

An Approach to Seismic Evaluation of Heritage Buildings

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ABSTRACT

Many heritage buildings and other old structures are vulnerable to earthquake loading. In seismically active regions, there is a need to evaluate the seismic resistance of such buildings to ensure acceptable level of safety and in some cases, protection against excessive damage. In such an evaluation, three main issues arise: 1) the difficulty of assessing the seismic resistance of structures containing historic materials, whose strengths and deformation characteristics are not easily quantifiable, 2) the need to retain the heritage character using minimum intervention, and 3) the cost of intervention. This paper describes a methodology established by the authors to assess the behaviour of heritage buildings to seismic effects that was applied to an existing thick stone masonry tower. Without such a detailed investigation, it is not possible to realistically assess the survivability of either the heritage building or its occupants.

BACKGROUND

Heritage and other old buildings are particularly vulnerable to earthquake loading because they were constructed at a time when seismic risk was not considered in structural design. Although by their survival these historic structures have demonstrated that they have adequate capacity to support normal gravity and wind loads, and sometimes also earthquake, their stability under future earthquakes cannot be guaranteed. Thus, issues of public safety as well as preservation of the heritage fabric demand that these structures be assessed for seismic adequacy.

The seismic evaluation of existing buildings requires the assessment of various unknown parameters such as loads, material properties, soil conditions, structural integrity, etc. Predicting the seismic behaviour is complex because generally little is known about the uncertainties associated with these parameters. This is further complicated by the need to retain the heritage character of these buildings by using minimum intervention, and by the economic realities that limit the type and number of investigations. To achieve a reasonable evaluation, the authors established a methodology of investigating heritage buildings made up of seven steps: 1) determination of the structural layout of the building, 2) investigation of the foundation conditions, 3) assessment of the seismic ground motions of the site,

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4) determination of the material properties of the building, 5) measurement of the dynamic properties of the building, 6) determination of the building response to different levels of seismic motions, and 7) assessment of the vulnerability of the building using a failure mode risk model. In this paper, the essence of the seven-part strategy is presented along with a demonstration of the methodology using a thick stone masonry tower.

SEISMIC EVALUATION OF HERITAGE BUILDINGS

While the various steps of investigation are applicable to the seismic evaluation of any type of building, for regular buildings such an elaborate program is usually not necessary. For heritage buildings, however, the building material properties are often unknown, methods of construction are no longer current, and the need for heritage preservation is important, both in the prevention of damage in a future earthquake as well as in the choice of acceptable upgrading schemes.

1. Survey of the building

The objective of this step is to gain an understanding of the history, composition, structural condition and integrity of the structure.

The historical survey should produce a brief history of the structure detailing the period and phases of its construction, heritage status and heritage character considerations, and dates and details of structural and architectural changes that have occurred over the life of the building.

As many as possible of the original plans need to be assembled to provide the dimensions and structural details of the buildings along with an indication whether or not the structure was generally built as specified. New sets of plans are needed to complement the existing ones, showing the in-situ elevation and cross-sectional plan of every storey. The identification of the materials used for the construction of the building such as type and size of stones, location of the likely quarries, the type and specifications of the mortar, etc. should be noted. Also, information on how the foundation, walls, floors, roof and turrets were built, and how the different structural members are inter-connected should be gathered. This information is important for the prediction of the structural response and of the potential failure modes in later phases.

Deterioration, which is manifested by cracks, leaching of the mortar, corrosion of metals, etc. needs to be documented. This information will reveal the state of health of the building and will identify possible areas of weakness that need to be taken into consideration for designing upgrading measures.

To complete the survey of the structure it is essential to identify the various non-structural elements that are connected to the main portion of the structure. The list should include both large and small elements such as decorative ornaments, stone columns, staircases, parapets, chimneys, etc. Failure of such large pieces can pose a risk to occupants and a loss of heritage value.

2. Foundation conditions

The objective of this step is to consider the effects of soil conditions on the seismic response of the building. A geotechnical investigation needs to be carried out to establish the type and thickness of soil layers, condition and adequacy of footings and piles, and soil properties. This information is needed to determine load carrying capacity of the soil, to carry out soil amplification calculations and to assess liquefaction potential where loose soils are present.

3. Seismic ground motion characteristics

The objective here is to establish the seismic input to the building. Detailed information regarding the seismic activities for any location in Canada can be obtained from the Geological Survey of Canada. To perform dynamic analysis, time histories are needed that are representative of the site and correspond to appropriate annual probabilities of seismic occurrences. In addition, appropriate scaled historical records that are representative of the local geology and seismicity should be considered when available. It is recommended that at least three time records be used, using various annual exceedance probabilities to examine the performance of the building at various levels of seismic shaking. From this, a probability of failure can be established for different failure mechanisms.

4. Material properties of the building

The objective of this step is to determine the mechanical properties in the form of strength and deformability of the different materials used for the construction of the building. This is sub-divided into three parts: review of the literature for material properties pertaining to the structure at hand; laboratory tests; and on-site tests. The literature review will provide some mechanical properties; however, it can only be used as a general guide because often the exact material compositions are not given nor is the experimental basis for the test results stated. On-site tests provide a more reliable estimate of the present state of stress, deformability and strength of the material. Since this usually can only be done on a limited scale, the characterization of the material can be supplemented by laboratory tests provided the results compare well with the in-situ ones. The material properties usually sought are density, modulus of elasticity, compressive strength, flexural tensile strength and shear strength. If possible, these properties should be obtained for the unit element, wallette and wall assemblies.

5. Measured dynamic properties of the building

The dynamic properties of a structure subjected to earthquake motions are of importance for two reasons: the behaviour of the structure during earthquake depends directly on the dynamic properties, i.e. natural frequencies, mode shapes and damping; and the measured dynamic properties of natural frequencies and mode shapes are used as a means of calibrating the various analytical models.

Ambient vibration test or controlled shaker excitation can be used to measure the dynamic properties of the structure. Although the mode at the lowest natural frequency in each principal direction is of primary importance, extraction of higher modes is recommended in order to fully validate the analytical model.

6. Determination of seismic response

The objective of this step is to establish the seismic performance of the heritage building to different level of ground motion. Given their complex geometry, connections, and material properties, analytical models become essential to describe the structural behaviour. For a calculation of the seismic response, various analytical methods ranging from a simple stick model, to frame and finite element representation, can be employed. However, in the linear range, confidence in the validity of the model can only be established when reasonable agreement with a number of modal frequencies and mode shapes is achieved. For nonlinear analysis, the selection of appropriate material model and failure criterion is largely limited by the current knowledge of the actual material properties, and establishing validity of such models is usually difficult even with extensive experimental testing.

7. Vulnerability of the building

The first step of risk assessment is to identify the potential failure mechanisms from structural analysis and to determine their corresponding annual probability of failure. Risk is defined in terms of different hazard scenarios (or failure mechanisms) affecting life, property, etc., and the probability of their occurrence. For heritage buildings, it is recommended that the failure consequences be established in terms of life safety, building function, repair cost and heritage impact.

For a seismic evaluation, the uncertainties in seismic loads, structural analysis models, geometry, etc. need to be considered. If other uncertainties concerning structural behaviour under seismic loads are not incorporated, this fact should be considered when the results of the seismic analysis are interpreted.

APPLICATION OF EVALUATION METHOD TO A STONE MASONRY TOWER

The principles outlined above have been applied to a stone masonry heritage tower structure. Because of space limitations, only partial results are presented here.

Survey of the tower

The tower is an unreinforced loadbearing stone masonry structure with an iron frame roof, Fig. 1. Floor slabs are iron joists with brick arches at the lower three storeys and wood planking on iron joists at higher levels. The tower, 83 m high, was built between 1874 and 1878. On three sides, it is attached at the lower levels to a building. A stepped masonry footing bears directly onto bedrock.

The stone walls vary in width from approximately 1.8 m at ground level to 1.4 m at the top. They consist of large limestone blocks laid in uniform courses of height varying from 340 to 620 mm. The exterior is clad with randomly coursed sand-stone laid up tight against the limestone and bonded into it. The interior masonry at the top of the tower changes from stone to brickwork where it is enclosed by the roof of the tower. The joint thickness on the interior varies from 10 to 25 mm for the horizontal joints and 20 to 40 mm for the vertical joints. A lime mortar was used except for the exterior pointing where a more durable hydraulic cement mortar was employed. The specifications indicate the walls are solid masonry with no gaps or rubble infill. A radar scan of sections of the wall confirmed there were no significant gaps or infill except at a few locations.

The wall construction of the turrets is slightly thinner than the main walls of the tower and the intersection between them appears to be properly keyed in. A circular staircase is located in one of the turrets. The steel floor joists are simply supported and extend approximately 200 mm into the wall. The roof of the tower consists of an iron frame made up of riveted angles. Vertical wood joists, attached to the angles, support tongue and groove sheathing boards which in turn is covered by copper sheeting. The roof is held down by ten iron rods attached to the frame and secured to iron floor joists in the top floor of the tower. The four bottom corners of the roof are bolted down to the stone masonry.

The tower does not appear to suffer any significant deterioration problems. Visual inspection showed minor cracks in the soffit stones over the top of three window opening. The interior mortar at the top of the unused portion of the tower had a dry chalky consistency probably due to leaching of the mortar by infiltrating water. At some locations steel straps were observed coming out of the interior mortar joints in the main walls of the tower and some randomly placed straps in the two turrets. These straps are in poor condition due to corrosion. Minor corrosion was found at the bottom of the steel roof frame. Segments of some decorative stone columns had moved relative to each other.

Prominent features of a non-structural nature include a 23 m high circular staircase made up of precast, cast iron segments; large exterior windows with decorative columns that are separate from the main structure; decorative steel spires on the turrets; and wood framing of heritage importance inside an office within the tower.

Foundations

The tower has its footing resting on concrete flattened bedrock. It is assumed that the ground motion will be transmitted to the building foundations without modification.

Seismic input

From a seismological investigation (Atkinson, 1992), four time histories were artificially generated for an annual exceedance probabilities of 0.01, 0.002, 0.0001 and 0.0005, and with a high and low frequency content.

Measured dynamic properties

From the ambient measurement, the first natural frequency of the tower was found equal to 1.77 Hz corresponding to the mode shape in the North-South direction. The mode shape displayed significant motion at the base of the steel roof relative to the top of the stone masonry. The first 4 measured modes are shown in Fig. 2.

Calculated seismic response

Analytical models were constructed using a stick model, a frame and a finite element representation. These were then calibrated against the measured frequencies by adjusting the elastic modulus of the material for the stone portion of the tower so that agreement was achieved for the frequencies of the first mode. It was found that only the finite element model was able to predict the modes of higher frequencies after this calibration. The first five modes computed using the finite element method are described in Table I. Using the generated seismic inputs and the corresponding results from the finite element analysis, the failure mechanisms and their annual probability of occurrence were established.

Vulnerability of tower

For the tower, risk refers to the annual probability of failure or damage during future earthquakes and the consequences in terms of life safety, building function, repair cost and heritage impact. Table II outlines the four major structural elements and one of the corresponding failure mechanism and consequences, along with its annual probability of occurrence in future earthquakes. The annual probability of failure is expressed numerically in terms of 5 levels established from structural analysis, ranging from level 5 (probability of about 1/100 per year) as most likely to occur during an earthquake and to level 1 (less than a probability of about 1/2000 per year) as least likely to occur during an earthquake. The consequences of failure are expressed qualitatively for three main categories using the terms: low, medium, high and very high. For life safety, the terms indicate the likelihood of death/injury given the postulated failure; for repair cost / function, they indicate the expected repair cost or extreme loss of function; and for heritage value, they indicate the effect on loss of heritage value. From such a list of all the failure mechanisms, ranked in accordance with risk for each of the categories of life safety, repair cost/function and heritage value can be compiled and priority for remedial action established.

SUMMARY

A seven-part strategy is proposed to evaluate the response of heritage buildings subjected to seismic loads. The primary advantages of the proposed approach are to establish a priority list in the categories of life safety, building function, repair cost and heritage impact. This translates into an efficient allocation of usually very limited resources for upgrading. The disadvantages of such an investigation are the time requirements, the lack of availability of the required information such as material properties, and the cost of the investigation, all of which need to be weighed against the potential loss of life and of heritage value. The approach presented was applied to a thick stone masonry tower.

REFERENCES

Atkinson, G. 1992. Private Communication.

ACKNOWLEDGMENT

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Table I. Natural frequencies & mode shape from finite element analysis model.

Mode No.	f, Hz	Description of mode shapes
1	1.77	<ul style="list-style-type: none"> • North-South lateral. • Large relative motion of steel roof in the NS dir.
2	2.15	<ul style="list-style-type: none"> • East-West lateral.
3	2.77	<ul style="list-style-type: none"> • The lower portion of the steel roof expands and contracts.
4	3.09	<ul style="list-style-type: none"> • Torsional about z-axis. • Twisting and lateral motion of the steel roof.
5	4.13	<ul style="list-style-type: none"> • Top portion of the tower expands and contracts.

Table II. Tower's abbreviated vulnerability assessment list

Major Structural Elements Corresponding Failure Mechanism	Probability	Consequences		
		Life Safety	Repair Cost/ Function	Heritage Value
Gothic Roof, Floor, Stairs				
Damage to the brick masonry wall due to pounding from the steel roof	5	low (unoccupied)	low	low
Ornamental Masonry, Iron				
Overturning of stone turrets	2	high	high	high
Tower Masonry				
Total collapse of stone masonry tower	1	very high	very high	very high
Building Adjacent to Tower				
Damage to masonry over gothic window in wall abutting tower	3	low	high	medium

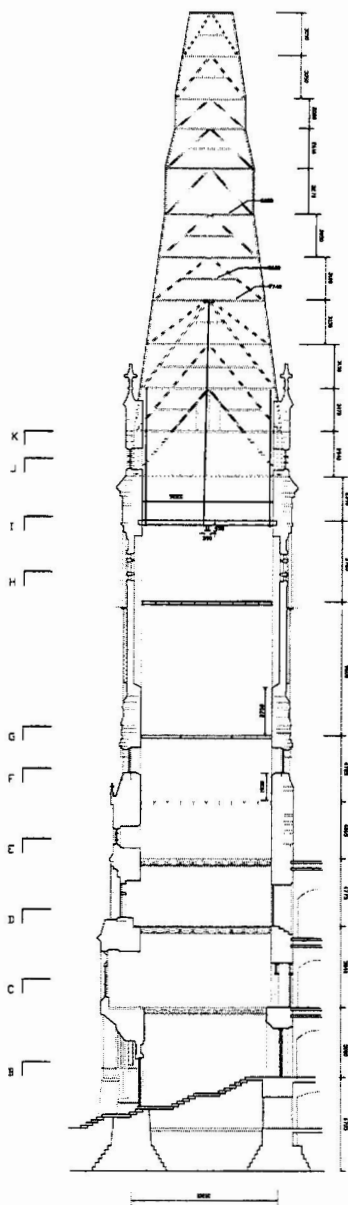


Fig. 1 Elevation view of the tower

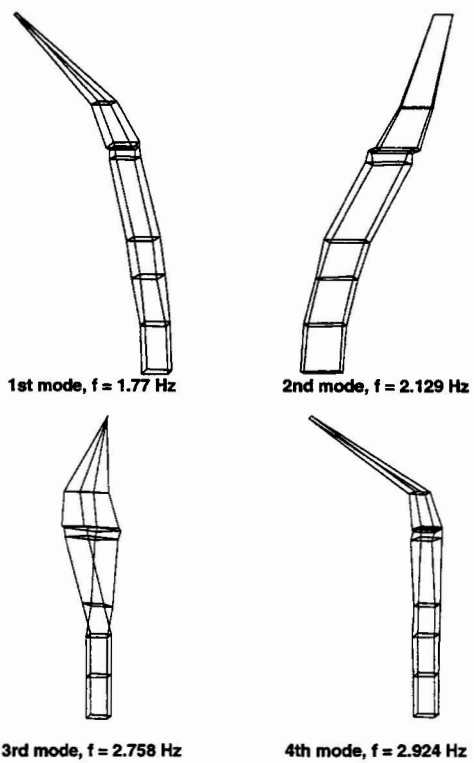


Fig.2 First four mode shapes obtained from ambient testing.