FULL-SCALE TESTING OF FLAT ARCH TERRACOTTA FLOOR DIAPHRAGMS OF CANADIAN PARLIAMENT CENTRE BLOCK BUILDING

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Abstract

The Centre Block of Parliamentary Buildings of Canada is being prepared to undergo a major rehabilitation project including a seismic upgrade. As part of this major rehabilitation project, an experimental investigation of the seismic behaviour of its existing terracotta flat arch floor diaphragms is being performed at the National Research Council Canada (NRC). Terracotta flat arch floor systems were used in North America in the early 1900s. This system has demonstrated adequate behaviour to gravity loads as well as providing fire separation; however, its response as a diaphragm when subjected to seismic loads is not well understood. The full-scale experimental program is to obtain data that will support the consulting design team with assessing the existing seismic performance of the floor diaphragms, as well as selecting appropriate retrofitting strategies for rehabilitating the Centre Block to ensure adequate seismic behaviour.

The testing program started with obtaining samples from the Centre Block of the existing 100-year old terracotta tiles. Material properties and exact physical dimensions of the tiles are obtained to replicate existing tiles to be used in constructing full-scale test samples. To study the seismic performance of terracotta flat arch diaphragms, several tests are performed on tiles, mortar mixes, tiles assemblies, and full-scale single-panel and multi-panel frames infilled with terracotta tiles. The single-panel samples are tested with different length to width ratios to resemble different on-site conditions. The single-panel frames are loaded diagonally under quasi-static loads, while the multi-panel frames are loaded laterally under cyclic loading.

In this paper, the experimental results from the testing of single-panel frames are presented. The load-displacement responses obtained from the testing can be used as input parameters by the consulting design team for the analysis and design of retrofitting alternatives for the floor system and the Centre Block Building. Three pairs of single-panel frames with and without super-imposed dead loads on the floors are tested. The overall dimensions of the single-panel frames are approximately 4.5 m × 1.5 m, 3.5 m × 1.5 m, and 1.6 m × 1.5 m. Testing is conducted to establish the capacity and behaviour of compression struts within the terracotta arches. Sample results from the testing of single-panel frames including peak and post-peak states of the frames, load-displacement response, and effects of gravity super-imposed loads on the compression strut capacity are discussed.

Keywords: Full-scale testing, terracotta floors, flat arch diaphragms, in-plane loading, seismic performance

1. Introduction

1.1 Canadian Parliamentary Buildings: Centre Block

Located on an escarpment overlooking the Ottawa River, the Canadian Parliamentary Buildings (see Fig.1) consist of the Centre Block (including the Peace Tower and the Library of Parliament), the West Block, and the East Block, surrounding three sides of the Central Lawn on Parliament Hill. The Centre Block contains the House of Commons and Senate Chambers as well as the hall of honour, memorial chamber and confederation hall and offices of a number of members of parliament. The Centre Block, originally constructed in 1859, was destroyed in a fire in 1916, except the Library of Parliament located at the north side of the Centre Block. Reconstruction started immediately after the fire and was completed by 1920 with the Peace Tower being completed by 1927. The Centre Block is in the early stages of a major rehabilitation project. Public Services and Procurement Canada (PSPC) is representing the Crown interest in this project. CENTRUS is the Consultant Design Team on the project.

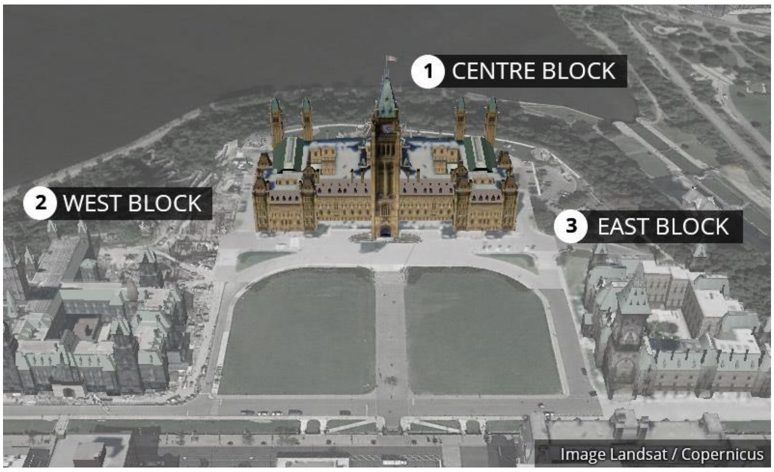


Fig. 1 – Canadian Parliamentary Buildings [1]

1.2 Seismic Upgrade of the Centre Block

The six-storey high structure of the Centre Block consists of heavy load-bearing unreinforced masonry walls on the perimeter, and a mix of unreinforced load bearing masonry walls and steel columns on the interior. The floor systems mainly consist of a steel beam system supporting the flat terracotta arch system which includes tie rods between steel beam. Seismic evaluation studies by CENTRUS have concluded that the Centre Block does not meet the current seismic requirements for Ottawa, which is classified in a zone of moderately high seismicity. As part of the largest heritage rehabilitation project in Canada, seismic upgrade of the Centre Block is in its early stages of design and the performance of the terracotta floor system is an important component that is being researched in detail as it is not well understood.

1.3 Condition Assessment

PSPC and CENTRUS are assessing the Centre Block to fully understand the construction of the building and the current condition of the materials after many decades of deterioration and aging. The findings of these assessments are intended to be used in plans for rehabilitation of the Centre Block. As part of these assessments, PSPC has engaged the National Research Council Canada (NRC) to evaluate in collaboration with CENTRUS the seismic performance of existing terracotta flat arch floor diaphragms , through different material and large scale test setups. These tests are intended to provide material properties of the terracotta tiles, the mortar, and their assembly, as well as the seismic performance of the terracotta flat arch floor diaphragm system.

2. Terracotta Flat Arch Floor Diaphragms

2.1 Floor Construction

Each terracotta flat arch floor was built using three typical tiles: skews, keys, and lengtheners (see Fig. 2). Skews are placed on either ends of the floor segment; they are the tiles that rest against the beam. Keys are the center tiles of the flat arch floors; there is only one key tile per segment. While lengtheners are the intermediate tiles found between the key tile and skew tiles.

a)
b)
c)
d)

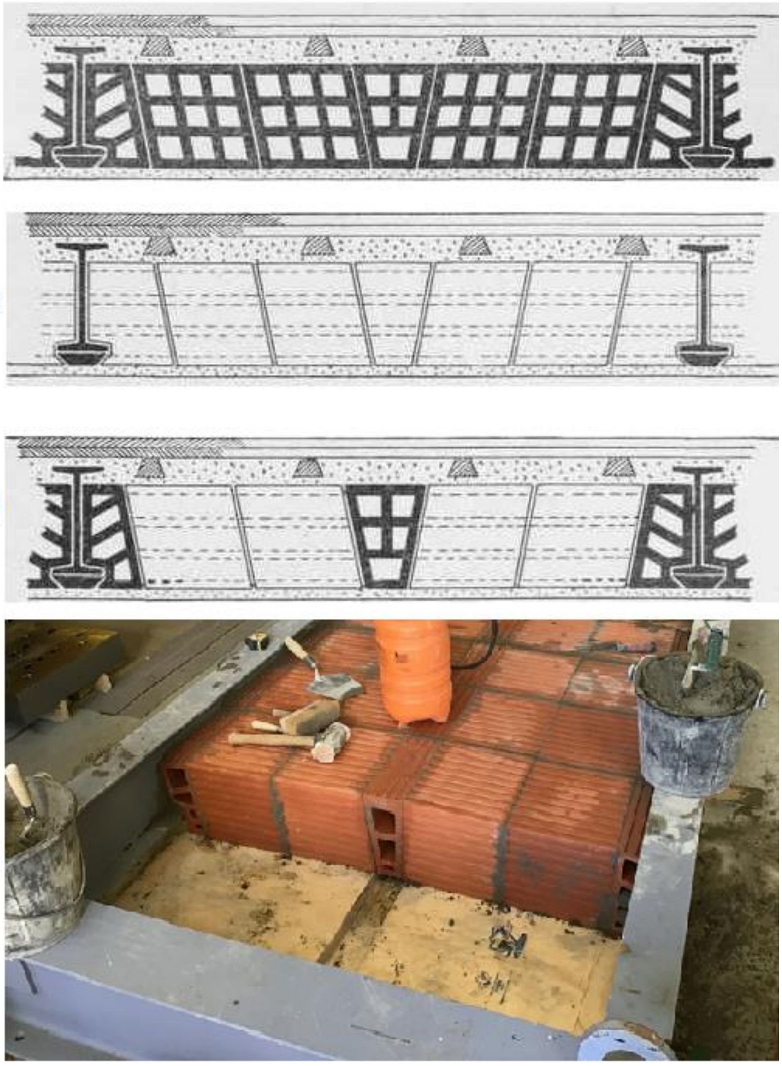


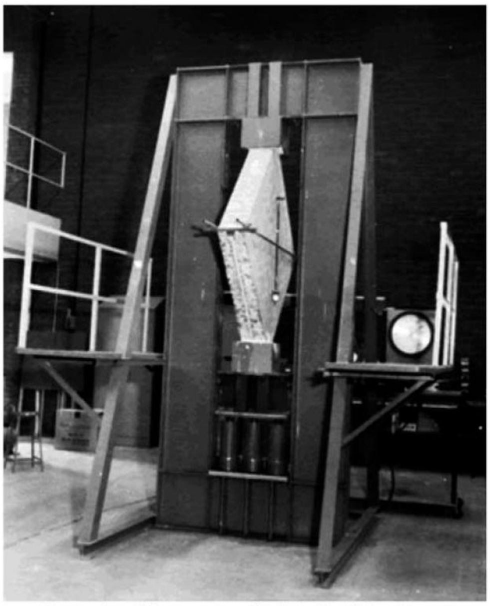
Fig. 2 – Types of terracotta flat arch construction: a) Side construction, b) End construction, c) combination of Side and End construction [2], and d) a sample of terracotta floor constructed in the NRC's structural lab

There are three construction methods for flat arch floors using terracotta tiles, namely: Side construction (see Fig.2-a), in which tiles are arranged so that the webs are parallel to the beams; End construction (see Fig.2-b) in which tiles are typically placed end to end, thus providing greater resistance to the thrust by creating a sequence of continuous webs from beam to beam; and combination of Side and End construction as shown in

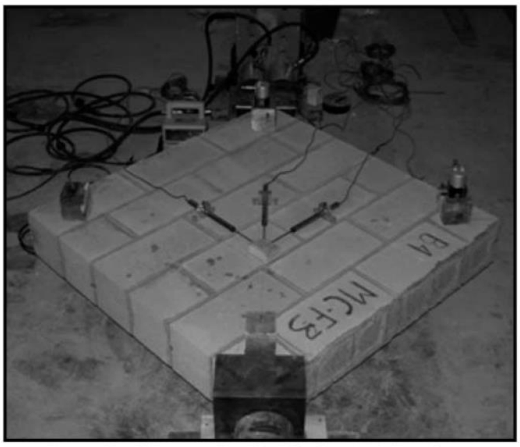
Fig.2-c) [2]. Fig.2-d) shows a sample of floor diaphragms constructed in the NRC's structural lab, which is representative of the construction method (combination of Side and End construction) in the Centre Block which consists of two skews, four lengtheners and a key for single panel specimens.

2.2 Challenges for Using Existing Testing Methods

In order to study the formation of the compression struts in the terracotta floor diagrams, single-panel test setups have been designed. To determine the diagonal tensile or shear strength of masonry assemblages, the standard practice uses square samples compressed along the diagonal axis, according to ASTM E519-15 [3]. This test results in tension failure with the specimen splitting apart parallel to the load direction, Fig. 3 presents examples of the typical vertical and horizontal test setups.



Example of Apparatus for Vertical Specimen



Example of Apparatus for Horizontal Specimen

Fig. 3 – ASTM E519-15 apparatus for determination of diagonal tensile or shear strength of masonry assemblages [3]

Samples loaded as per ASTM E519 typically form a compressive strut along the load, however this method cannot be used for the terracotta flat arch floors without modification. A new modified test setup instead of ASTME519-15 is proposed here to test terracotta floors to replicate their as-is condition, since they form a flat arch between steel beams. In addition, the proposed setup, as described in the next section, allows assessment of the floors with and without superimposed dead loads.

3. Full-Scale Flat Arch Terracotta Diaphragm Tests

In order to assess the seismic behaviour of existing flat arch terracotta diaphragms in the Centre Block, both single-panel and multi-panel frame test setups are developed. In this paper, only the single-panel frame tests are discussed.

3.1 Single-Panel Frame Test Setup

The single-panel frame test setup for terracotta flat arch diaphragms consists of three components, namely the loading frame and the actuator, the reaction frame, and the test sample that is placed between the loading frame and the reaction frame, as demonstrated in Fig. 4, (side view) and Fig. 5, (plan view).

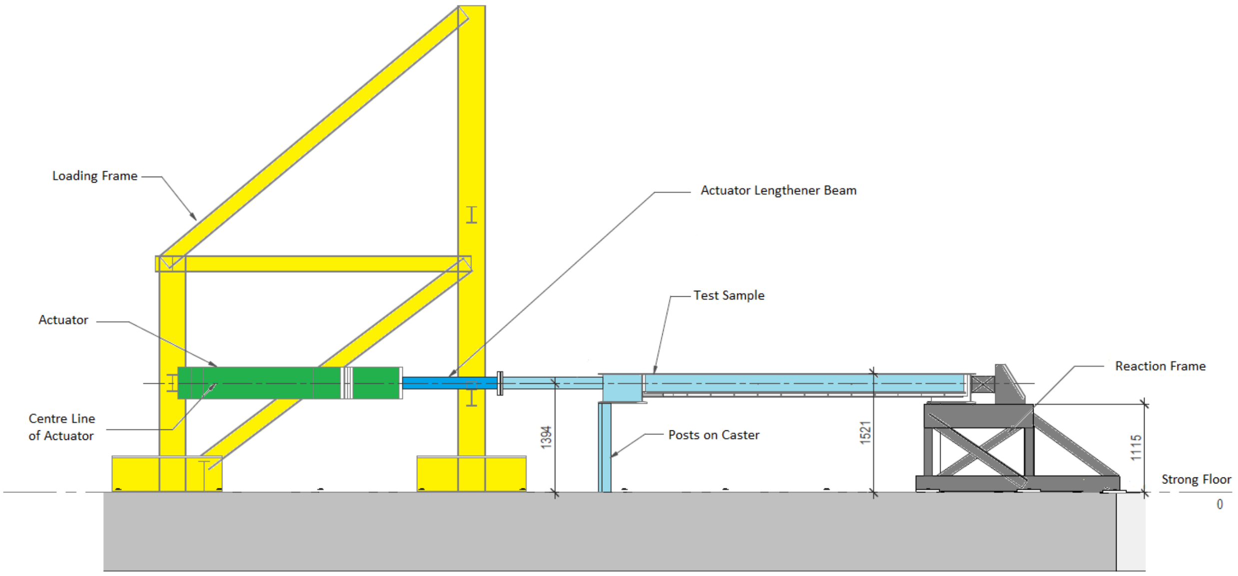


Fig. 4 – Single panel diaphragms test setup – side view [4]

Three corners of the test samples are supported on three posts with casters allowing free movement in two horizontal directions while the fourth corner is seated on the reaction frame restricting the movement in the horizontal plane. The test samples are placed at about five feet above the strong floor of the lab to provide visual access to the underneath of the samples during the test. This setup will make it possible to assess the damage progress that occurs at the top and bottom of the floor system being tested.

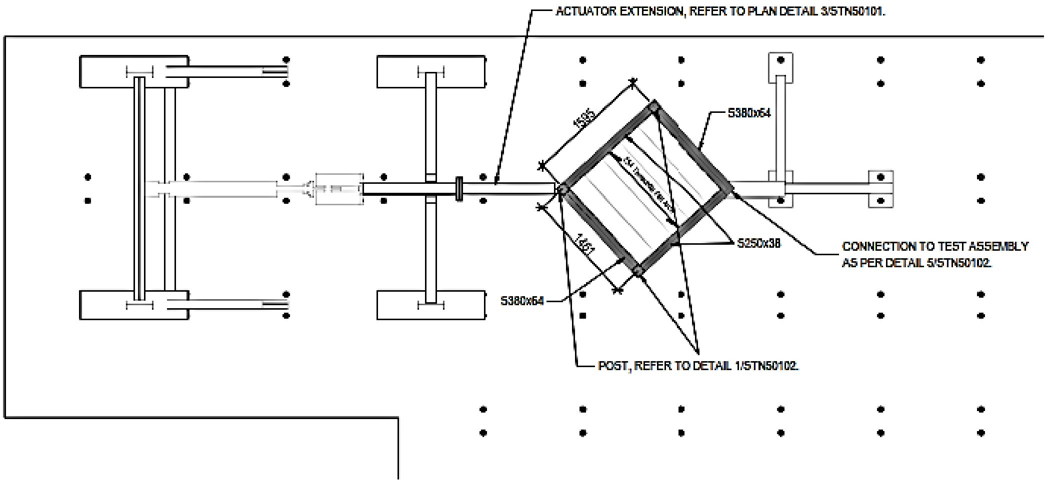


Fig. 5 – Single panel diaphragms test setup – plan view [4]

3.2 Test Samples

In order to replicate the flat arch terracotta floors as constructed in the Centre Block, sample tiles have been extracted as shown in Fig.6. A manufacturer in the United States has been retained by PSPC to produce the same shape and size of different terracotta tiles, including the skews, lengtheners, and the keys. It should be emphasized that the exact composition of tiles, and the method of construction in the early 1900s, are unknown. The new tiles are fabricated using the vacuum extrusion process, whereas at the time of construction of the original tiles, the extrusion process didn’t have the vacuum aspect. This difference results in tile with higher density and strength in the new tiles. Various material testing will be performed on both the new and old tiles in order to calibrate the results of the full scale tests.

Fig. 6 – Extracted terracotta tiles from the Centre Block

A single-panel test sample constructed using the new tiles in the NRC's structural lab was placed in the setup as shown in Fig.7. The test samples were instrumented to measure axial strains in the steel beams, corner displacements, as well as displacements transferred to the terracotta tiles.

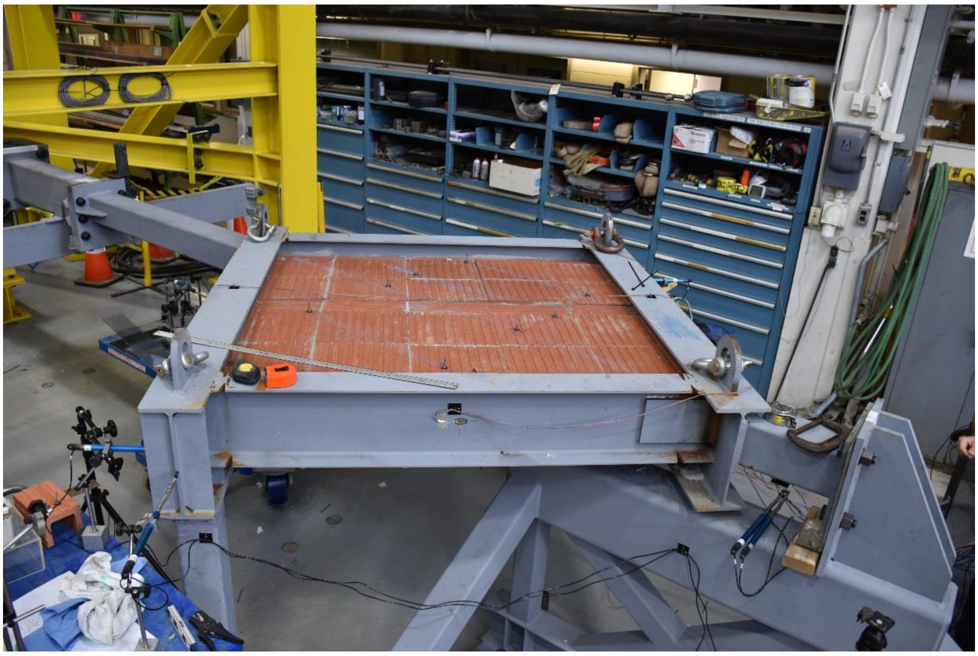


Fig. 7 – Test sample S1 in the test setup in the NRC's structural lab

In total, six full-scale samples will be tested in order to assess the seismic performance of single-panel terracotta diaphragms. These six samples are three pairs with different length-to-width (L/W) ratios, constructed to assess the effect of the arching actions on the shear strength and behaviour of these floor diaphragms. Specification details of these samples are provided in Table 1. The dimensions of these test samples are resultant of the dimensions of the existing terracotta tiles of typical floors of the Centre Block. The size of samples S1, S2 and S3 are intended to study the effect of the L/W ratio on this type of floor construction. While sample S1-C is to be tested under cyclic loading as described in the following section 3.3, and without additional gravity load, sample S1-M is to be subjected to monotonic loading. Both samples S2-CG and S3-CG are to be loaded with a gravity superimposed loading of 4.0 kPa to replicate the weight of exiting topping and finishes on typical floors in the Centre Block. Samples S2-C and S3-C are to be tested without any superimposed gravity loads.

Table 1 – Specification details of the single-panel test Samples

Sample ID	Width (mm)	Length (mm)	L/W Ratio	Lateral Loading	Gravity Loading
S1-C	1,461	1,595	1.1	Cyclic	No
S1-M	1,461	1,595	1.1	Monotonic	No
S2-C	1,461	3,485	2.4	Cyclic	No
S2-CG	1,461	3,485	2.4	Cyclic	Yes
S3-C	1,460	4,430	3.0	Cyclic	No
S3-CG	1,460	4,430	3.0	Cyclic	Yes

3.3 Loading Protocols

Testing of the terracotta diaphragms under cyclic loading followed a quasi-static loading protocol. This type of test permitted a conservative assessment of the seismic response of the diaphragms, specifically in terms of strength, displacement capacity, and accumulation of damage. This is due to the fact that quasi-static loading of unreinforced masonry materials provides a lower bound estimate of the capacity, while in a real earthquake with higher loading rate, the strength of material is higher. Recorded strength-deformation will provide the design team with the component relationship required for seismic assessment of the diaphragms and design of retrofitting alternatives (if required). Understanding the failure mechanism will facilitate the evaluation of any potential risk associated with the damage of terracotta tiles and the identification of mitigation alternatives. Given that the focus of the testing program is on the quasi-static response rather than the dynamic response of the terracotta diaphragms, dynamic testing has been disregarded at this stage.
Both FEMA 461 – Interim Protocol I [5] (as shown in Fig.8-(a)) and loading protocol developed by Mergos and Beyer [6] (as shown in Fig.8-(b)) were found to be suitable for testing the terracotta diaphragms due to the following reasons:

- Both protocols are expected to capture the strength-displacement response and failure mode of the terracotta diaphragms since the main interest of the testing program is to investigate different damage states associated with relative deformations.
- Both protocols are deemed applicable to structures in regions of moderate to high seismicity. FEMA 461 is expected to impose more damage given its development was based on earthquake records for regions of high seismicity.
- Neither of these protocols prescribes a cyclic sequence related to the ductility of the components. Therefore, incorrect determination of the reference parameter will not result in misleading results.
- Both protocols permit testing the terracotta diaphragms to failure even if the ultimate displacement is greater than the targeted maximum displacement.
- Both protocols are expected to result in more conservative estimates of the strength-displacement response compared to the expected response to near-fault or monotonic loading protocols.
- Both protocols are applicable to any building material and structural elements, including components sensitive to relative displacement such as the terracotta diaphragms investigated in this study.

The protocol proposed by Mergos and Beyer is found to be more suitable for moderate seismicity [6]. Since the seismicity of Ottawa has been classified as moderately high, this loading protocol is to be used for testing of the single-panel samples.

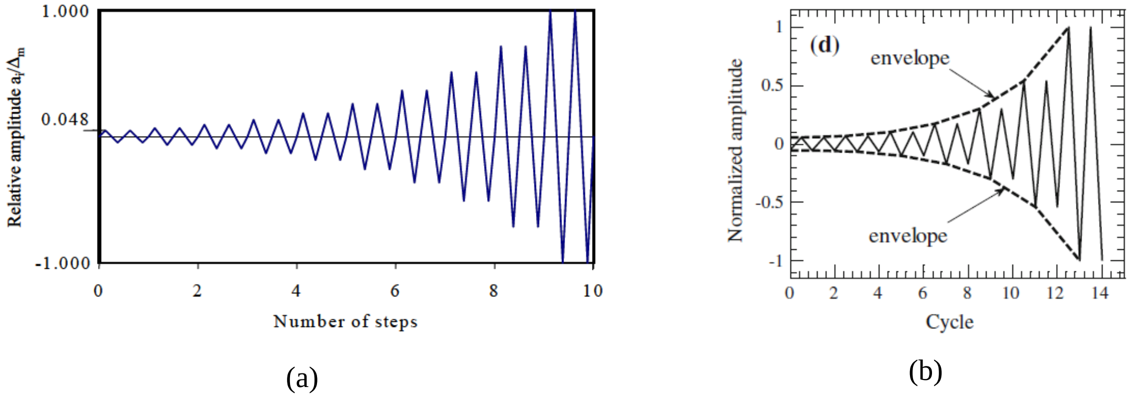


Fig. 8 – Quasi-static cyclic loading protocols: (a) FEMA 461 [5], and (b) Mergos and Beyer [6]

The rate of quasi-static loading should be in the range of static loading between 10^{-6}/s to 10^{-4}/s. Details of the protocols used for testing the terracotta diaphragms are provided in the following.

Loading protocol for single-panel diaphragms

Cyclic loading is applied on single-panel diaphragms per the loading protocol shown in Fig.9. The cyclic loading protocol is based on Mergos and Beyer [6]. This loading protocol is developed by CENTRUS based on the estimated yield displacement . Displacements are applied on the samples at a rate of 0.1 mm/s up to the 6th cycle, then the displacement rate is increased to 0.2 mm/s for the remaining cycles. It should be noted that for S1-C, both S2, and S3 samples, the unloading stage has been performed to zero force rather than zero displacement, as may be inferred from Fig.9. In addition, S1-C sample is loaded for each interval of the displacement starting from the residual displacement of the last cycle, which can be observed in Fig.10.

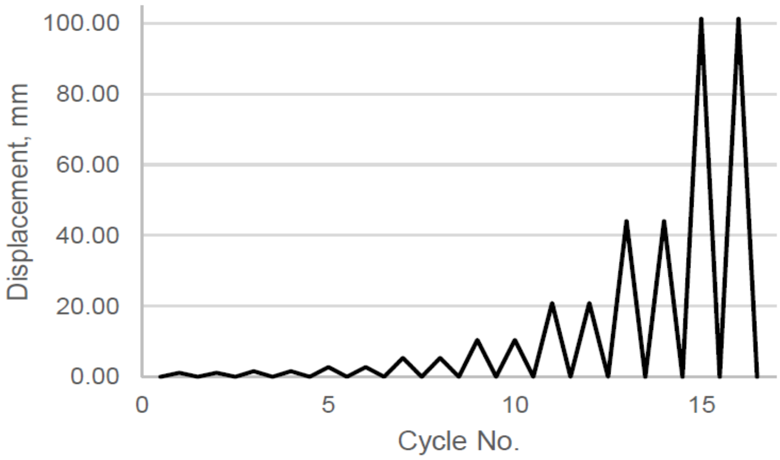


Fig. 9 Cyclic loading protocol for single-panel diaphragms

3.4 Results

Fig.10 shows the load versus displacement curves obtained from the test sample S1-C. This test was performed without any superimposed dead load and under cyclic loading. The unloading of the samples was done to zero force in order to prevent any direct tension in both the sample and the reaction frame.

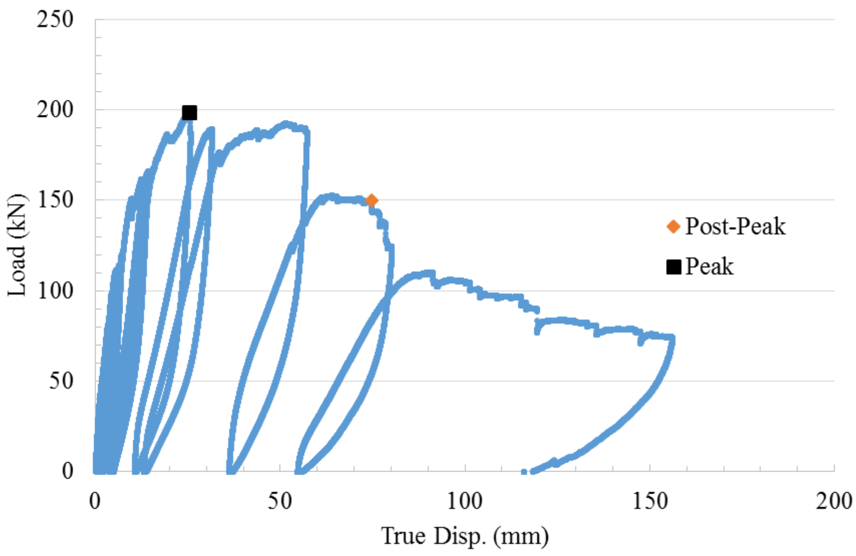


Fig. 10 Load-displacement response for sample S1-C under cyclic loading

As can be observed in Fig.10, there is significant stiffness and strength degradation resulted from the cracking of the terracotta tiles. During the test, most terracotta tiles were crushed upward as they were compressed, and forming arching action between the steel beams. Large displacements were possible to be applied on the sample without total loss of integrity of the diaphragm, due to the confinement provided by the steel beams on four sides of the sample. However, it was noticed that debris from damaged tiles and mortar grouts started to fall off the sample at smaller displacements. After the last cycle, the bare steel frame was also tested to obtain the contribution of the steel frame alone to the total resistance of the whole assembly. Fig.11 shows the deformed shape of sample S1-C reported at the peak load and a post-peak load of 150.8 kN, where a plateau in the load versus displacement curve for this test can be observed (see Fig.10).

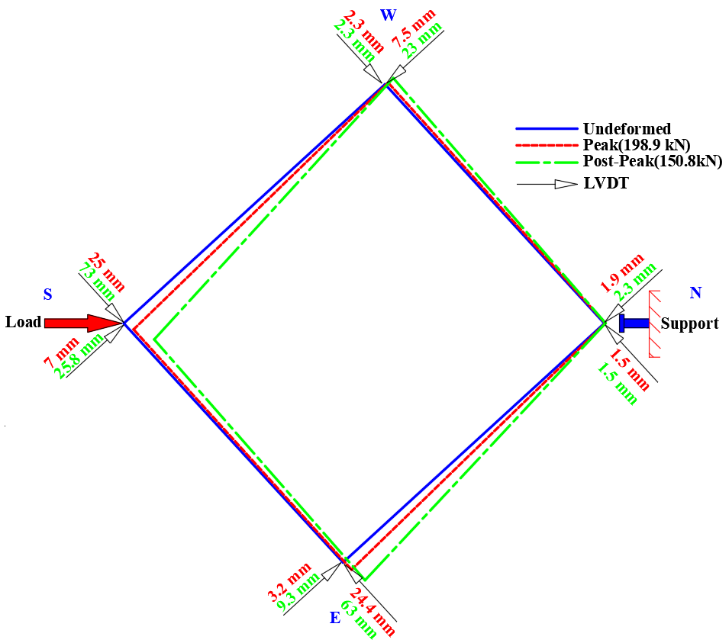


Fig. 11 Deformed shape of sample S1-C – plan view

Although the reaction frame was designed to restrain rotation, the samples pivoted about the support point when subjected to large displacements. This behaviour can be observed in the post-peak deformed shape as shown in Fig.11.

4. Summary

The Centre Block of the Canadian Parliamentary Buildings is at the start of a major rehabilitation project. The seismic retrofit of the existing building structure is a key component of this project. In order to propose the most efficient retrofitting strategy by the design team, a better understanding of the seismic performance of existing terracotta flat arch diaphragms is required. The existing floor stiffness, capacity and ductility to transfer lateral loads by diaphragm action, play a significant role in the seismic performance of the building.

In order to assess the seismic performance of the existing flat arch terracotta diaphragms in the 100-year old Centre Block of Canadian Parliamentary Buildings, a new test setup has been proposed. Several full-scale tests have been conducted and many more are in progress to be conducted on samples representing the as-is condition of floor diaphragms of the Centre Block Building. Preliminary results of the floor diaphragms tested to date, demonstrate large displacement capacity when the samples are only loaded in compression. Nonetheless, unreinforced brittle terracotta tiles tended to crack and produce debris even under small deformations.

5. Acknowledgements

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