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Experimental study on axially preloaded circular steel tubes subjected to low-velocity transverse impact

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ABSTRACT

Steel circular hollow section tubes are widely used as tubular structural members, and impact accidents usually occur while these tubes are in their working states. This paper presents experimental studies on axially preloaded circular steel tubes subjected to transverse low-velocity mass impact. A total of 32 impact tests, representing four types of scenarios, are conducted to investigate the influences of preloading and the boundary condition on the structural responses of tubes. An axial force loading system is designed, and a bladder accumulator is adopted in the system to compensate for the axial compressive loading. The test processes of the tubes under transverse impact are described in detail, and four failure modes are identified. All specimens of the four scenario types deformed according to the three-hinge mechanism. Based on the test results, the influence and mechanism of axial force are proposed. The effects of axial tension, axial compression and the boundary condition on the structural behaviour of tubes are discussed. The results show that the axial tension can enhance the bending resistance and lateral collapse capacity of tubes, while the axial compression reduces the collapse capacity significantly. By comparing the responses of tubes under different boundary conditions, the lateral resistance of tubes and the structural response are shown to have a strong correlation with the axial constraint.

1. Introduction

Steel circular hollow section tubes are widely used as tubular structural members. Compared with other structural members, circular steel tubes have the following advantages: insensitivity to the spatial layout orientation, large bending and torsional stiffness, small wind load resistance coefficient and easy handling during construction. Moreover, due to the advantage of low drag resistance against passing media, circular steel tubes are always used as pipelines to transport potentially hazardous materials. These components may be subjected to impact loads from accidental or intentional impact. Severe impact to a steel tube may lead to the progressive collapse of the corresponding structure or the release of hazardous materials into the environment. Much research in recent years has focused on steel tubes subjected to transverse impact. Menkes and Opt [1], Thomas et al. [2] and Watson et al. [3,4] were among the first researchers who studied the failure modes and deflection modes of structural members subjected to impact loads. Many of the publications on the transverse impact of steel tubes based on theoretical [5–8], experimental [9–12] and numerical [12] investigations were reviewed by Zhang et al. [13].

However, accidents usually occur while these tubes are in their working states, e.g., tubular members subjected to axial compressive loads or axial tensile loads, or pipelines subjected to internal pressure. Extensive studies on steel tubes subjected to transverse impact while carrying their normal service loads have been conducted by many researchers. Brooker [14] numerically investigated the denting deformation process of pressurized pipelines under localized radial loads. The plastic response of pressurized pipelines subjected to transverse quasi-static loading was numerically and empirically examined by Karamanos and Andreadakis [15]. They showed that the presence of internal pressure significantly increases the denting force. Jones [16] conducted large-mass low-velocity impact tests on pipelines pressurized with a nitrogen gas, and recommendations were made regarding the accuracy and suitability of some well-known empirical equations for predicting the permanent deformations of pressurized and empty pipelines subjected to large-mass low-velocity impact. Additionally, water-filled tubes subjected to impact have also attracted much attention. Refs. [17–19] experimentally investigated the perforation and cracking of water-filled tubes impacted at high velocity. The same conclusions were drawn, namely, the addition of any content within a pipeline causes a more localized deformation when compared with the behaviour of similar empty tubes, as reported in Refs. [16]. Compared with pipelines, steel tubes used

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Nomenclature

D	outside diameter of a tube
D_{max}	maximum diameter of deformed cross-section, defined in Fig. 9
D_{min}	minimum diameter of deformed cross-section, defined in Fig. 9
E	Young's modulus
F_{max}	maximum transverse force during impact process
ΔL	axial shortening of tube
L_c	length of the clamping device, defined in Fig. 2
L_R	thickness of the steel rings, defined in Fig. 2
$2L$	tube span
P_o	applied axial force before impact
P_f	axial force after impact
P_y	axial squash load of the steel tube
T	tube wall thickness
T_d	duration of the impact test process
σ_y	yield strength
σ_u	ultimate tensile strength
ε_u	ultimate tensile strain
δ	local denting deflection, defined in Fig. 9
δ_D	global beam deflection, defined in Fig. 9
ω	total deflection, defined in Fig. 9
Δ	distance between the line of the axial force and the deformed tube axis, defined in Fig. 15b

as tubular structural members always carry their own design loads, i.e., a compressive axial load or a tensile axial load, when subjected to impact. Wierzbicki and Suh [7] theoretically surveyed the large plastic deformations of tubes subjected to a combination of transverse indentation, bending moment and axial force loadings. Their results reveal that the resistance of a tube to transverse indentation sharply diminishes as the direction of the axial force changes from pretension to precompression. They also found that the boundary conditions have significant effects on the resistance of a tube to transverse indentation. Ruggieri and Ferrari [20] presented an experimental and numerical investigation of the behaviour of steel tubes under a lateral load, and they found that the load-dent depth response of tubes has a weak dependence on the axial tension. Recently, a numerical investigation of the structural behaviour of preloaded tubular members subjected to a transverse impact was presented in Refs. [21,22]. The influence of boundary conditions, preloadings and the position at which the lateral load was applied on the behaviour of tubes was examined. Zeinoddini et al. [23–26] conducted systematic studies on the plastic behaviour of axially loaded steel tubes subjected to transverse loads. In their studies, a notable experimental investigation was reported in Ref. [25], a self-reacting system that can be used to apply axial force was well designed, and a test involving preloaded tubes subjected to low-velocity mass impact was successfully realized for the first time. The results of Refs. [23–26] reveal that preloadings have a marked effect on the lateral collapse capacity of tubes. More recently, Firouzsalari and Showkati [27] designed a test system for testing axially preloaded tubes subjected to quasi-static loads. Via experimental, numerical and theoretical investigations, they proved that preloadings have a significant effect on the behaviour of tubes subjected to transverse loads.

A thorough search of the literature reveals a limited number of experimental investigations on preloaded tubes subjected to transverse impact. Few researchers have addressed the problem of applying the preloading and maintaining the load during the microtime test process [25], and there remains a need for an efficient method that can address this issue. In this paper, we design a test system for testing axially preloaded tubes subjected to low-velocity mass impact. A total of 32 specimens, including axial precompression tubes, axial pretension tubes, the boundary conditions on which included having one sliding support and one fixed support, and non-axial-loaded tubes, are transverse impacted by wedge-shaped indenters. The dynamic responses of tubes are elaborately described, and then the influence of impact energies and boundary conditions on the behaviour of the steel tubes is examined. Special emphasis is given to the effects of axial preloading on the lateral collapse capacities of the tubes.

2. Experimental details

2.1. Test system

A series of tests have been conducted in the Key Lab of National Defense Explosion Prevention and Engineering Protection at the School of Civil Engineering, Harbin Institute of Technology, to examine the structural behaviour of circular steel tubes subjected to transverse impact. A wedge-shaped indenter was used during the tests. Details regarding the test rig can be found in Zhang et al. [13].

The main aim of the systematic tests was to investigate the influence of the pre-loadings and boundary conditions on the behaviour of the steel tubes subjected to transverse impact. In order to realize the

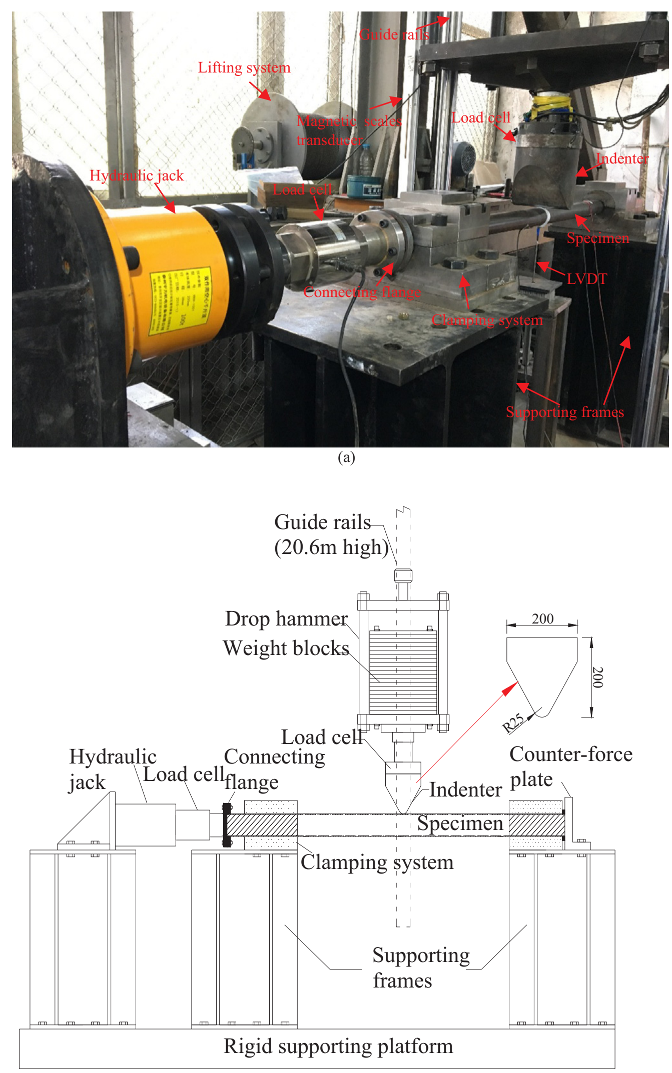

Fig. 1. Schematic view and details of the impact rig for testing of preloaded circular steel tubes.