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Experimental study on impact behaviour of steel plane tubular frames

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ABSTRACT

This paper experimentally examines the dynamic behaviour of two steel plane tubular frames subjected to impact loading with the same impact energy. One specimen is set up to be hammer impacted on the mid-span section of the top chord between two K-joints, while another is loaded on the mid-span section of the top chord within the middle K-joint. The dynamic response of both frames are described and discussed with emphasis on the effect of impact-loading locations. Based on the experimental results, the key deformation patterns, the time history of impact force, deformation and strain are identified. The two specimens suffer significant local indentation at impacted zone, the deflection of impacted chord between two joints and the global flexural deformation of the whole frame. Moreover, the impact mechanism and energy dissipation is also investigated to evaluate the impact resistance of steel tubular frames. Additionally, based on the plastic hinge line theory, a simplified calculation method of energy dissipation is proposed and verified against the experimental result. The studies in this paper also provide basis data for future anti-impact design of steel tubular structures.

1. Introduction

Tubular structure has been widely used in offshore platform, airport, train station, breakwater and highway toll stations due to its advantage of architectural appeal and structural efficiency. Nevertheless, during its service period, tubular structure may suffer the lateral collision from the supply vessels, floating ice and vehicles, or explosion and fire as a result of leaking oil and gas. Robson [1] summarized 557 ship/platform collision incidents from 1975 to 2001, where 26 collisions between offshore facilities and visiting vessels on the Norwegian Continental Shelf from 2001 to 2011 according to the earlier work by Olterdal [2]. It is found that these accidental loading events could lead to partial or total collapse of a tubular frame and cause casualties, property loss and/or environmental pollution.

During the past decades, some of the researches focused on the collision mechanics including the impact action and energy in order to further study the response of the impacted materials or tubular structures. Moan [3] discussed the development of accidental collapse limit state criteria for offshore structures by means of semi-probabilistic Accidental Collapse Limit State procedure. Pedersen et al. [4] developed an estimation function of impact loads due to bow collisions on the fixed offshore structures. Furnes and Amdahl [5] proposed a simplified theoretical calculation model to investigate the deformation characteristics and energy absorption of ship structure subjected to collisions. Travanca and Hao [6] describes a detailed finite element model developed for impact analysis of merchant vessel bows against tubular members. Ellinas and Walker [7] developed analytical expressions to study the collision and impact effects on circular tubular beam-columns and offshore bracing members. Ellinas [8], Visser [9], Jin et al. [10] and Zhang et al. [11] studied the mechanics of ship/jack-up collisions based on the available collision incidents, and then carried out the finite element analysis of typical impact scenarios and assessed the response of the tubular structure under the impact loadings.

On the other hand, some of the engineering scholars mainly focused on the dynamic behaviour of the tubular members, joints and structures commonly under the assumption that the ship/vehicle are strong enough to be treated as rigid through experimental, numerical and analytical models. Bai and Pedersen [12] derived a nonlinear force versus displacement relationship for the simulation of the local indentation in a hit tubular member. Guedes Soares and Soreide [13] presented an analytical formulation for the analysis of laterally loaded circus tubes with different constraint conditions. Jones and Shen [14] developed a theoretical rigid-plastic procedure to predict the quasi-static response of a ductile pipeline struck laterally by a rigid mass. On the basis of the solutions for the load-deflection characteristics of dented tubes advised by Wierzbicki and Suh [15] and the equal area axis method introduced by Jones and Birch [16] to estimate the local and global components of the total displacement from experimental

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Notation

B	the residual width of the impacted chord section after testing.
D	the diameter of top and bottom chord
DIF	the dynamic amplified coefficient under impact loading
E	the dissipated energy under impact loading
E_b	the calculated dissipated energy by bending
E_c	the sum of E_d and E_b
E_d	the calculated dissipated energy by local dent
E_e	the measured dissipated energy from the test.
E_k	the impact energy
F	impact force
H	the height between the central axes of top and bottom chord
H_0	drop height of the hammer
L_0	clear span of the impacted chord
L_t	the length of top chord,
L_b	the length of bottom chord
M_p	dynamic plastic moment of chord
T	the thickness of top and bottom chord
d	the diameter of brace
f_y	the static yield strength of steel
f_u	the static ultimate strengths of steel
h	the clear height between top and bottom chord
l_i	the length of the i^{th} plastic hinge line
m	the hammer weight
m_{pc}	the plastic moment of steel plate
r	the radius of impacted chord
r_1	the horizontal distance between plastic hinge line 1 and 2, as depicted in Fig. 12
r_2	the horizontal distance between plastic hinge line 2 and 3, as depicted in Fig. 12
r_3	the longitudinal length between plastic hinge line 5 and its center, as depicted in Fig. 12
r_4	the transverse length between plastic hinge line 5 and its center, as depicted in Fig. 12
t	the thickness of brace/impact duration
v	impact velocity
β	the rotation at saddle point B
ε	strain of steel component
$\dot{\varepsilon}$	average strain rate of steel component
δ	residual deflection of the impacted chord
δ_1	the vertical distance between plastic hinge line 1 and 2, as depicted in Fig. 12
δ_2	the vertical distance between plastic hinge line 2 and 3, as depicted in Fig. 12
δ_3	dent depth of the bottom surface of impacted chord, as depicted in Fig. 12
γ_1	the rotation at crown point A of plastic hinge line 1 depicted in Fig. 12
γ_2	the rotation at crown point C of plastic hinge 2 depicted in Fig. 12
θ	the angle between chord and brace
θ_i	the rotation of the ith plastic hinge line
θ_c	the rotation at the two ends of impacted chord

measurements, a classification of the impact response of the tubular members based on their relative resistance against shell denting and beam plastic collapse load is proposed by Cerik et al. [17]. Travanca and Hao [18] presented a procedure to develop simplified equivalent systems for efficient structural response analysis.

Moreover, recent numerical and experimental studies also indicated that the impacted tube experienced the coupling of the local and global deformations under impact loading. Cerik et al. [19] experimentally and numerically studied the resistance of steel ring-stiffened cylinders subjected to low-velocity mass impact, and a simplified analysis method was also proposed to obtain an equivalent circumferential bending strength. Qu et al. [20–22] carried out a series of experimental and numerical studies on the dynamic behaviours of tubular T- and K-joint under different impact loading conditions, with the aim to discover the failure mode and impact resistant mechanism of the tubular T- and K-joints in tubular frame. Experimental and numerical studies are performed by Wang et al. [23] to investigate the performance of T joints in a jack-up structure under lateral impact loading. Khedmati and Nazari [24] investigated the structural behaviour of preloaded tubular members under lateral impact loads by means of FE method.

At present, limited standards are recommended to design and evaluate the offshore platform subjected to impact loadings. The American Petroleum Institute (API) standards [25] recommended two formulas for assessing collision force with an assumption that the indentation in the steel tube is wedge-shaped. The NORSOK N-004 Standard [26] provides a recommendation to deal with the relationship between tube resistance and indentation due to a side-on collision. Amdahl et al. [27] investigated the resistance to denting of jacket legs and the resistance to indentation of shipside in broad side ship collision based on the analysis procedure recommended by NORSOR N-004 standard [26]. The recommended practice in DNV-RP-C204 [28] presents a design method on tubular frame jack-up suffering from ship collision and dropped objects. As the transition between strength design and ductile design in DNV-RP-C204 may be quite narrow, Storheim and Amdahl [29] considered the bow and stern impact of a 7500-ton displacement supply vessel against the column of a floating platform and against the jacket legs ad braces, and the obtained collision forces were then compared with the suggested force-deformation curves in the NORSOK code [26]. It is concluded that simplifying one body as rigid quickly led to over conservative and/or cost solution, and was non-conservative in some cases. Li et al. [30] studied the elastic and plastic response of jacket platform, and carried out an examination on NORSOK N-004 rule. Several conclusions have been drawn that NORSOK rule underestimates the resistance for certain indention due to inaccurate description of column deformation mode. Therefore, a comprehensively experimental study is necessary for the dynamic behaviour of tubular frame.

From above literature review, it is found that impact resistance of tubular structures mostly depends upon the interaction between the local indentation and the bending of the impacted components. It is also known that when the steel tube of tubular frame with a thin wall is subjected to the lateral impact loads, the local buckling of the tube surface or the bending deformation of tube and frame may lead to the deviation of the neutral axis from initial state seriously, which will aggravate the bending failure of the tube and tubular frame. There is a need to investigate the sensitivity of the local deformation on the response of tubular frame under impact. To this end, this paper examines the dynamic behaviour of two steel plane tubular frames subjected to the same impact energy through experimental investigation. One specimen is set up to be hammer impacted on the mid-span section of the top chord between two K-joints, while another is loaded on the mid-span section of the top chord within the middle K-joint. The experimental program including specimen details and test setup is introduced. The dynamic response of both frames are then described and discussed with emphasis on the effect of impact-loading locations. Additionally, based on the plastic hinge line theory, a simplified calculation method of energy dissipation is proposed and verified against the experimental results as well as some available analytical formulations elsewhere.