The 11th Canadian Conference on Earthquake Engineering

Canadian Association for Earthquake Engineering

MASONRY STIFFNESS FOR THE SEISMIC ASSESSMENT OF THE CENTRE BLOCK ON PARLIAMENT HILL

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ABSTRACT: Material properties are a fundamental part of any seismic analysis of a structure. This paper will summarize the difficulties involved with the selection of appropriate material stiffness for the seismic assessment of historic masonry structures. The significance of material property selection to the determination of seismic loads and capacity evaluation is discussed in detail in the context of a case study. A rational approach to the determination of key material properties for the calculation of upper and lower bound seismic loads is presented. Example calculations are given for a typical masonry assemblage used in the 19th and early 20th centuries in Canada, including different types of stone, brick and mortar.

1. Introduction

The Centre Block building located on Parliament Hill, Ottawa contains the Canadian House of Commons and Senate Chamber. Similar to many buildings constructed in Canada around the turn of the 20th Century, its construction materials consist of load bearing clay bricks and stone masonry. Many of these structures were built without knowledge or consideration of seismic loads. Research and past earthquake experiences around the world have demonstrated the susceptibility of unreinforced masonry structures to high levels of damage or collapse during an earthquake due to their inherent stiffness, low ductility and poor diaphragm behaviour. In response to this risk, it is desirable to complete seismic evaluations and upgrades to protect building occupants and/or contents in the event of an earthquake.

In order to evaluate the seismic capacity of an existing masonry wall building, it is necessary to know the material properties not only to assess the capacity of the existing elements but also to determine the seismic loads that apply to the structure. Fundamentally, the seismic load is proportional to the stiffness of the structure, which will largely be defined by the stiffness of the masonry walls. The stiffness depends both on the section properties of the seismic force resisting system and on the modulus of elasticity.

While the geometry of the masonry walls is often known or can be determined, information is seldom available with regard to important material properties, such as the strength or elastic modulus of the masonry assembly or its components. Historic construction practices were seldom based on specified strengths and in many cases, the original design information is no longer available. Furthermore, there is often a wide range of properties for a given material due to workmanship, manufacturing practices or, in the case of stone masonry, natural variability.

This paper will present a rational approach to the determination of material stiffness appropriate for use in the seismic assessment of the Centre Block on Parliament Hill.

Figure 1 – The Centre Block and Peace Tower on Parliament Hill, Ottawa, Canada

2. Building Description

Construction of the Centre Block main building structure was carried out from 1916 to 1920, following the fire that destroyed the original Centre Block building located on the same site. The Centre Block is comprised of six above grade storeys and one below grade storey. The floor structure of the Centre Block is typically constructed with flat terra cotta arches supported by structural steel beams, covered with a cementitious topping. The floor structures are typically supported on load bearing masonry walls, except for some larger volumes which are supported on steel columns. A photo of exterior courtyard walls (the far wall with embedded steel columns, the near wall without columns) being constructed in 1917 is shown in Figure 2.

Figure 2 – Photo of Centre Block Exterior Walls During Construction

The exterior masonry walls are composed of an exterior wythe of snecked sandstone masonry laid in random level beds with a multi-wythe common clay brick backing. Refer to Figure 3 for an example of the exterior wall configuration. Interior load bearing walls are composed of multi-wythe common clay brick masonry.

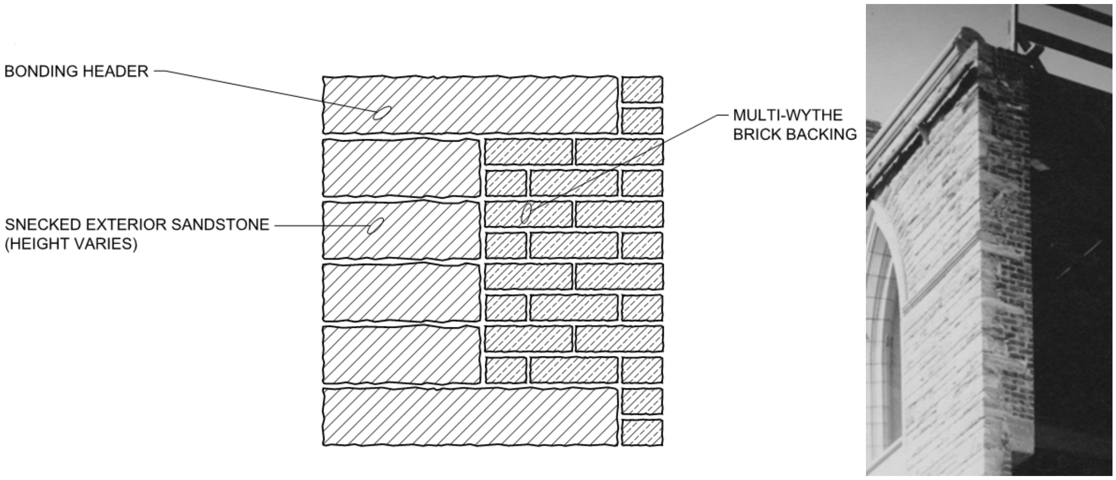

Figure 3 – Exterior Masonry Walls

The exterior wall thickness varies with an average thickness of approximately 610 mm, with the exterior wythe of sandstone masonry varying in thickness from approximately 152 mm to 254 mm, with an average thickness of 203 mm. The clay brick masonry composes the remainder of the wall thickness (Stephenson and Lumsdon, 2014).

3. Centre Block Material Properties

Three main materials make up the load bearing walls of the Centre Block: sandstone blocks, clay bricks and mortar. For each material, differing information is known about its properties, either from original construction documents or from material testing.

3.1. Exterior Stonework

The majority of the exterior stonework consists of Nepean Sandstone, although reports from the architect during construction note that the stone was purchased from numerous quarries due to the lack of supply, resulting in considerable variation in the quality of stone used. Testing of the compression strength of the stone units has been completed on several occasions on Centre Block materials and on similar stone used in the construction of the neighbouring West Block building. Results are presented in Table 1.

Table 1 – Measured Properties for Stone Units

Material Sample Description	Unit Compressive Strength (MPa)		
	Minimum	**Maximum**	**Average**
Comparable sandstone samples from the West Block (Chidiac et al., June 1995)	80	144	97
Comparable sandstone samples from the West Block (Shrive et al., 2008)	202	247	227
Sandstone samples from a ventilation tower of the Centre Block (Highbridge, 2012)	104	212	168

Based on these 3 sets of data, the average compressive strength of the stone units can be taken as 143 MPa for the purposes of determining the stiffness of the walls.

In addition, one set of tests, completed by Shrive et al. (2008), tested the elastic modulus of the stone units, and reported a maximum value of 67 GPa, a minimum value of 59 GPa and an average value of 62 Gpa.

3.2. Interior Bricks

The backing of the exterior walls and the whole width of the interior walls is constructed of common clay bricks, which were specified in the original construction documentation to have a crushing strength not less than 20.7 MPa. Testing of the compression strength of the clay bricks has been completed on several occasions in the past on the Centre Block. The results of those tests are presented in Table 2.

Table 2 – Measured Properties for Clay Bricks

Material Sample Description	**Unit Compressive Strength (MPa)**		
	Minimum	**Maximum**	**Average**
Clay brick from exterior courtyard wall of the Centre Block (Gervais and Nicholas, 2009)	30.5	61.5	46.5
Clay brick from a ventilation tower of the Centre Block (Highbridge, 2012)	26.5	42.1	33.6

Between the two sets of tests, the average compressive strength of a clay brick can be taken as 40 MPa for the purposes of determining the stiffness of the walls.

3.3. Masonry Mortar

Different types of mortar were specified in the original construction documents for the stone and brick masonry. For the stone masonry, the mortar was to be composed of the following:

- 3½ parts Portland cement;
- 4½ parts crushed rock no larger than 8.5 mm; and,
- 4½ parts sand.(Stephenson and Lumsdon, 2014)

For the brick masonry, the mortar was to be composed of the following:

- 1 part Portland cement;
- 3 parts sand; and,
- “a small amount of lime”. (Stephenson and Lumsdon, 2014)

Several investigations and tests have been completed in the past to assess the quality of the mortar for both the brick and stone masonry. There is no recognised method for accurately testing the compressive strength of existing mortar but two reports attempted to obtain representative values by testing samples of mortar with very small dimensions (usually the thickness of the mortar joint). The authors of these reports noted that these tests will not provide an accurate predication of the strength of the in-situ mortar due to the aspect ratio of the sample and the confinement applied by the test apparatus bearing plates (Highbridge, 2012 and Chidiac et al., January 1995).

However, tests completed by Highbridge (2012) indicate that mortar is very hard and has an average strength of 35 MPa for the brick mortar and 53 MPa for the stone mortar. Another test completed for Chidiac et al. (January 1995) indicated an average mortar compressive strength of 39 MPa. It was not indicated whether this was brick or stone mortar.

Gervais and Nicholas (2009) completed Winsdor Pin testing on in-situ brick mortar and recorded values between 20 and 30 MPa, with an average value 24 MPa.

Based on the initial compositions described in the construction specifications, and the observations and testing completed, the mortar can be assumed to possess similar properties to a Type S mortar, as defined in CSA A179.

3.4. Other Materials

In the Centre Block, there are many terra cotta block partition walls that are not connected to the floors and are not typically load bearing elements. As a result, their material properties are not considered in this paper.

Many other historic masonry structures, including the neighbouring buildings to the Centre Block on Parliament Hill possess walls constructed with a rubble infill core which can have a significant impact on the strength and stiffness of the structure. However, the Centre Block walls were not constructed in this manner and so the properties of rubble infill walls are not discussed in this paper.

4. Importance of Material Properties

One of the challenges of dealing with the seismic evaluation of historic masonry structures is that there is always a potential range of material properties that could be used in evaluating a structure and determining which value will produce a conservative estimate is not always immediately apparent.

The modulus of elasticity of an unreinforced masonry wall is typically correlated to its material prism compressive strength, which is intended to reflect the strength of the masonry as it is actually constructed, including the interaction between the masonry units and the mortar joints. From the perspective of evaluating the strength of a wall, it would be conservative to assume a lower prism compressive strength. However, assuming a lower prism compressive strength will lead the designer to assume a correspondingly lower modulus of elasticity.

In turn, the lower modulus of elasticity will reduce the stiffness (or increase the fundamental period) of a building model used to evaluate the seismic loads. Since design seismic hazard decreases with longer periods, the “conservative” assumption of low strength may also significantly decrease the predicted demand. Given that neither the capacity nor demand on the wall is directly proportional to the assumed compressive strength, it may not be possible to determine without analysis which assumption produces the worst case.

Consequently, caution should be used in applying low values for masonry unit or mortar strength in the absence of design or testing information. Material design codes intended for the use in the design of new structures typically use 5 percentile, lower bound characteristic material strength values. For example Table F.1 in Annex F of the CSA Standard S304.1-04 presents very low limits on the allowable compressive stress for unreinforced masonry to ensure that new designs have a reliable margin of safety against localized variation in material strength. However, use of these values even as a guideline could drastically underestimate seismic loads.

Similarly, in the absence of information about the composition or strength of the mortar, it is not reasonable to assume that the mortar is very weak for all historic masonry buildings, without careful consideration of the available information.

If material testing is not available to refine the analysis, the uncertainty in material properties can be best addressed by completing a sensitivity analysis that considers upper and lower bounds and compares the results. For the purposes of determining an overall seismic response for a building, such as the Centre Block, it is reasonable to estimate the range of stiffnesses of the structure using average compressive strengths. This differs from assessing the failure mechanisms of individual elements within the structure, where a lower bound approach of material properties is more appropriate.

5. Calculation of Masonry Wall Stiffness for Centre Block

The relationship between clay brick unit strength and clay brick prism strength is well documented in material design codes and research literature (Drysdale and Hamid, 2005). The relationship between clay masonry prism strength (f'_m) and clay masonry prism stiffness (E_m) is also reasonably well documented, although there is variation between codes of different jurisdictions and between research results (Wijanto, 2007). Unfortunately, there is little corresponding information available to relate stone unit compression strength to either stone prism strength or prism stiffness.

5.1. Clay Brick Masonry Stiffness

As mentioned in Section 4, material design codes intended for use in the design of new structures typically use 5th percentile, lower bound characteristic material strength values, to ensure that new designs have a reliable margin of safety against localized variations in material strength. The equations and tables presented in material design codes that define the relationships between clay masonry prism strength and stiffness are calibrated based on this assumption.

For existing structures, a lower bound characteristic material strength is often unknown. Material sample testing, which is usually of a limited sample size, produces an indication of average material strength only. The use of an incompatible average material strength value in the typical material code equations would produce an unconservative lower bound estimate of stiffness. Subsequently, relationships taken from literature that consistently correlate average unit strength to average prism strength and average prism stiffness should be used to calculate stiffness.

For the clay brick units on the Centre Block, both a minimum specified compressive strength (20.7 MPa) and an average compressive strength (40 MPa) are known. The specified prism compressive strength can be determined for Type S mortar using Table 3 of CSA S304.1 and the minimum specified compressive strength. For the average prism compressive strength, Figure 4-6 in Monk (1967) (reproduced as Figure 4.11 in Drysdale and Hamid, 2005) can be used to determine from an average clay brick strength value with Type S mortar. Additional figures are also available in Monk (1967) for different mortar compositions to determine average prism strength.

Following the determination of the prism compressive strength, the relationship between the elastic modulus and the prism strength is defined in Equation 1.

$$E_m = k \cdot f'_m \tag{1}$$

CSA S304.1 (6.5.2) specifies a value of 850 for *k* for all types of masonry based on the 5th percentile lower bound strength. Test data cited in Drysdale and Hamid (2005) gives values between 390 and 444 for *k* for the average prism compressive strength of clay brick.

Calculations of clay brick masonry stiffness based minimum compressive strength are as follows:

$$f_{brick} = 20.7MPa$$
$$\therefore f_{prism} = 7.9MPa$$
$$E_m = 850 \cdot 7.9MPa = 6.7GPa$$

Calculations of clay brick masonry stiffness based average compressive strength are as follows:

$$f_{brick} = 40MPa$$
$$\therefore f_{prism} = 16.5MPa$$
$$E_{mLowerBound} = 390 \cdot 16.5MPa = 6.4GPa$$
$$E_{mUpperBound} = 444 \cdot 16.5MPa = 7.3GPa$$

In this instance, the stiffnesses compare well with both methods for the information available. Although not directly applicable to the Centre Block, as a comparison, if a much weaker lime mortar with the same strength of brick is assumed, using Figure 4-4 of Monk (1967), it is possible to calculate a prism strength of 5.5 MPa and a range of stiffness from 2.1 GPa to 2.4 GPa using the relationship described above in Drysdale and Hamid (2005). Assumption of a very weak mortar can produce a stiffness of approximately one third of the Type S mortar, which could significantly reduce the predicted seismic demand.

5.2. Stone Masonry Stiffness

In the absence of any specific stone prism test data, a reasonable estimate of the stiffness of the stone portion of the wall assembly may be made by equating the stone portion to a similar high strength clay brick and assuming that it follows the same relationship between unit strength and prism strength. In reality, a stone prism made up of large individual stone units would likely be stiffer than a brick prism with equally strong but smaller units. As a result, the assumption will produce a reasonable lower bound estimate of stiffness. The overall stiffness of the composite wall section can then be calculated based on a weighted average of the stone and brick components.

The average stone prism compressive strength and stiffness can be determined by again using Figure 4-6 from Monk (1967) and the test data cited in Drysdale and Hamid (2005), respectively.

$$f_{stone} = 143MPa$$

$$\therefore f_{prism} = 38.6MPa$$

$$E_{mLowerBound} = 390 \cdot 38.6MPa = 15.1GPa$$

For the Centre Block, an alternate estimate of stiffness of the combined stone unit and mortar wall assemblage that may give an upper bound can be estimated using the fundamental mechanics of composite materials approach described by Chidiac and Foo (2000) in Equations 2 and 3.

$$E_m = \frac{1}{\frac{\delta}{E_s} + \frac{(1-\delta)}{E_j}} \tag{2}$$

Where:

$$\delta = \frac{t_s}{t_s + t_j} \tag{3}$$

t_s = height of stone unit

t_j = height of masonry joint

E_s = Elastic modulus of stone unit

E_j = Elastic modulus of mortar joint

The average height of a stone unit (t_s) for the Centre Block's walls is 190 mm and the average height of the mortar joints (t_j) is 13 mm (Stephenson and Lumsdon, 2014). From the testing that was completed by Shrive et al. (2008), an average elastic modulus of the Nepean Sandstone was determined from testing to be approximately 62 GPa.

In lieu of more accurate information, the elastic modulus of the mortar can be approximated from the average material test compression data from the Windsor Pin tests combined with the elastic modulus equation in ASCE 5-13 Section 4.2.2.4 for grout. For the purposes of calculating an upper bound stiffness value, this assumption should produce a conservative upper bound estimate of stiffness. The elastic modulus of the stone masonry is therefore calculated as per Equation 4.

$$E_j = 500f'_j = 500 \cdot 24MPa = 12GPa \tag{4}$$

where:

f'_j = compressive strength of mortar

The combined stiffness of the stone unit and mortar joints can then be calculated as described above:

$$\delta = \frac{t_s}{t_s + t_j} = \frac{190}{190 + 13} = 0.94$$

$$E_m = \frac{1}{\frac{\delta}{E_S} + \frac{(1-\delta)}{E_j}} = \frac{1}{\frac{0.94}{62GPa} + \frac{(1-0.94)}{12GPa}} = 49.6GPa$$

5.3. Composite Wall Stiffness

The upper and lower bounds of the elastic modulus of the Centre Block's typical exterior composite wall can be calculated based on a weighted average of the components, where the stone masonry is an average of one third of the wall thickness, and the brick masonry is two thirds of the wall thickness. The elastic modulus is calculated as follows:

$$E_{Lower\_Bound} = \tfrac{2}{3} \cdot 6.4GPa + \tfrac{1}{3} \cdot 15.1 = 9.3GPa$$

$$E_{Upper\_Bound} = \tfrac{2}{3} \cdot 7.3GPa + \tfrac{1}{3} \cdot 49.6 = 21.4GPa$$

This result demonstrates the wide variation in stiffness that needs to be considered in any seismic analysis of historic masonry, even when a reasonable amount of information on the component materials is known.

6. Material Testing

Given the wide range of published values for masonry components, it is important to understand the actual strengths and weaknesses of the masonry walls as closely as possible to avoid either erroneous or overly conservative results. If limited information is available from the original construction, material testing can be used to better understand the properties of the existing masonry and refine the results of the analysis.

The mortar should be tested for its chemical composition, which should give an approximation of its compressive strength. Compressive strength tests of samples taken from mortar joints typically do not provide any meaningful values because of the confinement applied to the very short samples by the testing apparatus bearing plates. Understanding the relative proportions of the cement, lime and sand components provides a more meaningful understanding of how the probable mortar material properties.

In the absence of chemical testing, the Windsor Pin test can be used to give an approximate indication of relative strength of the mortar but it should be used very cautiously in trying to predict actual compressive strength.

The brick and stone masonry prism units can be tested if it is possible to cut specimens from the existing masonry assemblage. If that is not possible, prisms can be built from units taken from the walls combined with a replacement mortar that is as similar as possible to the existing mortar composition. From these specimens, both compressive strength and elastic modulus can be calculated.

Alternatively, stone or brick units can be tested directly without the mortar to determine both the compressive strength and elastic modulus and the results interpreted as per the procedure described in this paper.

Flat jack testing with two flat jacks inserted into the wall on either side of a sample can also be used to determine in-situ compressive strength and elastic modulus.

7. Conclusion

As historic masonry buildings were built without consideration for seismic loads, there is often a desire to evaluate and protect these existing structures. In order to complete a meaningful seismic assessment, the a reasonable estimate of the potential range of material properties must be made to assess both the performance and loading requirements. The assumption of lower bound masonry material properties may lead to an unconservative estimate of a structure's stiffness and seismic demand.

A procedure for estimating the range of average elastic moduli for a composite stone and brick wall has been presented. It is evident that even when a reasonable amount of information regarding the component material properties is known, there can still be a wide variation in potential stiffness properties that need to be considered in a seismic assessment.

8. References

Canadian Standards Association, “CSA A179-04: Mortar and grout for unit masonry”, CSA, Mississauga, Ontario, 2004.

Canadian Standards Association, “CSA S304.1-04: Design of Masonry Structures”, CSA, Mississauga, Ontario, 2004.

CHIDIAC, S.E. et al., “Centre Block Masonry Stabilization Seismic Study for Tower of Pavilion and Chimneys”, for Public Works and Government Services Canada, January 1995, pp 26.

CHIDIAC, S.E. et al., “Seismic Evaluation of the MacKenzie Tower as a Basis for the Evaluation of the Parliament Buildings”, for Public Works and Government Services Canada, June 1995, pp. 69.

CHIDIAC, Samir, FOO, Simon, “Guidelines for the Seismic Assessment of Stone-Masonry Structures”, for Public Works and Government Services Canada, July 2000, pp.49.

DRYSDALE, Robert G., HAMID, Ahmad A., “Masonry Structures, Behaviour and Design”, 2005.

GERVAIS, M.G., NICHOLAS, T.J., “Brick and mortar sampling and testing, Inner Face, Wall 4, Centre Block, West Courtyard, Parliamentary Precinct”, for Public Works and Government Services Canada, February, 2009, pp. 2-3.

HIGHBRIDGE Materials Consulting, Inc. “Stone Testing and Examination Report, Centre Block, Parliament Hill”, for Public Works and Government Services Canada, January 2012.

Masonry Standards Joint Committee, “ASCE 5-13: Building Code Requirements and Specification for Masonry Structures”, MSJC, 2011.

MONK, C.B., “A Historical Survey and Analysis of the Compressive Strength of Brick Masonry”, Report No. 12, Structural Clay Products Research Foundation, 1967.

SHRIVE, N.G. et al., “Testing of Walls Representative of Those on Parliament Hill”, for Public Works and Government Services Canada, August 2008, pp. 36.

STEPHENSON, Doug, LUMSDON, Carole, “Centre Block Structural History (1916-2014)”, for Public Works and Government Services Canada, June 2014, pp 39-45.

WIJANTO, Ludovikus Sugeng, “Seismic Assessment of Unreinforced Masonry Walls”, University of Canterbury, Christchurch, New Zealand, December 2007.