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Performance and dynamic behaviour of FRP strengthened CFST members subjected to lateral impact

Md Iftekharul Alam [a], Sabrina Fawzia [a,*], Xiao-Ling Zhao [b], Alex M. Remennikov [c], M.R. Bambach [d], M. Elchalakani [e]

[a] School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology (QUT), 2 George Street, Brisbane, QLD 4000, Australia
[b] Department of Civil Engineering, Monash University, Clayton, Victoria 3800, Australia
[c] School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW 2522, Australia
[d] Department of Civil Engineering, The University of Sydney, Sydney, Australia
[e] The School of Civil, Environmental and Mining Engineering at the Faculty of Engineering, Computing and Mathematics, The University of Western Australia, Australia

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ABSTRACT

Due to the increasing popularity of concrete-filled steel tubular (CFST) members, there will be more chances of vehicles/vessels or terrorist attacks on these structures in near future. Fibre-reinforced polymer (FRP) strengthening can be an effective option to reduce impact damage or failure of CFST members. However, existing knowledge is very limited in understanding the behaviour of FRP strengthened CFST structures under lateral impact loading. This paper outlines drop hammer impact test results of a series of experimental programs of bare and FRP strengthened CFST specimens. A total of sixteen CFST specimens were prepared and tested under lateral impact at their mid-span. The results indicate that permanent lateral displacement of CFST members can be reduced up to 18.2% by externally bonded FRP sheets. The effects of FRP type, FRP wrapping direction, carbon fibre-reinforced polymer (CFRP) wrapping layers, wrapping length, and impact velocity were investigated to understand the influences of these parameters on the behaviour of strengthened CFST specimens. CFRP laminates were found to be weak under impact loading when wrapped in only longitudinal direction. However, a combination of longitudinal and hoop layers of CFRP laminates, or only GFRP wrapping, can remarkably minimise the severity of damage and failure of FRP in CFST specimens under lateral impact. A comparison of current test results with recent works has been presented to understand the effect of impact energy on the lateral displacement control ability of FRP strengthened CFST members.

1. Introduction

The application of concrete-filled steel tubular (CFST) structures has been growing rapidly in the construction industry. The faster construction and superior mechanical properties are the major advantages of these members over the reinforced concrete (RC) structures. In recent years, CFST members have been a very popular choice to use, not only as structural columns, but also in other forms of structural components such as bridge girders, utility transmission towers [1], and jacket legs and braces of offshore structures where axial static force is very low or negligible. Lateral impact forces may be expected on these members from transportation accidents, explosive attacks or from flying debris. Lateral impact loads can cause significant damage or failure of CFST members, if they are not designed to withstand these external imposed actions. A suitable strengthening technique needs to be developed to protect these CFST members where lateral impact force is more likely to be expected.

The fibre-reinforced polymer (FRP) wrapping of RC structures using high strength structural epoxy adhesives is a proven technique to enhance the capacity of the RC structural members. However, compared to the RC structures, literature is limited on the behaviour of FRP strengthened steel and steel-concrete composite structures. Over the last decade, researchers in the field of structural engineering have given their attention to investigating the effectiveness of FRP strengthening of metallic structures. A good number of studies have been conducted to understand the joint behaviour between carbon-fibre reinforced polymer (CFRP) sheets and steel plates under both static and dynamic loads [2–10].

* Corresponding author.
E-mail addresses: mdiftekharul.alam@hdr.qut.edu.au (M.I. Alam), sabrina.fawzia@qut.edu.au (S. Fawzia), ZXL@monash.edu (X.-L. Zhao), alexrem@uow.edu.au (A.M. Remennikov), mike.bambach@sydney.edu.au (M.R. Bambach), mohamed.elchalakani@uwa.edu.au (M. Elchalakani).

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Nomenclature

H	Impactor height
F_p	Peak impact force
F_r	Residual impact force
δ_p	Peak lateral displacement
δ_r	Residual lateral displacement
$CFRP_{Test}$	Epoxy cured CFRP laminate properties obtained from test
$GFRP_{Test}$	Epoxy cured GFRP laminate properties obtained from test

Strengthening of different hollow steel structures using CFRP sheets and plates under static loadings has shown great potential from experimental and numerical observations [11–21]. The performance of CFRP strengthened square hollow section (SHS) steel columns under lateral impact loading was investigated by Alam et al. [22,23]. Very recently lateral impact tests of FRP strengthened circular hollow-section (CHS) steel members were conducted to understand the failure modes and effect of FRP wrapping of strengthened members [24].

The axial compressive load enhancement of CFRP strengthening of CFST columns was noticed in early studies [25–32]. A number of recent works have shown that CFST columns provided improved impact resistance capacities compared to hollow tubular columns [33–36]. Thus, further strengthening of the CFST column can be a promising composite member to safely carry both axial static and lateral impact loads. In addition to that, FRP strengthening is highly effective to prevent corrosion of outer steel surfaces in sea water and any harsh environments. However, research of CFRP wrapped CFST columns subjected to lateral impact is very limited. Chen et al. [37] conducted drop mass impact testing of CFRP and glass-fibre reinforced polymer (GFRP) strengthened CFST columns. GFRP wrapping was found to be successful to minimise lateral displacement up to 50% of that of the bare specimen. Another very recent experimental research work has also confirmed that CFRP wrapping helped to increase the stiffness of strengthened CFST members subjected to falling mass impact [38]. The Finite Element (FE) numerical models of CFRP wrapped CFST columns were developed and validated in another study [39]. The results showed that after a certain bond length, any further extension of the wrapping length had a negligible or no effects on the deflection of CFST columns [39]. To examine the effect of a realistic vehicular impact, full-scale CFRP strengthened columns with a simplified vehicle model were previously developed [40,41]. The results of the analyses have shown that full CFST columns in low-rise buildings are vulnerable under vehicular impact loading with a vehicle speed of 90 km/h or more. Also it was found that, CFRP wrapping can successfully prevent the failure of CFST columns by providing additional tensile capacity from the tension face of the columns [40].

It is very important to understand the actual structural responses and dynamic failure behaviour of FRP strengthened CFST members under lateral impact through experimental tests. In the study of Chen et al. [37], the plastic deformations of the specimens were not significant due to low impact energy. Thus, it was not possible to understand the failure mechanism of FRP laminates after the tests. Moreover, the impactor and FRP wrapped specimens were not in direct contact due to the steel plate clamping at the impact zone and the actual failure modes of FRP strengthened specimens at impact location were unknown. In the case of Shakir et al. [38], they only considered one CFRP layer with one-third of the span length. According to the current knowledge of the authors, none of the above experimental works explicitly investigated the failure pattern of wrapped FRP sheets in CFST specimens depending on the FRP type, wrapping orientation and FRP thickness as well as the effect of different wrapping lengths. In summary, the difference of the current work described in this paper and prior works includes (i) sufficient impact energy is employed to produce plastic deformation in the specimens, (ii) test setup to ensure direct contact of impactor and FRP wrapped specimens so that local failure can be investigated, (iii) wide range of parameters are considered such as FRP type, wrapping orientation, FRP thickness and FRP bond length. Therefore, this paper aims to investigate the failure behaviour of FRP sheets and the structural responses of bare and strengthened CFST members against lateral impact by considering the above parameters (FRP type, wrapping orientation, FRP thickness and FRP bond length) to better understand the dynamic behaviour of such strengthened structures. A total of 16 specimens were tested with the combination of bare, CFRP and GFRP strengthened CFST members. The results are presented in terms of lateral displacement, impact force and failure modes of CFST and FRP sheets. The effects of different governing parameters were investigated followed by comparison of present results with early studies.

2. Experimental program

2.1. Materials properties

Five different materials: concrete, steel, CFRP, GFRP and epoxy adhesive were used in this research to prepare the FRP strengthened CFST specimens. The core concrete was supplied by Hymix Australia Pty Ltd with a maximum aggregate size and nominal compressive strength of 10 mm and 25 MPa, respectively. Five concrete cylinders of 100 mm in diameter and 200 mm in length were prepared according to the AS1012.9 [42] to determine unconfined compressive strength of the concrete sample. Another three cube specimens with dimensions of 100 mm × 100 mm × 350 mm were cast as specified in AS 1012.8.2:2014 [43] to obtain the tensile properties of the concrete by flexure testing. The compression tests were performed using a 2000 kN Instron universal testing machine as shown in Fig. 1(a). An axial extensometer with 150 mm gauge length was used to accurately measure the axial strains of the specimens (Fig. 1(a)). The four-point bending test setup of the concrete cube sample is displayed in Fig. 1(b). The average unconfined compressive strength and tensile flexure strength of concrete within a week of impact test were 29.7 MPa and 4.2 MPa, respectively. Cold-formed steel pipes of 6500 mm length were cut to 1600 mm length circular hollow section (CHS) steel tubes for specimen preparation. The outer diameter and wall thickness of tubular specimens were 114.3 mm and 4.5 mm, respectively. The specimens were supplied by OneSteel Limited, Australia, and manufactured as Grade C250L conforming to AS 1163 [44]. The standard steel coupons were fabricated from CHS steel tubes according to AS 1391 [45] to obtain the mechanical properties of the steel material. The average elastic modulus, tensile strength, and yield stress were 211 GPa, 366 MPa and 317 MPa, respectively. CFRP material used for the strengthening purpose was supplied by BASF Construction Chemicals Australia Pty Ltd. The CFRP sheets were commercially known as MBrace Fib 300/50 CFS. The unidirectional GFRP composite sheets used in this study were provided by CG