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Numerical derivation of pressure-impulse diagrams for square UHPCFDST columns

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ABSTRACT

Terrorist activities, especially bomb attacks, have become more and more frequent in the past decades which put thousands of innocent lives in danger. The most common failure mode of structures subjected to blast loading is progressive collapse which is mainly resulted from the failure of load bearing columns. In this paper, finite element analysis tool, LS-DYNA is utilized to study the behaviours of ultra-high performance concrete filled double- skin steel tube (UHPCFDST) columns under blast loading. The numerical model is firstly validated against a series of laboratory and field tests and then used to derive pressure-impulse diagrams for UHPCFDST columns in terms of their residual axial load-carrying capacity after being subjected to blast loading. Different parameters are studied to investigate the effects of axial load ratio, steel tube thickness, column dimension and concrete strength on the pressure-impulse diagrams.

1. Introduction

Concrete filled double skin tubular (CFDST) columns have the potential to be widely used in the construction industry owing to properties such as high strength and excellent ductility.

A large number of studies have been carried out to investigate the behaviours of CFDST columns under a variety of loading conditions, including: axial compressive loading [1–3], cyclic lateral loading [4,5], tensile loading [6,7], pure torsion [8] and fire [9]. Their results indicate that CFDST columns are able to provide robust performance under multi-hazardous environment.

Recently, the authors have carried out a series of laboratory and field blast tests on ultra-high performance concrete filled double-skin steel tube (UHPCFDST) columns [10,11]. In comparison to normal strength concrete, UHPC is known for its superior strength which can reach up to 200 MPa in compression and 40 MPa in tension, resulting in a significantly smaller cross-sectional area for the same axial load-carrying capacity. Due to the inclusion of steel fibres, the formation of large cracks can be effectively delayed, leading to an outstanding ductility and energy absorbing capacity so as to make it an ideal material for blast resistant structural components. Recent blast experiments indicated that steel-fibre reinforced UHPC slabs and columns are able to withstand severe blast loading without catastrophic failure [12–15].

In this paper, the pressure-impulse diagram is introduced to develop a systematic method of assessing structural damage in UHPCFDST columns after being subjected to blast loading. A pressure-impulse (p-I) diagram represents a group of loading histories (e.g. blast load) that cause the same level of damage to a structural component. It is widely used as the basis to assess the damage in a structural component or even the blast-induced human injury [16,17]. Fig. 1 depicts a typical pressure-impulse diagram. In terms of loading types, a Pressure-impulse diagram can be categorised into three zones: 1) the impulsive loading zone where loads are large in magnitude but with very short duration; 2) the quasi-static loading zone where loads are small in magnitude but with very long duration; 3) the dynamic loading zone which lies in between the impulsive and quasi-static loading zone. The impulsive zone and the quasi-static zone are differentiated by two vertical asymptotes, namely, the pressure asymptote and the impulse asymptote. In addition, in terms of damage levels, a pressure-impulse diagram can be divided into two zones, namely the safe zone (i.e. to the left and below the curve) and the damage zone (i.e. to the right and above the curve).

Various methods exist for deriving a pressure-impulse diagram and among which, experimental investigation, single degree of freedom (SDOF) analysis and numerical analysis are the three most popular. The

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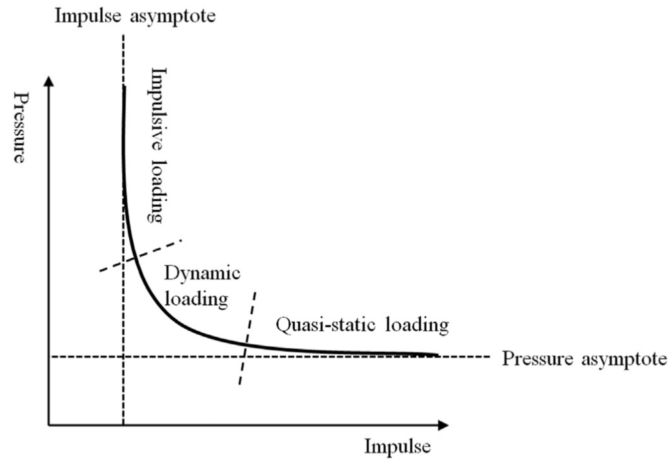

Fig. 1. A typical pressure-impulse diagram.

simplest method is SDOF analysis since it converts the entire structural member into a SDOF system, relying on various transformation factors, and only provides the deflection response of the mid-span of the member. Many studies have shown that SDOF analysis provides an easy means to predict the structural response under blast loading [18–20]. However, SDOF analysis cannot accurately incorporate the strain-rate effect therefore is likely to underestimate the structural damage under impulsive loading, and is incapable of accounting for different failure modes since its damage criterion is either based on the maximum structural deflection or end rotation. Experimental investigations, on the other hand, are able to provide more intuitive observation of structural members subjected to blast loading. However, as experiments are often associated with issues such as safety concern, budget control and time constrain, normally only a limited number of parameters can be investigated which often makes the findings incomprehensive and inconclusive. The third common method, namely numerical analysis, uses three-dimensional meshes to determine the dynamic response of a structural member over time. Nowadays, numerical tools are widely used to analyse situations where complex loading conditions and/or interaction between materials are involved. This method has demonstrated its ability to provide robust predictions of the dynamic response of different structural member subjected to blast loading, especially when used in conjunction with experimental results [21–27].

This paper presents a numerical method to evaluate the damage caused by blast loading in a UHPCFDST column. High-fidelity physics based finite element tool, LS-DYNA, is utilized in the current study to numerically simulate the dynamic response of UHPCFDST columns subjected to blast loads. LS-DYNA is widely adopted within the engineering society as a more efficient and economical alternative to field experiments. There are a large number of open literatures with regards to using LS-DYNA to study structural columns [28–34]. The results indicate that, with a properly calibrated model, LS-DYNA is able to accurately predict the structural response of a column under blast loading.

2. Numerical modelling

In this paper, the commercial software package LS-DYNA was used to investigate the behaviours of UHPCFDST columns under blast loading [35].

2.1. Meshing and boundaries

The UHPCFDST specimen studied herein is shown in Fig. 2. It can be seen from Fig. 2(a) that both ends of the UHPCFDST specimen were fully embedded in concrete slabs and the outer face of both end slabs were restrained against x and z directions so that it can only move along the axial direction. The meshing and element division are shown in Fig. 2(b). The average characteristic size of the concrete element was 7 mm and the mesh size convergence study shows that further refinement of the numerical model has little effect on the results but significantly increases the computational burden.

2.2. Application of the blast loading

During parametric studies to obtain the pressure-impulse diagram, the idealised triangular-shape pressure-time history was used to simulate the blast loading in the analysis. In addition, the blast wave was also assumed to be plane wave, therefore the blast load was uniformly distributed on the front face of the UHPCFDST specimen. It should be mentioned that, under circumstances where the explosive is placed in close vicinity of the target structure, this assumption could overestimate the blast load and as a result, i.e., overestimate the column damage.

2.3. Validation of the numerical model

Five tests, including three laboratory tests and two field blast tests, were used to demonstrate the ability of the proposed numerical model to accurately predict the behaviour of UHPCFDST structures. The equipment setups and results of all tests have been thoroughly discussed in the authors' previous works [36], therefore only the validation results are given hereafter.

Fig. 3 shows the validation of the uniaxial compressive test on 100 mmx100 mmx100 mm UHPC specimens; Fig. 4 shows the validation of the four point bending test on 100 mmx100 mmx400 mm UHPC specimens; Fig. 5 shows the validation of the three point bending test on 2500 mm long square UHPCFDST specimen; Fig. 6 shows the validation results of the blast tests of two square UHPCFDST. In both blast numerical models, the blast loading was simulated by using ConWep function in LS-DYNA. Fig. 7 and Table 1 compare the measured pressure and impulse values to the simulated ones (at the location where the pressure-transducer was placed), more in-depth analysis about the discrepancies can be found in [11]. The validation results are in reasonable agreement with the test results which shows the ability and fidelity of the proposed numerical model to predict the behaviours of UHPCFDST columns under different loading conditions.

3. Numerical derivation of pressure-impulse diagram

A pressure-impulse diagram can be numerically generated by having a set of data points that represent the same level of structural damage, however resulted from different pressure and impulse combinations. Although the numerical method can accurately describe the dynamic behaviour of a structure, it is very computationally expensive since it normally requires multiple trials to get one satisfactory point. In this paper, the standard procedure of generating a pressure-impulse diagram is shown in Fig. 8: 1) choose one pressure and impulse value as the starting point; 2) keep the pressure constant and gradually increase/decrease the impulse (by increasing/decreasing the loading duration) until the structural damage has reached the pre-determined level; 3) reduce the pressure and re-adjust the impulse value until the structural damage has also reached the damage level defined in step 2; 4) repeat step 1 – 3 for the rest of the data points until a smooth curve can be drawn.

3.1. Damage criterion

There are a number of criteria that are commonly used to quantify the damage accumulated in a column. In the current research, the damage in a UHPCFDST column caused by the blast loading is quantified by the residual axial load-carrying capacity: the more residual axial load-carrying capacity, the less accumulated blast