Thin-Walled Structures 130 (2018) 85–100

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Study on the performance of energy absorption structure of bridge piers against vehicle collision

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ARTICLE INFO

Keywords:
Bridge
Composite material
Vehicle
Collision
Experiment
Finite element method

ABSTRACT

Anti-collision structures are generally adopted to provide the protection of overpass bridge piers and reduce the damage of errant vehicles. The present paper introduces a new energy absorption device into the design of these systems, which consists of 'U' shape thin-walled steel plate with GFRP (Glass Fibre Reinforced Plastic) honeycomb-filled. A horizontal impact testing with guide system was conducted to examine the performance of the designed energy absorption structure against trolley collision. The experimental results are used to validate the FE model, which is also utilised to the parametric studies for higher impact kinetic energy and different constructions of the protection structure. It is found that the designed protection structure with thin-walled steel plate and fibre composite provide good crashworthiness and functioned well for protecting the bridge pier.

1. Introduction

Overpass bridge piers are at the risk of collision by vehicle. The collision between them results in serious repercussions, such as bridge collapse, vehicle damage and occupant injure that could lead to the loss of human life and economy. In the United States, there are 61% of overpass bridge piers were collided by errant vehicles [1]. Fifteen percentage of bridge failures were caused by vehicle impact according to the investigations of Harik et al. [2] and Lee et al. [3]. During 2001–2006, approximately half of the urban overpass bridge piers were collided by vehicle in Beijing, China, which accounted for 20% of total damaged bridge caused by accident.

With regard to the causes of bridge collapse due to the vehicle impact, it was found that there exists non-conservative requirements in AASHTO-LRFD 4th edition [4], according to the studies of El-Tawil et al. [5] and Buth et al. [6]. Hence, in 2012, the equivalent static force (ESF) of 1800 kN at a distance of 1200 mm above ground was increased to 2670 kN at a distance of 1500 mm above ground in the latest version of AASHTO-LRFD 6th edition [7]. In China, the ESF in the requirements of JTG D60 [8] and TB [9] for railway bridge is still 1000 kN at a distance of 1200 mm above ground, which is significantly smaller than that (2670 kN) in AASHTO-LRFD 6th edition [7]. Here, JTG and TB are the abbreviations of Jiao Tong Guobiao that means the standard of national transportation department and Tielu Biaozhun that means the standard of railway. This non-conservative value of ESF given in the JTG and TB requirements might not appropriate and then could increase the risk of bridge collapse collided by vehicle. However, the revision of the ESF value in the JTG and TB requirements need many researches and further verifications, which would take very long time to go.

Hence, before the updated versions of JTG and TB requirements are published, it is necessary to use the protection structure to increase the safety level of bridge piers in the vehicle impact accident [10]. Such as in BS5400 requirement [11], it states that the bridge piers that overpass highway should install protecting structure, when the speed limit of highway is beyond 80 km/h; moreover, the bridge piers at roadside within clearance zone range are also required to install anti-collision fence in AASHTO [7].

The anti-collision fence and barrier are often used to protect bridge piers. However, the specified height of barrier in AASHTO [7] is 1070 mm. In this circumstance, it is still possible that the errant vehicles with high center of gravity, e.g. truck, could impact the bridge pier after turn over the barrier [12]. Moreover, in some circumstances, there is no enough space to install barrier due to the dimensional limitation of highway width. Alternatively, installing the energy absorption structure around bridge pier is also an effective approach to protect the bridge piers and even errant vehicles.

For this reason, firstly, an energy absorption structure against

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https://doi.org/10.1016/j.tws.2018.05.008
Received 26 September 2017; Received in revised form 3 May 2018; Accepted 9 May 2018
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vehicle collision are designed for protecting bridge piers by decreasing and distributing the impact force, which intends to be installed around the bridge piers. Many different kinds of material can be used in the energy absorption structure, such as metals (thin-walled steel or aluminium [13]), polymer or aluminium foams [14], carbon-fibre reinforced polymers (CFRP) and glass-fibre reinforced polymers (GFRP) [15]. Not like car or aircraft industry that prefer to the material with light-weight and high strength to weight ratios for saving the consuming of oil, the capacity of energy absorption and cost of protection structure are the mainly priority concerned aspect for the widely application in civil engineering. Hence, considering the material from the point of economy, the thin-walled steel with GFRP honeycomb-filled is adopted in the energy absorption structure at the present study. The key advantage of this structure made of steel and GFRP is that combines their mechanism characteristics, and is also easy to be fabricated.

After the material type and principle dimensions of the energy absorption structure is determined, it is vital to evaluate its crashworthiness and performance characteristics for future utilization of this protection system. For road safety barriers, the analytical method could provide reasonable accuracy predicting the impact depth and peak force, but which only consider the rigid, concrete safety barrier [16]. With the development of numerical simulation, explicit dynamic analysis method is also an effective and efficient method for estimating the collision response for concrete barriers [17,18], safety barriers [19] and guardrails [20].

However, it is still very important to use experimental results for the validity of theoretical method. Relative to various types of road safety barriers, the experimental study of energy absorption structure consisted of 'U' shape thin-walled steel with GFRP honeycomb-filled is sparse for protecting bridge pier against vehicle collision [21]. The present paper reports the initial idea of designing the energy absorption structure, and then a horizontal impact testing was conducted to provide experimental data and understand its impact behaviour. Based on the experimental results, the FE model of the proposed energy absorption structure is developed, which is subsequently utilised to investigate the effects of various parameters on its crash performance.

2. Experimental investigations

2.1. Structural design of energy absorption structure

2.1.1. Determination of principle dimensions

The designed protection structure is supposed to be installed around the bridge pier against vehicle collision as shown in Fig. 1. The collision load (using equivalent static force (ESF)) position is 1.2 m above ground in AASHTO [7], JTG [8], TB [9], and is 1.25 m in BS5400 [11]. The height and width of action area by collision load are 0.5 m × 1.5 m in AASHTO [7] and 0.6 m × 1.5 m in BS5400 [11], respectively. Hence, the height and length of the protection structure at least should cover this area and are set as 1.5 m and 2.87 m in the present test (Fig. 2), respectively. The thickness of the protection system is very important, which should have enough space to provide the effective impact duration for energy absorption, and at the same time should be as small as possible not to obstruct the passing vehicle. Based on the numerical results of Pan et al. [22], the thickness of this protection system is 453 mm eventually after fabrication herein, which is considered as full scale structure.

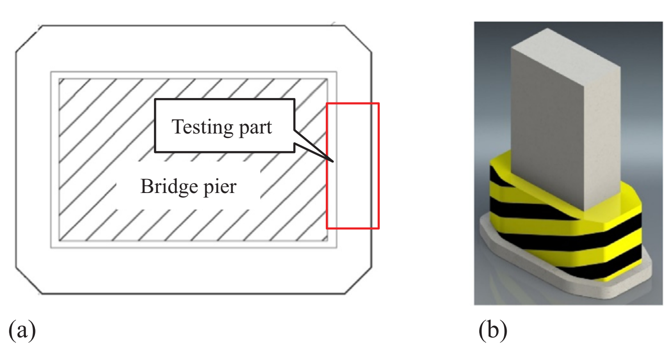

Fig. 1. Energy absorption structure.

2.1.2. Material and construction selections

As summary in introduction, there are many kinds of material and form that can be used as energy absorption structure, such as thin-walled steel and fibre-resin composites structures. The fibre-resin composites have high strength to weight ratios, but also have brittle, unstable failure modes including extensive micro-cracking development, delamination, fibre breakage [23]. Steel material provides the ductile and stable plastic mechanism behaviour, and then gives controlled and stable failure mode during absorbing impact energy [24]. Recently, plenty study results showed that the combination structures of metal and fibre-resin composite could utilize their each advantage of mechanic characteristics, which are the ductile plastic of metal and the high strength of FRP. Using the fibre-reinforced metal structure, it was found that the crush resistance and capacity of energy absorption per unit mass increase around 82% and 52%, respectively [25].

To identify the potential novel crashworthiness for steel sandwich panel under lateral impact, Klanac et al. [26] performed a qualitative assessment of 10 different core geometries. It was found that the steel sandwich structures with X and channel (U) shaped core geometries have good impact tolerance and potential capacity of energy absorption, which have been also tested by Wevers and Vredeveldt [27] and Xu et al. [28] for investigating their impact behaviour. If only fibre-resin composite was used as protection structure, various moulds with different dimensions and shapes are needed for manufacturing this kind of structure, which would significantly increase total economy cost. Moreover, when the energy absorption structure with steel frame by welding is installed around bridge piers, and their shapes could be easily fitted each other (Fig. 1). The shape and dimension of bridge piers are various in many circumstances. Hence, considering the fabrication process, 'U' shape thin-wall mild steel is adopted as external framework structure that is denoted as solid-black line (Fig. 2).

For the form of filled structure, the honeycomb structure could give high capacity of total absorbed energy per unit mass [15,29], which can be made of aluminium or fibre-resin composites including glass, carbon and Kevlar fibres. Carbon and Kevlar fibres have very high strength and stiffness values, and are widely used in many industry applications [30,31]. However, glass fibre is less expensive than aluminium, carbon and Kevlar fibres, hence, considering the financial cost and fabrication process, GFRP hexagon tubes are adopted as filled structure as shown in Fig. 2. Before this testing, a series of numerical simulations had been conducted for the analysis of crashworthiness optimization by Pan et al. [22], and the corresponding results were used to determinate the principal dimensions and construction of the energy absorption structure. The thicknesses of steel plate and GFRP hexagon tubes are 3 mm and 3.2 mm; the laminate set-up of fibre-resin composites is set as $[0^{\circ}/90^{\circ}/45^{\circ}/-45^{\circ}]_s$ and its thickness of each layer is 0.2 mm. The GFRP honeycomb structure has been manually fabricated by tape laying on a hexagon mould.

The black solid lines present the thin-walled steel and the steel plates are also used on outer top and bottom surfaces to hold the components of the structure together. The hexagon GFRP tubes were adhered together by Epoxy resin adhesive, which were directly put into the steel frame. For the convenience of fabrication, there were no adhesive between steel plate and GFRP tubes. The shapes of 'U' shape thin-walled steel are the same with the honeycomb of GFRP tubes, which could provide constraint between them.

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