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Structural performance of water tank under static and dynamic pressure loading

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ABSTRACT

The structural performance of water tank under static and dynamic pressure loading was experimentally investigated in this paper. The loading was applied using hydraulic actuator/dropped projectile on an inflated high pressure airbag to assert static/dynamic pressure on the specimens. The failure modes and maximum resistance of the specimens were obtained from the test and compared to the numerical results. It was found from the static pressure test that the water tank filled with water exhibited up to 31% increase in flexural resistance under static loading as compared to the empty water tank with the same material and geometry. The improvement was attributed to the effects of water in maintaining the section modulus and delaying the local buckling of the tank. Water was also found to be useful in reducing the deformation of the tank under dynamic pressure loading. Nonlinear finite element analysis was conducted to investigate the behavior of water tank subject to static and dynamic pressure loading and the accuracy of the numerical models was verified by comparing the predicted displacement responses with those observed from the tests.

1. Introduction

In recent years, it has become more apparent that extreme events and threats related to blast loading are on the rise even for non-critical buildings and infrastructures. These have sparked the need for blast resistant design or retrofitting of existing buildings and infrastructures. However, the probability of blast occurrence on structures is considered low particularly for non-critical infrastructures. Hence, it would be more appealing if the blast-resistant design could be integrated with other aspects of the buildings' operations, such as solar thermal shielding or energy harvesting. An innovative water storage façade shaped in the form of thin steel tank has been proposed by the authors [1] with an aim to harvest solar energy and reduce thermal heat penetration into buildings for routine use and it also serves as an effective protective layer in the event of blast to achieve its multi-functional use. This paper investigates the structural performance of water tank under static and dynamic pressure loading to extend its use as blast resistant façade to be attached to the external of the building.

The use of water to mitigate blast energy has been quite extensively researched through experimental and numerical methods [2–8] and significant reduction of peak pressure and impulse was observed especially when the water was stored close to the explosive. The underlying principle is that the high pressure shock wave aerosolizes the water and causes both a phase change of water and redistribution of internal and kinetic energy over the detonation gases, blast wave and barrier material [8]. The aforementioned researches on blast wave mitigation using water were based on the scenario where water was directly exposed to blast wave while there are minimal reported works on the effects of confined water in the open literature. Even though the aforementioned mitigation principle would not apply on confined water, the structural performance could still be improved due to added mass and improved load distribution. The effects of water on the structural response of the blast barrier water façade were tested under both static and dynamic pressure loadings in order to demonstrate and understand the water effects on the structural response.

Static pressure test can be conducted by applying the static load via a water pressure chamber [9] or an inflated airbag [10,11]. In the current study, the inflated airbag method was adopted since it is easier to operate. For dynamic pressure loading, field blast test may be used to generate high pressure load over a short duration

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[12–17]. Such test is generally expensive and requires remote testing site. The shock tube method, which is comparably less costly and can be better controlled, has been used to simulate the blast loading though restricted by the specimen size and relatively longer loading duration as compared with field blast test for most cases, especially for the close-in detonation [18,19]. Mostaghel [20] developed a simple non-explosive test to generate dynamic pressure loading using a membrane formed inflated airtight chamber mounted to a frame system. A plate was dropped onto the membrane from various heights to achieve the required impulse magnitude and duration. The method was later adopted by Chen and Hao [21] and the airtight chamber was replaced with inflated airbag to apply impulsive loading on multi-arch double layered panels. Remennikov et al. [22] has also extended this method to test column under impulsive loading. In the present study, the inflated airbag loading method was also applied in the dynamic pressure test on the water tanks.

This paper starts with a description on the performance of water tank under static pressure load, following by its performance under dynamic pressure load. Besides the experimental study, Finite Element (FE) method was also adopted to simulate the test and the experimentally-verified FE model was further used to study the behaviors of water tank under blast loading.

2. Static pressure load test

2.1. Design of specimens

Stainless steel (SS316) tanks with and without infilled water were investigated to study the influence of water on the resistance of the steel tank structure. Two stiffeners with cut-out holes for water flow were welded to the top and bottom plates and the tank was enclosed by four side plates. As seen in Fig. 1, a 20 mm (¾”) inlet pipe and an outlet pipe of the same size, both with threaded plug, were provided so that the water tank can be filled with water before test. For comparison purpose, the pipes were also included in the empty tank. The schematic drawings of the empty tank (SES) and water filled tank (SWS) are shown in Fig. 2 and the details are summarized in Table 1.

2.2. Test setup and instrumentation

The water tank was proposed as one type of water storage façade, which can be installed on the outer skin of the building to achieve energy saving and blast resistance functions. Attaching the water storage façade to the edge beams of the building in a simply-supported manner is a convenient way of installation. Hence, the simply-support boundary condition was adopted in the static pressure loading test setup. As shown in Fig. 3, the specimen was simply-supported at both ends by two 80 mm (diameter) round bars and the clear span between the bars was 900 mm. The load was applied at the mid-span point through an inflated airbag which was placed on top of the test specimen via a 1000 mm × 1000 mm × 30 mm thick transfer steel plate. The distance between the transfer plate and the specimen was kept at 120 mm throughout the test. To load the specimen, the airbag was continuously charged using a compressed air pump so that the inflating airbag, which was restrained at the top by the fixed transfer plate, will apply increasing pressure onto the specimen. This loading method allows a slower change in contact area between airbag and specimen as compared to displacing the actuator at a certain displacement-controlled rate. The rate of displacement at the mid-span point of the test specimen was monitored to ensure that it was within the static loading rate of less than 1 mm/min.

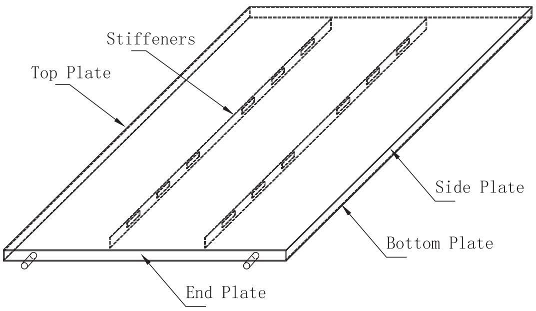

Fig. 1. Notation for water tank.

As the air pressure in the inflating airbag was continuously increased during test, the difference between compressed tank air supply pressure and the airbag pressure would be reduced, which in turn reduced the air charging rate and deformation rate of specimen. Hence, the air supply pressure was manually increased from time to time by using the regulator to maintain an approximately constant deformation rate for the specimen. The non-contact area from edge of specimen to contacting edge of airbag and specimen was measured at every loading interval of 20 kN or less.

Fig. 4 shows the static test control and data acquisition system and Fig. 5 shows the positions of Linear Variable Displacement Transducers (LVDT) and strain gauges. Seven LVDTs were provided to measure the displacements and deflection shapes of the specimens along the span length and across the width direction. Seven strain gauges were provided to measure the strains at the bottom plates of the specimens. Strain gauge S3 was arranged in the width direction while all other strain gauges were in the span direction. The strain and displacement data were recorded using the data logger.

2.3. Discussion on test results

2.3.1. Load–displacement response and failure mode

Both of the empty and water filled tanks underwent large ductile deformation beyond peak load as observed from their respective static pressure load–displacement curves in Fig. 6. For the water filled tank, its maximum resistance is 31% higher than the empty tank. The increase could be attributed to the effectiveness of infilled water in maintaining the shape of the steel tank during loading and delaying the occurrence of local buckling.

Fig. 7 shows the flexure failure of the empty and water filled tanks with plastic hinge at mid-span. Buckling was observed near mid-span of the side plates of both tanks, as shown in Fig. 8 for the empty tank. This is due to the unsymmetrical load acting on the side plate, which could be visualized as web of a C-channel with the top and bottom plates as flanges. Buckling of top plate along the stiffener at the weaker cut-out positions was also observed from the figure. At the post failure range, leakage of water from the water filled tank occurred due to cracking of welds between the stiffener and bottom plate as shown in Fig. 9. The final deformed shape of the water filled tank (after leakage) was similar to the empty tank.

2.3.2. Load–strain response

The development of strains with loading along the span and across the width of the specimen is plotted in Fig. 10 and Fig. 11 for the empty and water filled tanks respectively. Before reaching the peak load, the strain readings at mid-span and quarter-span (Fig. 10(a)) of the empty tank were similar. Beyond that, the strains at both quarter-spans began to decrease while the one at mid-span continued to rise. This indicates that plastic hinge was