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SEISMIC ASSESSMENT OF HISTORIC MASONRY STRUCTURES: HOW SIGNIFICANT IS MATERIAL STRENGTH?

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Abstract

The selection of appropriate material properties for use in seismic assessments of historic masonry structures often poses a considerable challenge to practicing structural engineers. Material properties influence the dynamic characteristics and therefore seismic demands imposed on a structure, and the capacity of a structure to resist those loads. In-situ or laboratory testing of individual masonry components may provide some guidance; however, the results often yield a wide range of potential material properties. In theory, the seismic capacity/demand ratio of unreinforced masonry structures could be significantly influenced by their material properties. In this study, however, it is demonstrated using the Centre Block of Parliament building in Ottawa, Canada as an example that the seismic capacity/demand ratios of many historic masonry buildings are relatively insensitive to the precise choice of material properties. This insensitivity is due to the high lateral stiffness common to many historic masonry buildings combined with masonry wall modes of failure that are largely controlled by the level of axial load present.

Keywords: historic masonry; material properties; seismic assessment

1 Introduction

Material properties influence the dynamic characteristics and therefore seismic demands imposed on a structure, and the capacity of a structure to resist those loads. The selection of appropriate material properties is therefore an important step in a seismic assessment. This often poses a considerable challenge for practicing structural engineers performing seismic assessments of historic masonry structures. Original construction documentation regarding the properties of the masonry materials used is seldom available. Even if specific information is available, there is often a wide range of possible assemblage properties for a given masonry material due to workmanship or natural variability (especially in the case of stone masonry). In-situ or laboratory testing of individual masonry components may provide some guidance; however, these tests can be challenging and the results also often yield a wide range of potential material properties. Samples of the individual masonry components taken from existing historic masonry structures are typically dimensionally small, leading to inaccurate reported strengths. This is especially the case for mortar samples, as the sample size is limited to the mortar joint thickness. More accurate results may be obtained by experimental testing of replicas of the original wall construction, but in most circumstances this approach is typically prohibitively costly and time consuming.

Fig. 1 - Centre Block of Parliament, Ottawa, Canada [1]

In light of this, a practicing structural engineer has little choice but to make a reasonable and conservative assumption regarding an historic masonry building’s material properties. Application of lower bound material properties will result in a lower bound estimate of a structure’s capacity but may also result in a lower bound estimate of a structure’s stiffness and corresponding lower bound estimate of seismic demands. The reverse is true for the application of upper bound material properties. It is not immediately apparent which assumption will govern the assessment of a structure’s overall capacity/demand ratio [2]. One possible approach is to use lower bound material properties to estimate a structure’s capacity and upper bound material properties to estimate a structure’s seismic demand. This yields a conservative estimate of the overall capacity/demand ratio, but the deliberate inconsistency in material assumptions is not particularly rational. A more reasonable approach is to assess the possible range of capacity/demand ratios corresponding to a consistent application of lower bound and upper bound material properties.

Fig. 2 - Victoria Memorial Museum Building, Ottawa, Canada [3]

Fig. 3 - Langevin Building, Ottawa, Canada [4]

In theory, the seismic capacity/demand ratio of unreinforced masonry structures could be significantly influenced by their material properties. It is the observation of the authors, however, that for many historic masonry buildings, including the Centre Block of Parliament (Fig. 1), the Victoria Memorial Museum Building

(Fig. 2) and the Langevin Building (Fig. 3) located in Ottawa, Canada, this sensitivity to material properties is not as significant as might initially be expected. Our experience with the seismic assessment of these structures has shown that the high lateral stiffness common to many historic masonry buildings combined with masonry wall modes of failure that are largely controlled by the level of axial load present (rocking and sliding shear) result in a relative insensitivity to the precise choice of material properties. Discussion regarding the influence of the selection of material properties on the seismic demand and masonry wall capacity of historic masonry structures is presented below. The numerical results of a seismic assessment of the Centre Block of Parliament are used as an example.

2 Discussion

2.1 Masonry properties and seismic demand

In force-based design procedures, seismic demand is a function of the building weight and the acceleration at its fundamental period. A codified acceleration response spectrum is typically used to relate a building's fundamental period to a spectral acceleration from which the structure's lateral seismic forces are derived. The greater the lateral stiffness of a structure, the shorter its fundamental period and the larger the required response spectrum seismic design force. For very short fundamental periods the response spectrum plateaus at a maximum seismic force level, as shown below.

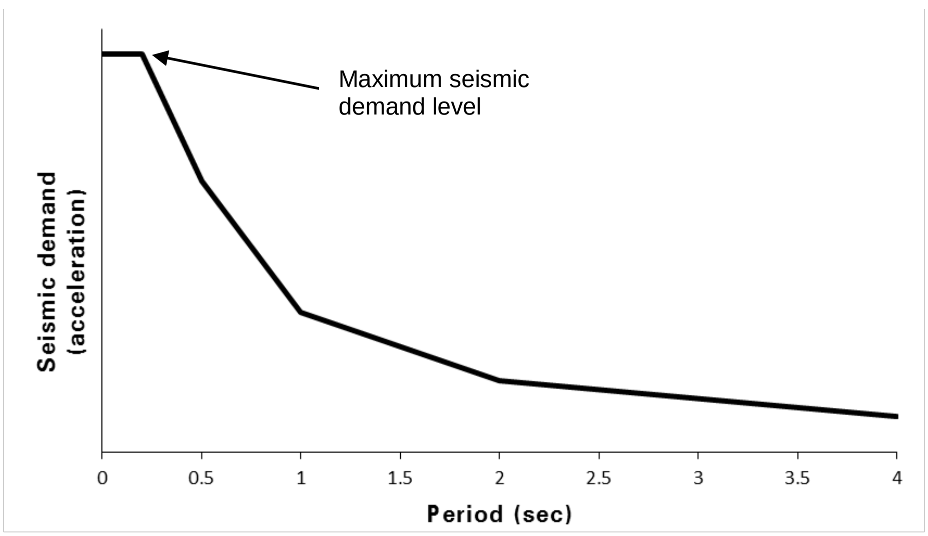

Fig. 4 - Example seismic demand response spectrum

The lateral stiffness of a structure is a function of both its material properties and the geometry of its seismic force resisting system. For laterally stiff structures with fundamental periods located within the short period range, the seismic demand will obviously be relatively insensitive to a variance in assumed material properties.

This will often be the case for historic masonry structures as they commonly utilize load-bearing masonry walls to support their vertical gravity loads and subsequently possess a very high total length of wall. This high total length of wall results in very laterally stiff structures with short fundamental periods. A partial plan example of the Centre Block of Parliament, Ottawa, an historic load-bearing masonry wall structure, is provided in Fig. 5 below.

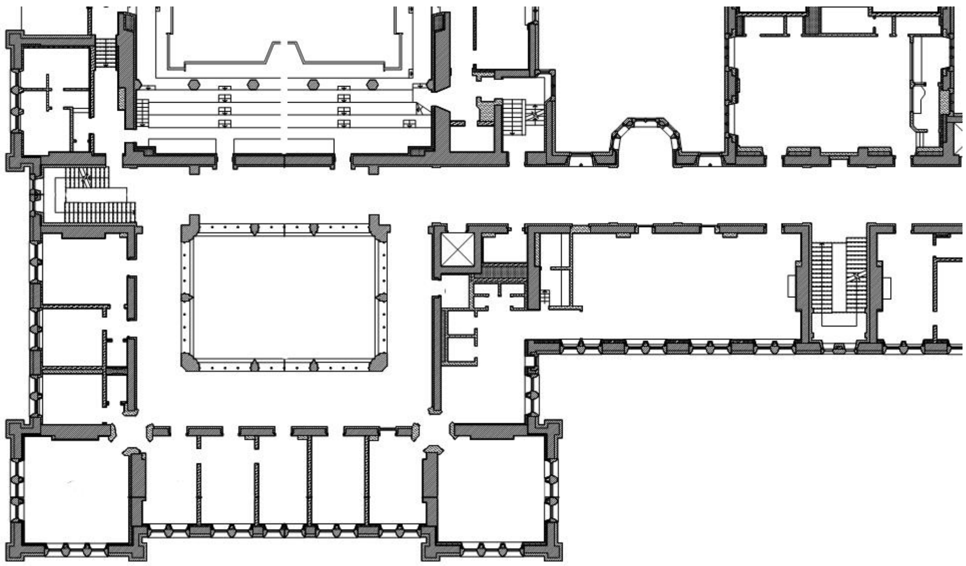

Fig. 5 - Partial floor plan of Centre Block [5]

As part of a seismic assessment study of the Centre Block, potential ranges for the masonry compressive strength (f'_m), the associated elastic modulus (E), and the resulting periods and seismic design force were determined. These findings are shown in Table 1 below.

Table 1 - Centre Block of Parliament material properties and results [6]

	Lower bound	**Upper bound**	**Mean**	**Variance**
Masonry compressive strength, f'_m	9 MPa	26 MPa	17.5 MPa	±49%
Modulus of elasticity, E	9.9 GPa	21 GPa	15.5 MPa	±36%
Period, T	0.25s	0.20s	-	-
Seismic design force, V	344 000 kN	390 000 kN	367 000 kN	±6%

Table 1 shows that although there was a very large potential range in compressive strength (±49% from the mean compressive strength) and material stiffness (±36% from the mean elastic modulus), the resulting upper and lower bound fundamental periods were found to only range from 0.20 to 0.25 seconds. This minor change in period was due to the stiffness of the structure being governed by the geometry of the seismic force resisting system (high total length of wall) and not by the masonry properties. The resulting variance in seismic design force was calculated to be ±6%. Consequently, it was observed that due to the inherent stiffness of the structure placing the building on or near the response spectrum plateau, the seismic demand was relatively insensitive to the choice of material properties.

2.2 Masonry properties and seismic capacity

As previously discussed, many historic masonry buildings have a high total length of wall; however, the majority of the wall lines often have a significant number of door and window openings, as illustrated in Fig. 6 below.

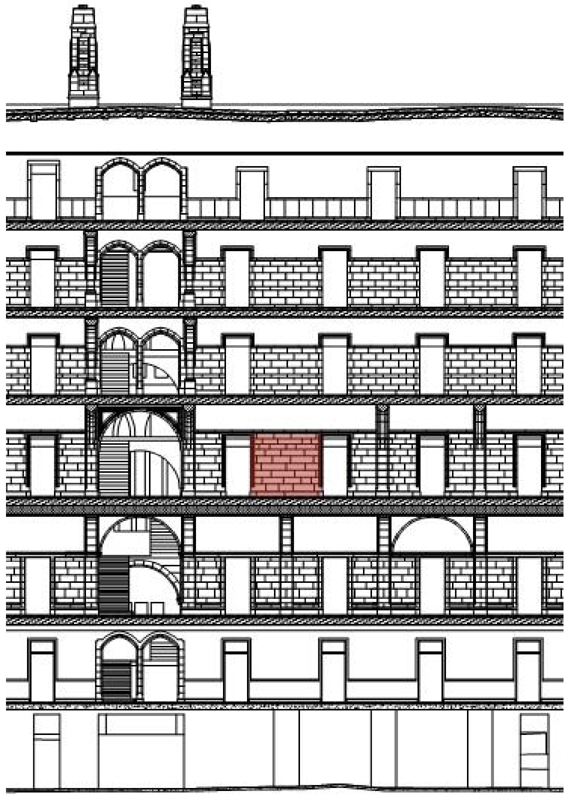

Fig. 6 - Interior elevation of Centre Block [5]

Localized failure of the masonry piers between these openings controls the overall capacity of each wall line. In-plane failure of the individual masonry pier elements is governed by one of three potential modes of failure [7,8] as illustrated and outlined below:

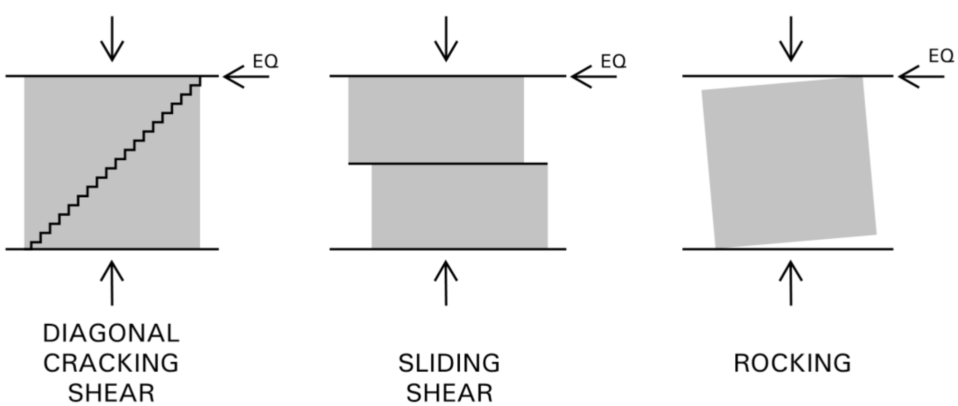

Fig. 7 - Masonry wall failure modes

The in-plane capacities based on these failure modes can be calculated using the following equations:

$$V_{r\text{-diag. shear}} = \phi_m (v_m b_w d_v + 0.25P) \quad (1)$$

$$V_{r\text{-sliding}} = 0.16\phi_m (f'_m)^{0.5} A_{uc} + \phi_m \mu P \quad (2)$$

$$V_{r\text{-rocking}} = P \times (0.9\ D) / H \quad (3)$$

where:

ϕ_m = resistance factor for masonry

v_m = masonry shear strength

b_w = section width

d_v = effective shear depth

P = axial compressive load

f'_m = compressive strength of masonry

A_{uc} = uncracked area of the pier

μ = coefficient of friction

D = in-plane length of pier

H = height of pier

Diagonal tension cracking shear is characteristic of loading cases with high shear and high axial loads. Eq. (1) provides the in-plane diagonal shear resistance according to the Canadian masonry code [9]. The masonry shear strength, v_m, is a function of the masonry compressive strength, f'_m. Eq. (1) shows that the diagonal shear capacity of a masonry pier is dependent on both the compressive strength of the material and the axial load on the pier.

Sliding shear occurs when the shear force exceeds the sliding resistance of the wall along a bed joint. The Canadian masonry design code [9] equation for in-plane sliding shear resistance, given in Eq. (2), includes both a cohesion component ($0.16\phi_m (f'_m)^{0.5} A_{uc}$) and a friction component ($\phi_m \mu P$). The cohesion component is a function of the compressive strength and the uncracked area of the masonry section, while the friction component is dependent on the axial load on the pier. For certain pier length-to-height ratios, rocking can cause excessive cracking, reducing the contribution of the cohesion component to the total sliding shear capacity of the pier. This results in a sliding shear capacity that is primarily dependent on the axial load on the pier, with the precise material properties of the masonry having little to no impact.

The rocking failure mode is characteristic of masonry piers with low axial compression loads and large overturning moments. This condition leads to tension-controlled cracking normal to the bed joints, followed by rocking. The capacity of a pier to resist rocking can be evaluated using Eq. (3), where it is a function of the axial load on the pier and the pier's geometry [8].

The sensitivity of the masonry wall capacity/demand ratios to the potential range of masonry compressive strengths was investigated for the Centre Block assessment. Using the appropriate variation in demand (±6%, as shown in Table 1) with the associated variation in material strength (±49%, as shown in Table 1), a variation of ±10% to the capacity/demand ratios was observed. Our analysis of the structure found that the capacities of a majority of the masonry piers were controlled by either the rocking or sliding shear mode of failure. As previously discussed, the failure capacities of these two modes are primarily a function of axial load and not material strength. The lack of sensitivity to masonry wall material strength was due to the prevalence of these failure modes.

The overall capacity of the building was therefore found to be relatively insensitive to the precise choice of material properties, as assuming a higher value for the masonry compressive strength had no impact on the rocking failure mode capacity and little impact on the sliding failure mode capacity.

3 Conclusions

The selection of appropriate material properties for application in a seismic assessment of an historic masonry structure can be a challenge due to the natural variability of masonry and the resulting wide range in potential values. Experimental material testing of components of an historic masonry wall structure or testing of full replicas of the entire wall assemblage may yield more refined estimates of material properties.

It is observed, however, that the seismic capacity/demand ratio for many historic masonry structures is often relatively insensitive to the precise choice of material properties due to their high lateral stiffness caused by a high total length of wall and a tendency for rocking and sliding pier modes of failure to dominate. It is recommended that the potential range of seismic capacity/demand ratios be established using a consistent application of lower bound and upper bound material properties.

4 References

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