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

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ABSTRACT

Concrete-filled double-skin steel tubes (CFDSTs), which consist of two concentric steel tubes with concrete sandwiched between them, have found increasing use as a new sustainable alternative to existing structural bridge piers and building columns, over the recent years. They can hence become vulnerable to lateral impact loads such as those from collision of vehicles, vessels, barges or flying debris from a nearby explosion. This paper treats the response of such columns under a combination of static axial and dynamic lateral impact loads using a fully coupled numerical analysis with the finite element code LS-DYNA. The capability of the numerical model to trace the response and to predict the failure modes of the columns has been validated using extensive results from experiments carried out recently at Queensland university of Technology. A parametric sensitivity analysis is conducted to investigate the effects of several load-related parameters on the key response of the CFDST columns. Results provide new information on the impact response of CFDST columns and the effects of controlling parameters to form an extensive database. This can be employed to develop appropriate equations and design calculation methods for CFDST columns under lateral impact loading.

1. Introduction

Concrete-filled double-skin steel tube (CFDST) consists of two concentric steel tubes separated by a concrete filler. They have long been used as legs of offshore platforms [1] to mitigate stability concerns in hollow steel tubes. Over the recent years, CFDSTs have been widely used as an alternative to existing structural bridge piers and building columns [2–4] due to their outstanding characteristics that that favour their use as load-bearing structural components. The CFDSTs which are used as legs of offshore oil and gas platforms, bridge piers, columns at the frontage of buildings or in car parks are highly vulnerable to various accidental or intentional lateral impacts such as those from collision of vehicles, vessels, barges or flying debris from a nearby explosion. Catastrophic progressive structural failure may occur as a result of such impacts on these columns. 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 would 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 provided the motivation for the present study.

Corbett, Reid and Al-Hassani [5] conducted an experimental study on small scale CFDSTs to investigate their response to high velocity projectile impacts. The impact load was applied by means of a hemispherical projectile fired from a compressed air gun. The test results indicated highly localised circular shape dents on the outer tube and axially extended dent on the inner tube. Recently, Li, Lei and Wang [6] numerically investigated the impact response of simply supported (i) hollow steel tubes, (ii) concrete-filled hollow steel tubes and (iii) CFDSTs for use in oil and gas pipeline applications. Results showed that the maximum global displacement and indentation depth and area of CFDSTs were smaller than those of the other tubes. More recently, Wang, Qian, Liew and Zhang [7] assessed the lateral impact performance of double-skin steel tubes filled with ultra-light weight cement composite (ULCC) through drop weight impact tests and numerical simulations. The results indicated superior impact performance with higher impact resistance, smaller global deformation and local indentation of CFDST members compared to steel hollow tubes. The ULCC layer effectively limits the development of the local indentation.

The aforementioned studies evidently demonstrated that CFDST members have good impact resistance, in general. However, these studies are among the first on this topic, limited in scope and their conclusions are preliminary. They lack insight into the response of CFDST members when used as structural columns subjected to a combination of lateral impact and axial load induced by live and dead loads of building slabs or bridge decks. The lateral impacts have been traditionally considered at the mid-height though column mid-height is not the

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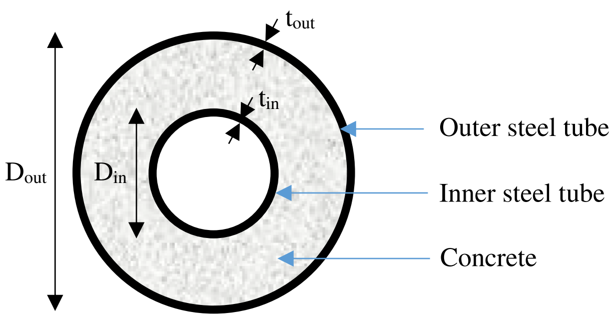

Fig. 1. Typical profile of the CFDST specimens.

most likely place for an impact to occur. For example, in columns at the frontage of buildings, vehicular impacts are more likely to occur closer to the ground level than at the mid-height. From a thorough literature search, no reference was found on the use of a validated finite element model to simulate the lateral impact performance of axially pre-loaded CFDST columns. Moreover, the influence of various parameters on the response of these columns has not been investigated yet.

The main novelty of the present paper is the response of the CFDST columns under the combined action of axial and impact loads. In particular, this paper carries out a comprehensive study on the influence of several load-related parameters on this response. In addition to the effects of load-related parameters, the influence of structure-related parameters must be considered to develop a comprehensive database of CFDST column behaviour under lateral impact. The effects of structure-related parameters have been studied by the authors in a previous paper [8].

To this end, this paper develops and applies a finite element (FE) model using the software, LS-DYNA, to study the dynamic behaviour of CFDST columns subjected to static axial and dynamic lateral impact loads. The modelling techniques are comprehensively validated by comparing the numerical results with those from experimental impact testing. The validated model is then used as an efficient alternative to expensive and time-consuming tests to (i) conduct a parametric sensitivity analysis, (ii) develop an in-depth understanding of the effects of various load-related parameters and (iii) determine the sensitivity of the column behaviour to such parameters.

2. Brief description of the experimental program

The experimental program was comprehensively described elsewhere [9], but it is briefly presented here for completeness and for clarifying the development of the finite element model.

2.1. Specimen preparation

The dimensions and material properties of the specimens were selected based on commercial availability (in Australia) and to satisfy the construction and laboratory constraints imposed in the experiments, but allowing the columns to reach a plastic phase whilst maintaining a stable response (*i.e.*, preventing complete collapse) under combined axial load and lateral impact load. The typical CFDST section is shown in Fig. 1. Eight CFDST specimens, each 3 m long, were tested. The outer tubes had an outside diameter (D_{out}) and wall thickness (t_{out}) of 165.1 mm and 5.4 mm, respectively. The inner tubes had an outside diameter (D_{in}) and wall thickness (t_{in}) of 33.7 mm and 4 mm, respectively. To prepare the specimens, a 10 mm thick steel base plate (or end plate) was welded to one of the ends of the inner steel tube, making sure that both their geometric centres were aligned. The outer tube was then positioned, symmetrically, around the inner tube at this end and welded to the same base plate. The inner tube was then centralised in the outer tube at the other specimen end, using a spacer. Concrete was poured into the annulus between the tubes and vibrated. The specimens were then left to properly cure until testing. Prior to testing, the spacer was removed and this concrete surface was ground smooth. A 10 mm steel base plate was then welded to the outer tube at this end. It should be noted that the inner tube was not welded to the base plate at this end as it was not constructionally possible. This constructional constraint did not affect the behaviour of the CFDSTs. The base plates applied the axial load uniformly over the specimens' cross-section and the investigation which has been done after the tests did not show any sign of failure at these locations. Finally, the specimens were degreased and grid marked on their surfaces.

2.2. Material testings

Tensile coupon tests carried out under conditions specified in AS 1391 (2007) [10] 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, respectively, for the inner steel tube. The difference in strength of inner and outer tubes could be related to the use of different virgin materials during manufacturing process or different extent of cold work required to roll the tubes. 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 [11] and AS1012.10 [12], respectively.

2.3. Test matrix

Four series of tests, with a total of eight tests, involving different combinations of axial load and impact location were considered as shown in Table 1. To ensure repeatability, more than one specimen was tested for each series except for the first one. To identify the specimens, each was labelled, where the last letter *A* refers to the first test in the particular series and the letters *B* or *C* represent the repeated tests in the same series. The numbers before the last letter refer to the test series number (1, 2, 3 or 4) and the rest of the letters refer to the column type (*i.e.*, CFDST).

2.4. Testing method

The specimens were tested under a combination of static axial load and dynamic lateral impact using an innovative horizontal impact-testing system (HITS). The HITS, shown in Fig. 2, is a repeatable, compact, efficient and cost-effective impact testing system, which greatly assists in collection of data on the fundamental behaviour of structural

Table 1
Test matrix.

Test series	Series #1	Series #2			Series #3		Series #4	
Specimen	CFDST1A	CFDST2A	CFDST2B	CFDST2C	CFDST3A	CFDST3B	CFDST4A	CFDST4B
Axial load (kN)	0 (0% of axial capacity of column)[b]	200 (15% of axial capacity of column)[b]			200 (15% of axial capacity of column)[b]		400 (30% of axial capacity of column)[b]	
Impact location	Mid-span	Mid-span			Off-centre[a]		Mid-span	

[a] The axial capacity of CFDST was calculated using the formulae presented in [13].
[b] Off-centre: two-third of column length away from one of the supports.