauharnois dam is a typical example of a composite steel frame-masonry curtain wall structure built at the beginning of the $20^{th}$ century. The structure is considered a historical heritage and is protected as such. More than 50 powerhouses of dams and sub-stations in Quebec are constructed by applying the same mixed system. In 2006, a bi-lateral project for experimental and analytical investigation of the seismic stability of the brick masonry walls of the Beauharnois powerhouse located in Quebec, Canada, was initiated. The project was realized by cooperation between "Hydroquebec" (Montreal, Canada) and the Institute of Earthquake Engineering and Engineering Seismology - IZIIS (Skopje, Republic of Macedonia). The main objective of the investigation was to evaluate the seismic stability of the masonry walls of the machinery building at the Beauharnois powerhouse according to the new design codes in Canada.

In accordance with the main objective of the investigation, the following activities were carried out:

1. Experimental in-situ full scale testing of a selected segment of the powerhouse by use of the ambient vibration technique;

2. Experimental shake-table testing of a reduced scale model of a section of the wall to the scale of 1:3 under a representative earthquake excitation;

3. Experimental shake-table testing of a model of a section of the wall to the scale of 1:1 strengthened by anchor-dampers DC-90;

4. Numerical modeling of the seismic stability of the walls applying sophisticated non-linear models.

## Description of the Beauharnois Powerhouse

The Beauharnois power plant is located on St. Lawrence River near Montreal. The power plant consists of a gravity dam, a powerhouse and a water intake structure. An aerial view of the dam is presented in Fig 1. The superstructure of the Beauharnois powerhouse consists of single bay steel frames spaced at 5.1 m along the length of 826m. The masonry brick walls, incorporating the columns of the steel frames, serve as enclosures. Fig. 2 represents a cross section of the dam together with powerhouse. The height of the walls is 20m. Their thickness varies form 0.3 to 0.6m and they accommodate a series of large window frames. The walls were built after completion of the steel structure and they are integrated with the majority of the steel frames.

Figure 1. Beauharnois dam, Canada (aerial view).

Figure 2.  Beauharnois dam with powerhouse (cross section).

**In-situ testing by ambient vibration method**

In the first phase of the experimental testing, ambient vibration measurements were carried out in order to define the dynamic characteristics of the walls - resonant frequencies, mode shapes and damping coefficients for the transversal (out-of-plane) direction. Three seismometers (Ranger type, produced by Kinemetrics) were used and the measured signal was amplified by a four channel signal conditioner (also produced by Kinemetrics). The amplified and filtered signals from the seismometers were than collected by a high-speed data acquisition system, which transforms analogue signals into digital. Special software for on-line data processing was used to plot the time history and the Fourier amplitude spectra of the response at any recorded point.  For post-processing and analysis of the recorded vibrations at all the measuring points, the ARTeMIS software was used. This software is based on the "peak picking" technique and "frequency domain decomposition" and provides very good graphical presentation of the obtained data.

To define the dynamic characteristics of the walls, a portion of the structure between steel frames 86 and 88 located in the middle of the length of the power house, was chosen (Fig.3).

Figure 3. Part of the structure selected for ambient vibration measurements (frames 86 -88, middle of the powerhouse).

Fig. 4 shows the obtained dominant frequencies and damping coefficients, while the first mode shape is presented in Fig.5, showing very clearly the shape of deformation of the structure and the locations where the maximum deformations can be expected in case of dynamic excitation of the structure. The obtained dominant frequencies are within the frequency range of 2.15-9.47 Hz. They can be considered as natural (resonant frequencies) of the structure in out-of-plane direction of the wall-steel frame composite system of the powerhouse. The mode shapes show the most critical part of the structural system such as the points around the wall openings. The damping coefficients obtained from the power spectra density plots show that the system possesses a high damping capacity, i.e., capability for relatively large energy dissipation, which is a very good property of the system for earthquake conditions. For the first four modes, the values range between 4.7-9.3 % of the critical damping. The results from this test are useful in both directions, representing a good basis for calibration of the numerical model developed for estimation of the seismic stability of the powerhouse, as well as for design of the reduced scale model for the shake-table test.

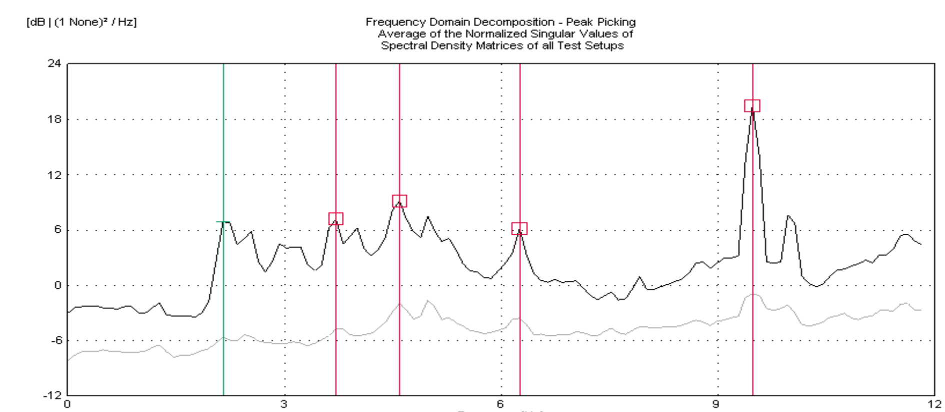


Figure 4. Peak Picking of the dominant frequencies.

Table 1.  Dominant frequencies and damping.

| **Mode** | **Freq. [Hz]** | **β [%]** |
|---|---|---|
| Mode 1 | 2.15 | 9.348 |
| Mode 2 | 3.71 | 5.891 |
| Mode 3 | 4.59 | 6.412 |
| Mode 4 | 6.25 | 4.753 |
| Mode 5 | 9.47 | 0.604 |

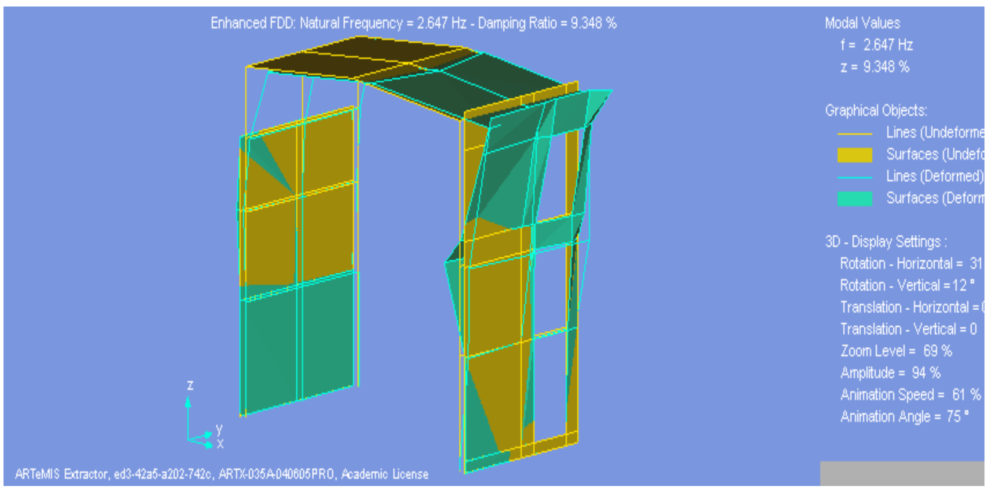


Figure 5.  Mode 1  Vibration shape for frequency f1=2.15 Hz.

## Shake-table test of a model in reduced scale 1/3

The shake-table testing of a scaled model of the Beauharnois walls was performed on the two-component seismic shake-table in the IZIIS Laboratory, applying excitation in horizontal and vertical direction with increasing intensities.

### Design of the model

The selected portion of the Beauharnois powerhouse measured by in-situ ambient vibrations was designed according to the similitude requirements defined for model testing on a shake-table. Considering the prototype structure dimensions, as well as the dimensions and the load capacity of the shake-table, the model was designed to the geometric scale of 1:3. An adequate model (combined true replica-artificial mass simulation model) was adopted. For simulation of the steel frame, the same material as that of the prototype structure, i.e., steel, was used. For simulation of the wall, the mechanical characteristics (stress and modulus of elasticity) were reduced 2.11 times.

## Construction of the Model

The brick masonry wall was constructed following the specific connection between the bricks and the steel columns. Its height was 6.5m. The finalized model is shown in Fig. 6.

Figure 6. Model of the wall ready for shake-table testing.

## Dynamic Characteristics of the Model

Considering the adopted modeling technique, an additional mass of 32KN was added on the top of the steel structure for correct simulation of the dynamic properties and simulation of the gravity forces. Before the seismic testing, the dynamic characteristics of the model were obtained by measuring the ambient vibrations at selected points and processing the records by use of the ARTEMIS software. The obtained results are given in Figs. 7 and Table 2.

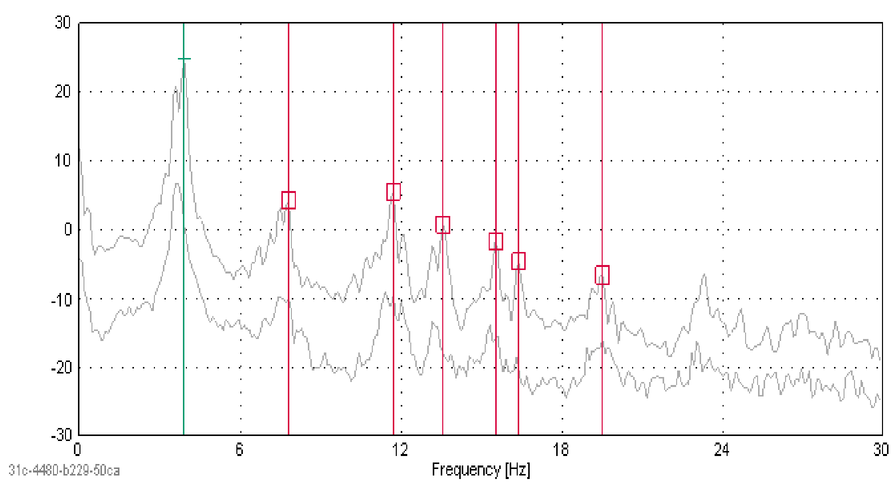


Figure 7. Dominant frequencies of the model.

Table 2. Dominant frequencies of the model.

| Mode | Model freq. (Hz) | Prototype freq. (Hz) | Required ratio $f_m / f_p$ | Obtained ratio $f_m / f_p$ | Difference (%) |
|---|---|---|---|---|---|
| Mode 1 | 3.91 | 2.15 | 1.7 | 1.8 | +5.9 |
| Mode 2 | 7.81 | 3.71 | 1.7 | 2.1 | +23.5 |
| Mode 3 | 11.72 | 4.59 | 1.7 | 2.55 | +50.0 |
| Mode 4 | 13.57 | 6.25 | 1.7 | 2.17 | +27.6 |
| Mode 5 | 15.53 | 9.47 | 1.7 | 1.64 | -3.5 |

## Seismic Out- of-plane testing of the model

### *Seismic excitation time history for shake-table test*

The seismic excitation selected for the shake-table testing of the model was the representative (modified) accelerogram recorded during the 1985 Nahanni, NWT earthquake of M6.8, horizontal component H1, with peak acceleration of 0.2g (Fig. 8).

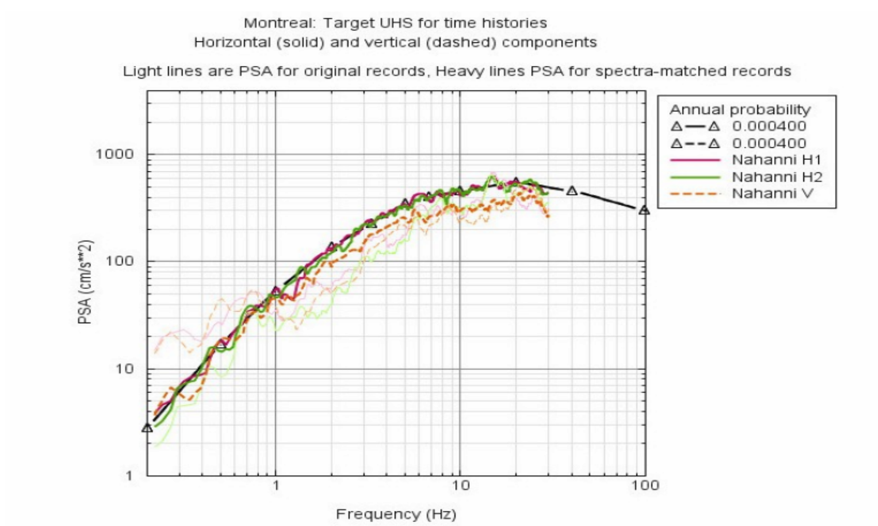


Figure 8. PSA for Nahanni M6.8 earthquake (After Atkinson, 2006).

### *Shake-table testing results*

The main conclusion after the performed out-of-plane seismic tests on the model is that, under the expected intensity level for the site where the Beauharnois powerhouse is located, i.e., 0.2g, the behavior of the model is stable, without any cracking. The dynamic amplification factor (top/base) was less than 2. The first cracks occurred under an intensity of 0.7g, i.e. under very intensive excitations, mainly in the part of the wall next to the openings. Some of the vertical bricks below the level of the first opening were broken. The part of the structure without openings was practically undamaged, with only a few micro-cracks developed during the most intensive excitation.

## Shake-table test of a segment of the model in scale 1/1

### Description of the tested model

The model of the masonry wall was constructed in scale 1:1 and it consists of one steel column and a part of the masonry wall between two windows. According to the available space (height) in the Laboratory, a portion of the wall was selected, as presented in Fig. 9. The total height of the model was 7.8m, its length was 1.3m and the thickness was 0.55m. The model was constructed following the specific way of connection between the bricks as well as between the bricks and steel column.

After placing of the model on the shaking table, its natural frequencies were obtained by measuring ambient vibrations at the top level. Two Ranger seismometers were placed at the top, one on the steel column and one on the wall. The resonant frequency of the model for the first mode was dominating and its value was f=7.2Hz.

### Testing procedure

The testing of the model was performed on the two-componental shaking table at IZIIS Laboratory on seismic excitation representative for the structure. The testing was performed only in horizontal direction, out-of-plane. The seismic excitation selected for the shaking table testing of the model was the accelerogram recorded from the 1985 Nahanni, NWT earthquake of M6.8, horizontal component H1, with peak acceleration of 0.2g. Improvement of the connection between the wall and the column has been done by implementing “anchor-damper” DC90 devices, having two functions: to fix the wall to the steel column and to dissipate the seismic energy in plastic range for small relative displacements, 1-5mm. (Fig. 9).


Figure 9. Position of DC90 anchors with dampers and measured levels.

## Conclusions

The main issue of the performed investigation was how this mixed system behaved under strong earthquake especially in the out-of-plain direction. The in-situ ambient vibration tests were performed in order to define the resonant frequencies of the structure, the mode shapes and the damping. The obtained results show that the fundamental frequencies of the structure are between 2.65-6.06 Hz. Having in mind that the predominant frequency range of the considered response spectrum is around 10 Hz, the wall should not enter at resonance in the case of this earthquake. On the other hand, the recorded damping for the above mentioned modes is rather high (4.7-9.3 % of the critical) leading to the conclusion that this system is capable to dissipate a big amount of energy in case of the earthquake action.

The shake-table test of the model to the scale of 1/3 confirmed the previous conclusions regarding the seismic behavior of the steel frame-wall mixed system. The main conclusion after the performed out-of-plane seismic tests on the model is that, under the expected intensity level for the site where the Beauharnois powerhouse is located, i.e., 0.2g, the behavior of the model is stable, without any cracking. The dynamic amplification factor of the wall is less than 2, which shows that the system doesn't enter a dangerous resonance state. The first cracks occurred under an intensity of 0.7g, related to a very intensive and unexpected earthquake on the site, under which development of cracks was recorded, mainly in the part of the wall next to the openings. Some of the vertical bricks below the level of the first opening were broken. The part of the structure without openings was practically undamaged, with only a few micro-cracks developed during the most intensive excitation.

The shake table test of the segment of the model in scale 1:1, showed that anchor-dampers DC-90 added to the wall, improve the connection between the steel structure and wall and increase the damping capacity of the structure

## References


Krstevska L., Tashkov LJ., Gocevski V., Garevski M. 2009. "Experimental and analytical investigation of seismic stability of masonry walls at Beauharnois powerhouse", *Bulletin of Earthquake Engineering,* Publisher: Springer, Netherlands, (Published online: 28 July 2009)

Tashkov Lj., Krstevska L, Garevski M., Shaking table test of a segment of brick-masonry wall at Beauharnois powerhouse *Report - Institute of Earthquake Engineering and Engineering Seismology – IZIIS, Skopje, Report 2007-51.*

Gocevski V., 2007. Centrale de Beauharnois – Analyse et confortement sismique de l'enveloppe de la centrale. *Rapport D'avant-projet, Hydro-Québec Unité Structure, RPOOW 12242*

Fridman D., 2004. Analysis of Steel-Structure/Masonry-Walls Interaction in Historic Buildings. Proceedings of the Fourth International Seminar on Structural Analysis of Historical Constructions, 10-13 November 2004, Padova, Italy 103-110.

Atkinson G., 2006. Earthquake Time Histories for Montreal, Quebec, 2% in 50 year exceedence probability, July 5, 2006