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Experimental Seismic Performance Assessment of Existing Multi-Panel Flat Arch Terra Cotta Floor Diaphragms

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Abstract:

As part of a major rehabilitation project on the Centre Block of Parliamentary Buildings of Canada, an experimental investigation of the seismic behaviour of its existing terra cotta flat arch diaphragms is performed at the National Research Council Canada (NRC). Terra cotta flat arch diaphragms are a brittle floor system 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 to seismic loads has not been well assessed. An experimental program was needed to obtain data that will support the consulting design team in assessing the existing seismic performance of the floor diaphragms, as well as selecting appropriate retrofitting strategies for rehabilitating to meet the design objectives in mitigating seismic hazards. The overall testing program included obtaining samples of existing 100-year-old terra cotta tiles and determining material properties and exact physical dimensions of tiles. This information was needed to replicate existing tiles to be used in full-scale samples. To study the seismic performance of existing terra cotta flat arch diaphragms, several tests were performed on tiles, mortar mixes, tiles assemblies, and full-scale single-panel and multi-panel frames infilled with terra cotta tiles. Several single-panel and multi-panel samples were tested with different length-to-width ratios to resemble different on-site conditions. The single-panel frames were loaded diagonally under quasi-static loads, while the multi-panel frames were loaded laterally under cyclic loading. In this paper, the experimental results from the testing of multi-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. Three multi-panel frames are tested with overall dimensions of approximately 4.5 m × 4.5 m. Testing is conducted to establish the capacity and behaviour of sliding shear within the terra cotta arches. The testing results of the multi-panel frames including peak and post-peak states of the frames, load-displacement response, and the sliding shear capacity are discussed.

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

1 Introduction

The construction of the terra cotta flat arch floor system was common in steel structures during the early 1900s, consisting of an arrangement of terra cotta blocks in a flat arch supported by steel beams and tie rods. These terra cotta blocks were stacked in an arched structure spanning between the supporting beams. The terra cotta blocks were produced by molding and firing a mixture of clay and water in a kiln, producing a strong, dense material that could withstand moisture and heat. Despite being replaced by modern construction methods, including reinforced concrete slabs and precast concrete panels, this technology is still found in historic buildings, providing a fascinating look into early 20th-century building techniques. This system gained popularity among office, commercial, and industrial buildings due to its fire resistance, durability, and sound-proofing qualities. Due to its mass and rigidity, this floor system did also perform well under vibration loads. However, the seismic performance of this floor system has not been well studied.

Sitting on an escarpment that overlooks the Ottawa River, the Canadian Parliamentary Buildings comprise the Centre Block, the West Block, and the East Block, encompassing three sides of the Central Lawn on Parliament Hill. The Centre Block is home to the House of Commons and Senate Chambers, along with the hall of honour, memorial chamber, confederation hall, and the offices of several members of parliament. Originally built in 1859, the Centre Block was consumed by a fire in 1916, except for the Library of Parliament located on the northern side. Reconstruction started immediately after the fire and was finalized by 1920, with the Peace Tower being completed by 1927. Presently, the Centre Block is undergoing significant rehabilitation work, with Public Services and Procurement Canada (PSPC) overseeing the Crown's interest in the project. This is the largest, most complex heritage rehabilitation project ever seen in Canada and is one of the largest in the world [1].

The Centre Block is a six-storey high structure with unreinforced masonry load-bearing on the perimeter and a combination of masonry walls and steel columns on the interior. The floor systems are primarily composed of steel beams, which support a flat terra cotta arch system that includes tie rods between the beams. Previous seismic evaluation studies have determined that the building does not meet current seismic requirements for Ottawa, as per the requirements of the National Building Code of Canada (NBC). One crucial aspect of the seismic upgrading of this building was the research needed on the performance of the terra cotta floor system.

As part of the current condition assessments of the building, PSPC engaged the National Research Council Canada (NRC) to evaluate, in collaboration with the consultant design team (CENTRUS), the seismic performance of existing terra cotta flat arch floor diaphragms, through different material and large-scale test setups. These tests were intended to provide material properties of the terra cotta tiles, the mortar, and their assembly, as well as the seismic performance of the terra cotta flat arch floor diaphragm system. In this paper, sample results from the full-scale multi-panel tests are presented and discussed.

To study the seismic performance of existing terra cotta flat arch diaphragms, several tests were performed on tiles, mortar mixes, tiles assemblies, and full-scale single-panel and multi-panel frames infilled with terra cotta tiles. Several single-panel and multi-panel samples were tested with different length-to-width ratios to resemble different on-site conditions. The single-panel frames were 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 multi-panel frames are presented [3].

2 Terra Cotta Flat Arch Floor Diaphragms

2.1 Existing Floor Construction

To replicate the flat arch terra cotta floors constructed in the Centre Block, sample tiles were extracted, as illustrated in Figure 1. PSPC engaged a manufacturer in the United States to produce similar-sized terra cotta tiles, including skews, lengtheners, and keys. However, it should be noted that the exact composition of the original tiles and the construction method used to make the tiles in the early 1900s are unknown. The new tiles are fabricated using the vacuum extrusion process, which was not used during the construction of the original tiles, resulting in higher density and strength in the new tiles. Various material testing was carried out on both the old and new tiles to calibrate the results of the full-scale tests.

Figure 1. Extracted terra cotta tiles from the Centre Block

Figure 1 shows the original sample tiles from Centre Block assembled, and Figure 2 shows a sample of floor diaphragms constructed in the NRC's structural lab, which is representative of the construction method used in the Centre Block. This method of constructing the flat arch consists of two skews, four lengtheners, and a key tile within each panel of the specimens. Skews are placed on either end of the flat arches; 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 panel. The lengtheners are the intermediate tiles found between the key tile and skew tiles [2]. Each multi-panel specimen for this experiment consists of three panels to replicate the typical bay in the Centre Block (see Figure 2).

Figure 2: A sample of a multi-panel terra cotta floor constructed in the NRC's structural lab

In the NRC structural lab, three multi-panel terra cotta flat arch diaphragms were constructed to represent the floor system in the Centre Block in its as-is condition. These diaphragms, named MB1, MB2, and MB3, are full-scale and have identical dimensions of 4,135 mm by 4,381 mm. While MB1 was loaded perpendicular to the joist direction, MB2 and MB3 were loaded parallel to the joists. Figure 3 shows the layout of testing for MB1. Notably, MB3 was built with a gap between the first and last course of terra cotta (skew) tiles to simulate a common condition found on-site, where constructing the arch to be tight between the beams would require specific tile sizes or spacing between the joist beams. The average mortar strength for the three multi-panel samples are provided in Table 1.

Table 1. Terra Cotta Tile Mortar – Compressive Strength

Sample Mortar	Compressive Strength (MPa)	
	@ 28 days	@ Testing day
MB1 (twelve samples)	16.6 [1.1]	18.2 [2.6]
MB2 (fifteen samples)	18.6 [1.8]	20.3 [1.2]
MB3 (twelve samples)	10.7 [3.2]	10.3 [3.2]

[1] Numbers in [ ] represent the standard deviation in MPa.

2.2 Test Setup

In this study, the test setup design consists of four main components in order to assess the seismic performance of terra cotta flat arch diaphragms, as shown in Figure 3. These components are 1) the yellow-highlighted reaction frame, 2) the light blue-highlighted support frame, 3) the grey-highlighted floor specimen, and 4) the green-highlighted actuator. The test setup is capable of subjecting the floor diaphragm to cyclic in-plane shear, similar to those experienced during strong ground motion. The floor specimen is positioned approximately 1,500 mm above the strong floor, allowing for observation of falling hazards resulting from terra cotta tile crushing, as well as assessment of damage levels during testing both from above and below the floor. The floor specimens are free to slide along the actuator line, while they are restrained in all three axes at the other two corners to subject the floor diaphragms with in-plane shear loading.

A variety of sensors were utilized on the test setup to measure different displacements, forces, and strains. Laser displacement sensors and linear variable differential transformers (LVDTs) were used to measure different components of the displacement of the multi-panel samples at four corners, as well as the deformation of the supporting and loading frames. Load cells were used to measure the applied force from the actuator and the force induced in the tie rods. While steel beams and tie rods were equipped with strain gauges to record axial deformations.

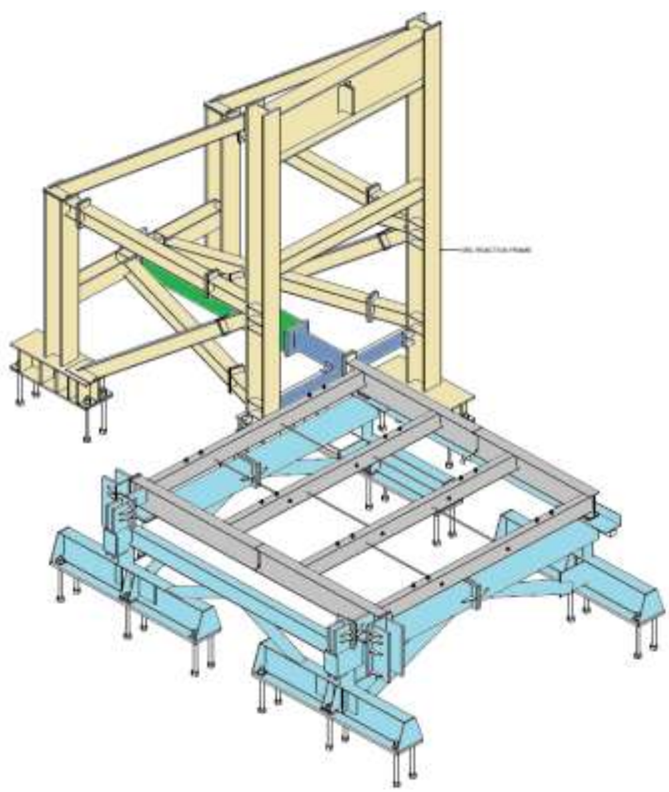

Figure 3. Multi-panel test setup for MB1

2.3 Loading Protocols

The testing of the terra cotta diaphragms under cyclic loading followed a quasi-static loading protocol. This method provides a lower bound estimate of the diaphragms' seismic response in terms of strength, displacement capacity, and accumulation of damage. Quasi-static loading of unreinforced masonry materials yields a lower bound estimate of capacity, which is a conservative approach, as the strength of the material is higher during a real earthquake with a higher loading rate. The recorded strength-deformation data will provide the design team with the required component relationship to assess the seismic performance of the diaphragms and design retrofitting solutions, if necessary. Understanding the failure mechanism will assist in evaluating any potential risk associated with terra cotta tile damage and identifying mitigation alternatives.

Both FEMA 461 – Interim Protocol I [4] (as shown in Figure 4 (a)) and the loading protocol developed by Mergos and Beyer [5] (as shown in Figure 4 (b)) were found to be suitable for testing the terra cotta diaphragms due to the following reasons:

- Both protocols are expected to capture the strength-displacement response and failure mode of the terra cotta 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 of the terra cotta diaphragms to failure even if the ultimate displacement is greater than the targeted maximum displacement.
- Both protocols are expected to result in lower bound estimates of the strength-displacement response compared to the 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 terra cotta diaphragms investigated in this study.

The protocol proposed by Mergos and Beyer is found to be more suitable for moderate seismicity [5]. Since the seismicity of Ottawa has been classified as moderately high, this loading protocol is used in the testing of the multi-panel samples.

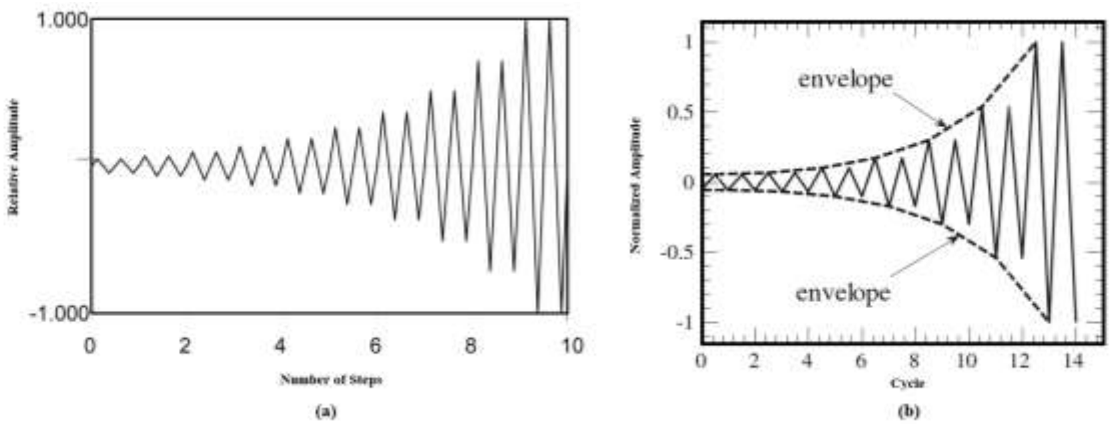

Figure 4 Quasi-static cyclic loading protocols: (a) FEMA 461 [4], and (b) Mergos and Beyer [5]

Cyclic loading is applied on the multi-panel diaphragms per the loading protocol shown in Figure 5. The cyclic loading protocol is based on Mergos and Beyer [5]. There are fifteen cycles in this loading protocol that was applied on the multi-panel samples. Seven pairs of complete cycles were provided for the multi-panel samples based on the expected peak displacement estimated by the design team. The last cycle is a ± 200mm displacement based on the maximum stroke of the actuator and the location of the sample setup. Displacements were applied at a constant rate of 0.2 mm/s to achieve a quasi-static loading condition.

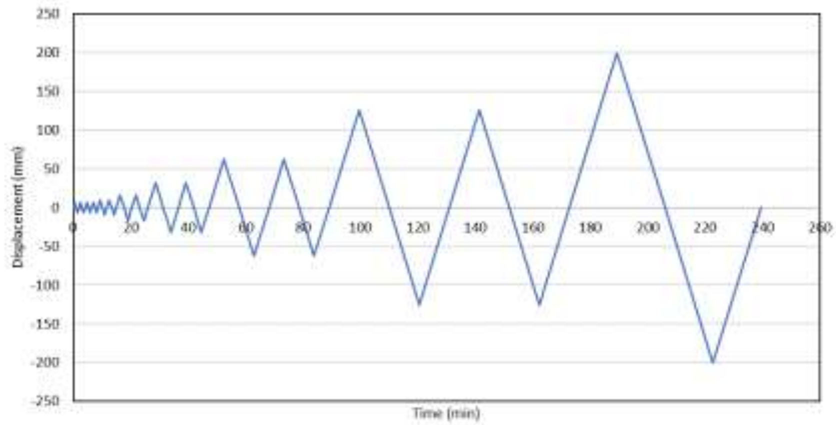

Figure 5. Loading protocol for multi-panel samples

3 Results

3.1 Mode of failure

The original expectation was that the terra cotta flat arch diaphragm would behave similarly to infill masonry frame structures when subjected to in-plane shear deformation. In such structures, the infill masonry forms a compressive strut while the columns and beams are in tension. However, several observations from both single-panel and multi-panel tests showed that the terra cotta flat arches slide along the mortar joints as the main mode of failure when subjected to in-plane shear forces, and no significant axial forces were recorded in the surrounding steel beams (see Figure 6).

Figure 6. Post testing MB1 sample, after the removal of weights

Moreover, the single-panel tests revealed that the strength of the floor diaphragms depends on the amount of super-imposed dead load on the floor. This is mainly due to the fact that the super-imposed dead loads increase the friction along the mortar joints due to the arching action of the terra cotta tiles. As a result, the greater the super-imposed dead load on the floor, the stronger the diaphragm becomes. These observations suggest that the behaviour of terra cotta flat arch diaphragms under in-plane shear forces is different from what was originally anticipated and should be taken into consideration in the design of retrofit options. The superimposed dead loads were applied on all multi-panel samples using steel weights.

During larger deformation cycles, the corners of each panel exhibited terra cotta tile crushing, leading to debris falling from the floor soffit. Initially, the floors were pushed upward due to arching actions, but as damage accumulated over cycles, the camber of the floors upon returning to their at-rest state was reduced compared to their undamaged condition.

3.2 Force-Displacement curves

The force-displacement responses of the multi-panel terra cotta diaphragm for sample all three samples (MB1, MB2, and MB3) subjected to in-plane reversed cyclic loading, are shown in Figure 6. It should be noted that on all three samples, a superimposed gravity load of 4.0 kPa using the steel load blocks was applied to replicate the existing condition on site.

As previously stated, sample MB2 is the same as sample MB1 but with a 90-degree rotation. Although the response of MB1 was largely symmetrical and reached a maximum capacity of approximately 250 kN, MB2 has a greater capacity under compression cycles (negative force ~260 kN) than under tension cycles (positive force ~220 kN), as shown in Figure 6. Both MB1 and MB2 exhibit significant damage accumulation and structural softening, leading to hysteresis loops with a pinched shape in their force-displacement curves.

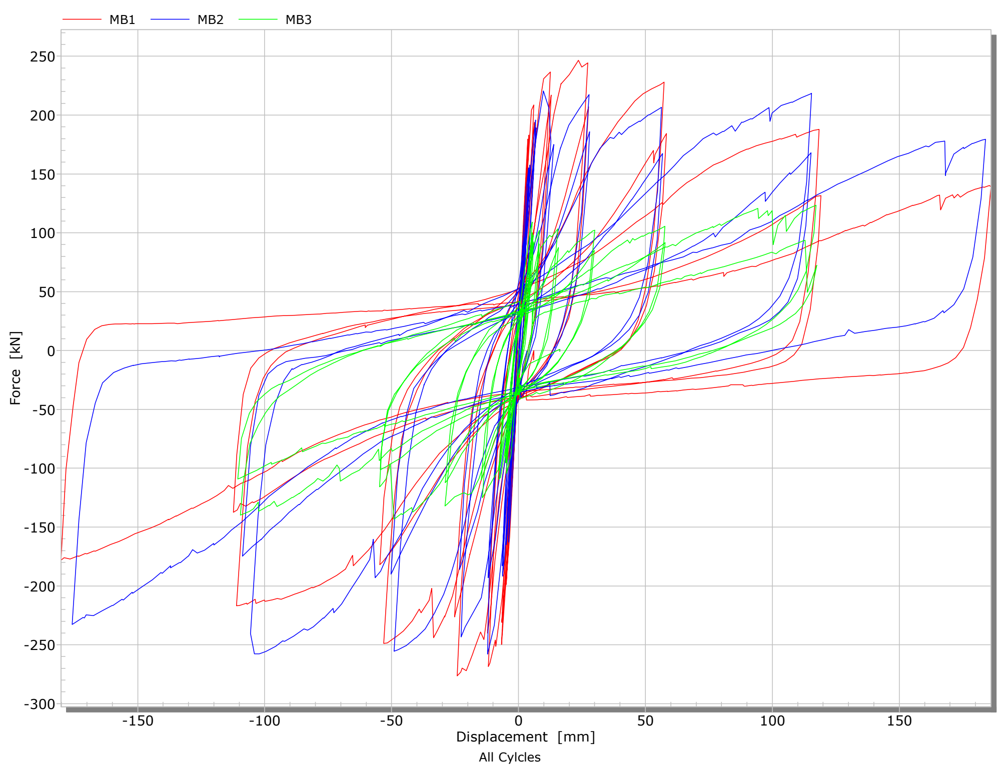

Figure 7. Force-displacement curves for multi-panel tests

The MB3 sample is identical to MB2; however, it was constructed with a gap between the first and last course of terra cotta tiles to represent localized as-is conditions found on site. As shown in Table 1, the MB3 sample had also lower mortar compressive strength compared to values for MB1 and MB2. In addition, a few of the tie-rods of MB3 were installed with a deficient welded extension on the exterior panels. Figure 8 shows one of these failed tie-rods during the test. Due to the combination of the aforementioned deficiencies, the MB3 sample experienced a partial failure of the slab, as shown in Figure 9. The capacity of MB3 is much lower in both compression and tension (roughly 120 kN in tension, and 140 kN in compression) compared to MB1 and MB2 as can be seen in the force-displacement curves shown in Figure 7.

Figure 8. Tie-rod failure in multi-panel test MB3

Figure 9 Failure of multi-panel test MB3

4 Summary

The Centre Block of the Canadian Parliamentary Buildings is currently under a major rehabilitation. This is the largest, most complex heritage rehabilitation project ever seen in Canada and is one of the largest in the world. The seismic retrofit of the existing building structure is a key component of this project. In order to propose the most efficient retrofitting strategy for the design team, a better understanding of the seismic performance of existing terra cotta flat arch diaphragms was 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.

A testing program was proposed to assess the seismic performance of the existing flat arch terra cotta diaphragms in the 100-year-old Centre Block of Canadian Parliamentary Buildings. Several full-scale tests were conducted. The results of the multi-panel floor diaphragms demonstrated large displacement capacity while severe pinching was observed in the force-displacement curves. Nonetheless, unreinforced brittle terra cotta tiles tended to crack and produce debris even under small deformations.

The main failure mode was observed to be the sliding along the mortar joints, with the super-imposed dead load playing a role in the lateral strength of the floor diaphragms under in-plane shear forces due to an increase in friction along the mortar joints. It was identified that the mortar strength, the gaps in the terra-cotta floor system, as well as deficiencies in the ties at end bays can have a significant impact on diaphragm capacity and performance. This should be considered both in determining the existing capacities of the diaphragm system under cyclic loading as well as when developing retrofit strategies.

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