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Analysis of axially restrained water storage tank under blast loading

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ABSTRACT

The water storage tank was proposed as a multi-functional facade system characterizing energy saving and blast resisting. The energy saving performance, not presented in this paper, has been evaluated by experimental and numerical methods. The aim of this study is to propose simplified methods to reasonably predict the response of water storage tank under blast loading. Based on the equivalent single-degree-of-freedom (SDOF) method, the shock spectrum and dimensionless pressure–impulse (P–I) diagram were established, which can be used to evaluate the damage levels of water storage tanks subject to blast loading. The equivalent SDOF method cannot capture the varying deflection shape of structure during motion, herein the Lagrange equation method that allows for multiple deflection shape functions was proposed to predict the structural response. It was shown that the Lagrange equation method was better than the SDOF method since it could provide conservative predictions in all response regimes. Furthermore, the varying dynamic increase factor (DIF) with strain rate was incorporated into the Lagrange equation method to capture the strain rate effects.

1. Introduction

The probability of bomb attack on structure has seen an increasing trend in recent years. Consequently, many important buildings are equipped with blast resistance either in preliminary conceptual design stage or by means of strengthening with additional protective measures. Since the occurrence probability of blast attack is low, the benefits of adopting a blast-mitigating or blast-enhanced design could be maximized by combination with other aspects of the buildings' operations, such as sustainability and energy efficiency. The water storage tank was proposed to harvest solar energy and meanwhile reduce the thermal heat penetration into buildings in tropical region. Its energy saving performance has been studied by utilizing numerical [1] and experimental methods. Fig. 1 shows the temperature monitoring test on the proposed water storage tank at Tuas, Singapore and the external wall temperature with installation of water storage tank could be reduced significantly as compared to the bare wall that directly exposed to solar radiation. Besides the shield function in reducing the heat penetration into buildings, the water storage tank could also function as solar energy collector through circulating the warm water to end-users to save the energy used to heat up water. Since the current water storage tank can also be taken as the protective facade of buildings in the event of blast attack, this work aims to propose simplified models to predict the response of water storage tank under blast loading to facilitate its blast resistant design.

Pressure–impulse (P–I) diagram is an iso-damage curve for a particular structural member loaded with a particular blast load history [2]. It will be established for the water storage tank as a convenient way to evaluate its damage level for a given blast scenario. There are mainly two methods to construct the P–I diagram, which are the commonly adopted single-degree-of-freedom (SDOF) [3–7] and the more recently applied finite element (FE) methods [8,9]. The advantage of the SDOF method is that the pressure and impulse asymptotes, which are two critical parameters of P–I diagram, can be given as functions related to structural parameters such as stiffness, mass and allowable maximum displacement. In the SDOF method, deformation is utilized to gauge the damage level. This is reasonable for such structural members as beams and slabs but not appropriate for columns since the failure is generally governed by residual axial strength. Therefore, researchers prefer the FE method to construct the P–I diagram of the columns. For instance, Shi et al. [8] and Mutalib et al. [9] applied the FE method to generate the P–I diagram for reinforced concrete (RC) and fiber-reinforced polymer (FRP) strengthened RC columns, respectively. In their studies, the residual axial strength was simulated and applied as the damage level indicator, which is more representative than the maximum displacement for column. The disadvantage of FE method is that the pressure and impulse cannot be directly defined.

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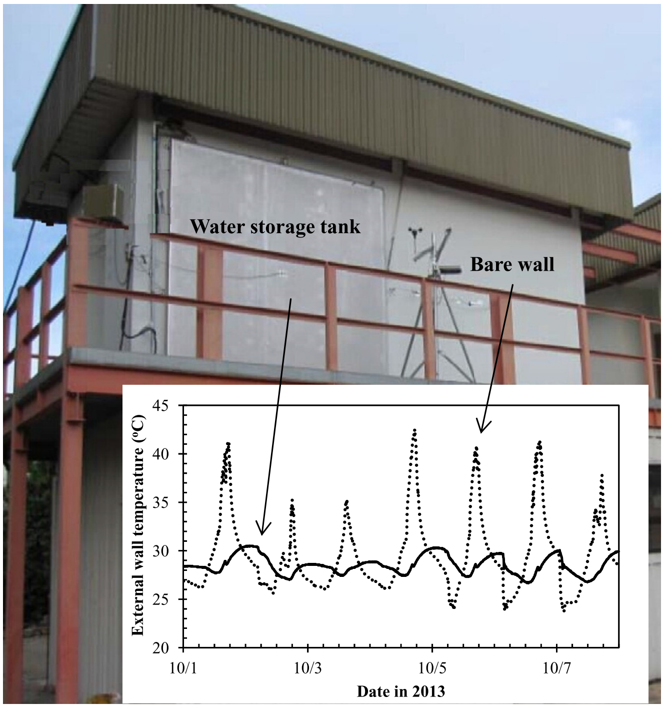

Fig. 1. Temperature monitoring test on water storage tank.

Parametric studies and curve-fitting are usually utilized to establish these parameters. In this paper, the dimensionless P–I diagram involving pressure and impulse asymptotes were constructed using SDOF method and its accuracy was verified with the FE analyses.

The equivalent SDOF method was proposed by Biggs [10] as a simple method to evaluate the response of continuous member under blast loading. This method has been widely adopted to evaluate the structural response [11–15] and some modifications have been made to consider the strain rate effects [16,17] and different failure modes [18,19]. A structural member can be made equivalent to its SDOF system through transformation factor K_{LM}, which relates to deflection shape [10]. Hence, a good and representative deflection shape function would provide a closer estimation of the actual response. Normally, the deflection shape function is obtained by analyzing the member under uniformly distributed static load. In reality, the deflection shape varies during motion due to the existence of inertia force. As a result, the load distribution on the member is changed. It is accepted that the effect of deflection shape function on the structural response is not significant if the deflection shapes are adopted in accordance with the boundary conditions. However, the difference in maximum displacement obtained using different assumed shape functions may be over 10% in elastic range and may be even more when the member enters into plastic range [20]. It was found in this study that the SDOF method usually underestimated the response of water storage tank when the response regime was impulsive. Hence, the Lagrange equation method [21] with combined shape functions was adopted in this paper to accurately predict the response of water storage tank in all response regimes, i.e. quasi-static, dynamic and impulsive. A constant dynamic increase factor (DIF) was usually included in the SDOF analysis to represent the average strain rate effect on material strength [11–13]. In fact, DIFs vary with strain rates. Hence, a constant DIF may not accurately capture the strain rate effect. To overcome this limitation, Nassr et al. [16] proposed a strain rate model that defined the maximum strain rate in terms of scaled distance for beam column. However, this model is unable to provide varying DIF in terms of strain rate during motion. The varying DIF in terms of strain rate was recently included in the continuous beam model [17,22] and SDOF model [17] to analyze the simply supported RC panels under blast loading. Both of these two papers introduced the DIF by updating the resistance at each time step according to the strain rate at the corresponding time step. The energy principle was adopted in this study to include the varying DIF into the Lagrange equation method to accurately capture the strain rate effect.

This paper starts with a description on the establishment of FE model and its verification with test results, followed by the establishment of SDOF system and dimensionless P–I diagram. Finally, the Lagrange equation method with combined deflection shape function and varying DIF is presented.

2. FE model verification

2.1. Test on water storage tank

The tests on the water storage tanks under static and dynamic pressure loads [23] were adopted to verify the established FE model in this section. The schematic test setup is shown in Fig. 2. The specimen was seated on two round bar supports with clear span of 900 mm. The inflated high pressure airbag was placed in between the specimen and a 1000 mm × 1000 mm × 30 mm thick transfer steel plate. The high pressure airbag was utilized to transfer the static loading from actuator or dynamic loading from drop hammer to the specimen to apply the static pressure or dynamic pressure loading. For the static pressure test, the applied load from actuator, air pressure inside the airbag, strains and displacements on the critical locations of the specimen

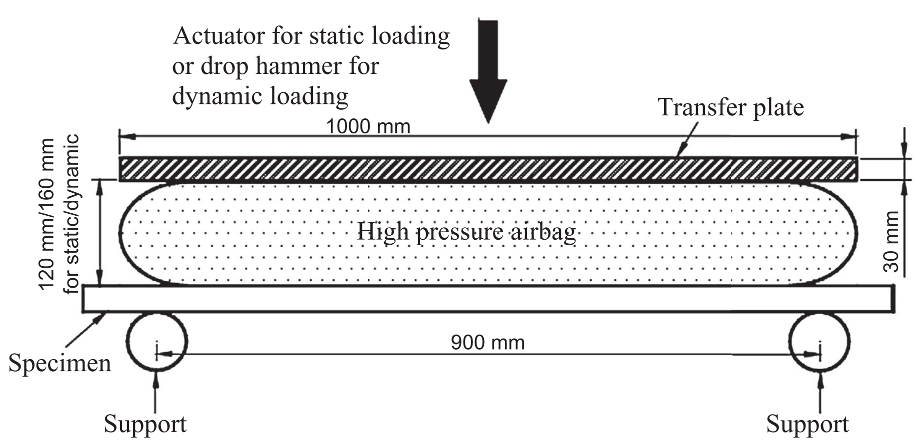

Fig. 2. Schematic test setup of water storage tank under static and dynamic pressure loads.