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Effects of structure-related parameters on the response of concrete-filled double-skin steel tube columns to lateral impact

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ABSTRACT

Concrete-filled double-skin steel tubes (CFDSTs) find increasing use as bridge piers and building columns. This paper treats the impact response of such columns using numerical simulations. The modelling techniques are validated using experimental results to establish the capability of the numerical model to capture the impact response and failure modes of the column. The validated numerical model was used to carry out a parametric study on the effects of several structure-related parameters on the impact response of the CFDST columns. The findings of this paper can be used to develop appropriate design information for CFDST columns under lateral impact loading.

1. Introduction

Concrete-filled double-skin steel tube (CFDST) is simply formed by two concentric steel tubes separated by a concrete filler. CFDSTs were first introduced as a new form of construction for deep-water vessels to resist external pressure [1]. They have long been used as legs of offshore platforms [2] to mitigate stability concerns in hollow steel tubes. Over the recent years, CFDSTs have been widely used as a new alternative to existing structural bridge piers and building columns [3–5] due to their outstanding characteristics that favour their use as load-bearing structural components. Predominant usage of CFDSTs in civil infrastructure makes them susceptible to lateral impacts. Due to direct exposure, these CFDSTs which are used as legs of offshore platforms, bridge piers, columns at the frontage of buildings or in car parks may inevitably suffer from various accidental or intentional lateral impacts such as those from collision of vehicles, vessels, barges or flying debris from a nearby explosion. Such impacts may cause serious damage that can be very costly to repair or at worst can cause a structure to collapse with the associated risk of human injury or fatality. It is therefore necessary to design such members to possess adequate capacities to withstand credible accidental or deliberate impact loads. Understanding the impact behaviour of such members will provide the basis for developing rational design procedures which ensure the safety of the member and the structure as a whole. There is, however, a paucity of literature on the lateral impact response of CFDST columns subjected to lateral impact loading and this motivated the present research.

Among the few studies on behaviour of CFDST members under lateral impact, Corbett, Reid and Al-Hassani [6] conducted an experimental study on small scale CFDSTs to investigate their ability to resist high velocity projectile lateral impact loads (*i.e.*, sharp local impact or penetration) when they are used as a replacement to the original section or as a protective jacket to the subsea steel tube piping system or steel pressure vessels. They prepared three specimens with the same outer and inner tube wall thickness and inner tube outside diameter and different outer tube outside diameters resulting in fabrication of specimens with three different concrete filler thickness. The specimens were struck radially along the diameter by means of a hemispherical tipped projectiles fired from a compressed air gun. The results of the experiments indicated highly localized circular shape dent on the outer tube and axially extended dent on the inner tube. The results also showed that increasing the concrete filler results in a significant increase in the energy required for complete preformation. Recently, Wang, Qian, Liew and Zhang [7] numerically investigated the effectiveness of CFDSTs for use in oil and gas pipeline applications in offshore industries, particularly in arctic environments, to resist penetration by an impacting object such as ice floes, icebergs, and heavy objects such as anchors and installation equipment. To conduct the study, they developed finite element models using finite element programme LS-DYNA. These models were not validated against any experimental data. To study the effect of inner pipe on the CFDSTs, they removed the inner pipe in one of the models and named the model as concrete-filled hollow pipe. All models were simply supported, had the same outer pipe outside

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diameter but different outer pipe wall thickness, inner pipe outside diameter and wall thickness as well as concrete layer thickness. The numerical results indicated that the CFDSTs have a strong resistance under lateral impact loading. Additionally, it was found that outer pipe plays an indispensable role in improving the lateral impact resistance of CFDSTs. Concrete core can assist in preventing the buckling of the tubes. Changing the inner tube thickness hardly affects the lateral impact performance of the CFDST. However, removing the inner tube from CFDST results in a significant increase in the maximum indentation. Additionally, Li, Lei and Wang [8] numerically examined the behaviour of CFDSTs when used as structural members in high rise buildings or bridges subjected to lateral impact from striking plane, boat or vehicle. They developed a finite element model using finite element software ABAQUS. This model was not validated against any tests data. The model simulated simply supported CFDST members subjected to lateral impact using a drop-weight. The results of numerical analysis suggested that the failure modes of CFDSTs under lateral impact includes the global bending deformation and local bucking at mid-span. Very recently, Wang, Qian, Liew and Zhang [9] conducted an experimental study to assess the lateral impact performance of double-skin steel pipes filled with ultra-light weight cement composite (ULCC) when used as submarine oil and gas pipelines. The tests programme involved six hollow pipe specimens and sixteen ULCC-filled pipe-in-pipe specimens subjected to the lateral impact using drop-weight impact test facility. All specimens had the same outer tube outside dimeter but different outer tube wall thickness. For ULCC-filled pipe-in-pipe specimens, the inner tube outside diameter and cement layer thickness were also varied. The results suggested superior impact performance with higher impact resistance, smaller global deformation and local indentation of ULCC-filled pipe-in-pipe specimens compared to steel hollow tubes. It was found that the outer pipe thickness directly influenced the impact resistance and the global bending deformation. The ULCC layer effectively restricts the indentation within a highly localized region around the impact point and limits the deformation of steel pipes.

The studies mentioned above indicate that CFDST members have good impact resistance, in general. However, they are among the first on this topic, limited in scope and their conclusions are preliminary. These existing studies have not yet evaluated the response of CFDST members when used as structural columns subjected to a combination of lateral impact and axial load induced by the live and dead loads of building slabs or bridge or offshore platform decks. Moreover, to the best of the authors' knowledge there are no validated finite element computational models reported in the literature on the simulation of the lateral impact performance of axially pre-loaded CFDST columns. Additionally, the influence of various structural-related parameters has not been investigated yet.

Therefore, the aim of this paper is to build on the preliminary research investigations and develop an extensive database of CFDST column behaviour under combination of static axial and dynamic lateral impact loads. A numerical simulation technique for studying the behaviour and failure modes of axially pre-loaded CFDST columns subjected to lateral impact loading was developed and validated against experimental testing data. Effects of several structure-related parameters on the response of the impacted column was then carried out using the validated numerical model.

2. Finite element model (FEM)

In this study, the explicit dynamic nonlinear finite element code LS-DYNA [10] is employed as a platform for developing the numerical model. The developed model was validated against lateral impact tests conducted using an innovative horizontal impact testing system at Queensland University of Technology (QUT).

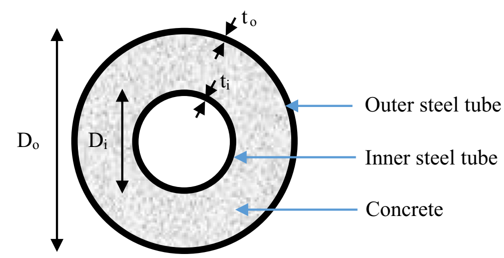

Fig. 1. Typical profile of the CFDST specimens.

2.1. *Description of the experimental testings*

2.1.1. *Specimen characteristics and fabrication*

Four series of tests, with a total of eight tests, involving different combinations of axial load and impact location were considered. Fig. 1 shows the typical CFDST section. The characteristics of each test specimen in the test matrix are presented in Table 1, where D_o is the outside diameter of the outer tube, t_o is the wall thickness of the outer tube, D_i is the outside diameter of the inner tube, t_i is the wall thickness of the inner tube, L is the length of the specimen and n is the axial load level defined as the ratio of applied axial load to axial capacity of the CFDST specimen. Simply-supported boundary conditions were applied at the ends of the specimens.

To fabricate the specimens, a 10 mm steel base plate (or end plate) was welded to the hollow tubes (*i.e.*, inner and outer tubes) at one end, making sure that their geometric centres were aligned. The columns were then securely held upright and the concrete was poured from the top and vibrated in the annulus between the outer and inner tubes. They were left to air-dry until testing. The longitudinal gap caused by concrete longitudinal shrinkage was filled (using Sikadur 31/41 Rapid; a high-strength adhesive mortar) so that the concrete surface was flush with the steel tube at the top. Prior to testing, this surface was ground smooth and flat using a grinding wheel to ensure the axial load could be applied evenly across the cross-section and simultaneously to steel and concrete. A 10 mm steel base plate was then welded to the outer tube of this end. Finally, the specimens were degreased and grid marked on their surfaces.

2.1.2. *Material properties*

Tensile coupon tests performed under conditions specified in AS 1391 (2007) [11] showed that the mean yield and ultimate strengths of outer steel tubes were 299.5 MPa and 358.5 MPa, respectively. They were 401.3 MPa and 433.4 MPa, correspondingly, for the inner steel tube. The concrete core had a nominal compressive strength and maximum aggregate size of 25 MPa and 10 mm, respectively. The mean measured unconfined compressive strength and splitting tensile strength of 100 mm × 200 mm concrete cylinder at the day of testing was 32.35 MPa and 4.11 MPa as determined in accordance with AS1012.9 (1999) [12] and AS1012.10 [13], respectively.

2.1.3. *Testing method*

The specimens were tested under a combination of static axial and dynamic lateral impact loads using an innovative horizontal impact-testing system (HITS) as shown in Fig. 2. A detailed description on the HITS and its components can be found in [14]. In this system, the lateral impact load is applied using a horizontal pneumatic instrumented striker. This striker is firmly fixed in place *via* two anchors, which are bolted to the strong floor. It is powered