Nonlinear finite element analysis of Concrete Filled Steel Tube (CFST) columns under projectile impact loading

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Abstract

This paper presents a three dimensional nonlinear finite element analysis for Concrete Filled Steel Tube (CFST) columns subjected to lateral impact load. The finite element models were developed using commercial code ABAQUS/Explicit, which were validated against the experimental results. The study has been carried out to examine the influence of several parameters such as the length of the tube and projectile configurations. The Laser Doppler Velocimeter (LDV) and High Speed Camera (HSC) were used to capture the impact velocity and the deflection of the specimens, respectively, which were then implemented in the numerical modelling. It was found that the finite element simulations are in a good agreement with the experimental results, in terms of load-displacement traces and deformation modes. It was also demonstrated that with the increasing the length of the tube the lateral displacement was increased and the impact force was decreased.

Keywords: Concrete filled steel tube, Impact, Failure, Finite element analysis.

Introduction

Concrete Filled Steel Tube (CFST) is increasingly used in many structural applications such as seismic-resistance constructions, high buildings, bridges' piers, decks of railways, and offshore structures [Shanmugam and Lakshmi (2001); He et al. (2011); Sundarraja and Prabhu (2011)]. CFST have more advantages than the conventional reinforced concrete and steel structures, namely high speed of construction work resulted from the omission of framework and the reinforcing bars, low structural costs and conservation the environment [Morino et al. (2001); Morino and Tsuda (2002); Starossek et al. (2008)]. CFST offered a good damping merits and excellent seismically resistant [Kang et al. (2007)].

In recent years, a number of researches had been conducted to study the impact behavior of the CFST members through experimental and theoretical works and finite element analysis. [Bambach et al. (2008); Deng et al. (2012); and Al-Thairy and Wang (2013)]. [Wang et al. (2013)] investigated the impact performance of the concrete filled steel tube members. It has been demonstrated that the lateral deflection and the impact force have been affected by the axial load.

At present with the development of digital computers and numerical techniques, the finite element method (FEM) has emerged as a powerful analytical tool for structures analysis. This is opened spacious world for engineers to model rationally many aspects of the phenomenological behaviour encountered in CFST [Starossek et al. (2008)]. These aspects include the confinement effect, modelling of cracking and crushing, the behaviour of the materials properties after cracking and crushing and many other properties.

Due to the ability of finite element technique to simulate the behaviour and the failure mode of CFST, many numerical studies were conducted to study the behaviour of CFST with various parameters and different type of loadings.

[Schneider (1998)] presented experimental and a numerical study to investigate the behaviour of CFT under axial compression load. ABAQUS software programme was used in this study. The concrete core was modelled with 20-node brick element while the steel tube modelled with 8-node shell element, a gap element was used to simulate the contact behaviour between steel and concrete core. Uniaxial stress-strain curve with the available model in ABAQUS was used to simulate the behaviour of concrete with confinement effect. A comparison between the numerical and experimental results was made and it showed a good agreement for the columns strength and the failure mode.

[Yu et al. (2010a)] presented a nonlinear finite element analysis study on concrete filled steel tubular frame structures undergo dynamic load in fire conditions. Steel I-section beams and circular CFST columns composed the frame structures. The numerical results were in good agreement with the test results. It was concluded that the bending moment of the CFST subjected to fire was highly affected and reduced due to the internal forces redistribution in the frame.

[Deng et al. (2012)] carried out a theoretical and numerical research to study the CFSTs and post-tensioned CFSTs under flexural load. The concrete properties were modelled using Drucker-Prager plasticity model, while the behaviour of steel tube was modelled as elastic-perfectly plastic. The results predicted from the theoretical sectional analysis and finite element model were compared with the test results. It was found that both of the theoretical sectional and finite element analyses were efficient to predict the ultimate moment capacity.

A study of three test series had been conducted by [Yousuf et al (2012); (2013); and (2014)]. They investigated the transverse impact resistance of the hollow and concrete filled mild and stainless steel square tube columns. This study included both static and dynamic tests. The performance of the hollow and concrete filled mild and stainless steel tube columns was studied through finite element analysis using the software ABAQUS. The numerical results showed a good agreement with the experimental findings. They found that the impact energy was improved by using the stainless steel columns and the axial compressive load affects the static and impact strength especially for the stainless steel tubes.

The main aim of this study is to perform a numerical simulation of CFST columns subjected to lateral impact loading using the nonlinear finite element programme ABAQUS.

Experimental work

Twenty two specimens of CFST column with outer diameter 114.3 mm and 3.6 mm wall thickness have been tested under lateral impact loading with height 2.6 m and maximum mass 107.5 kg as shown in Fig. 1. The specimens were in three different lengths (686, 1029, and 1543) mm short, medium and long tubes respectively. To examine the indenter shape effect on the behavior of the CFST, two types of indenter were used in this test; the first one is spherical indenter with three different diameters 60 mm (BI), 40 mm (MI) and 20 mm (SI). The second type is Flat Indenter (FI) with 40 mm square section. A high strength steel clamp was used to provide a fixed ends for the specimens to simulate the real case of the fixed ends column. A Laser Doppler Velocimeter (LDV) with the Dantec Flowlite LDV system was used to obtain the impact force and local indentation in this study. A High Speed Camera (HSC) was used to capture the local and overall displacement and the mode of failure of the specimen. It has been concluded that with increasing the specimen's length, the peak force decreased and the local displacement increased and the increasing of the spherical diameter leads to increase the peak force and reducing the local indentation.

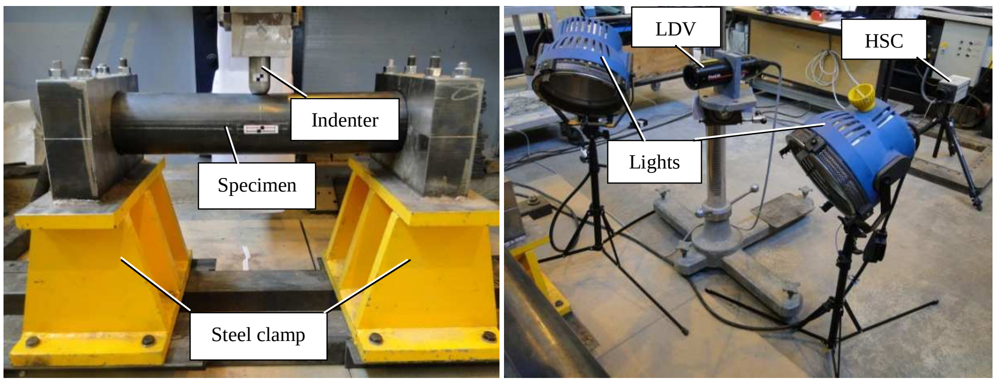


Figure1. The experimental work setup with data recording system

Finite element modeling

General

The commercial finite element program ABAQUS was used to simulate the behaviour of the CFST columns under lateral impact loading. There are two main constituent materials considered to model the impact behaviour of CFST column. The materials are the concrete core and the steel tube. In addition, the type and the properties of the contact between the steel tube and the concrete core are very important to simulate the CFST.

Finite element type and boundary conditions

Due to the symmetry, three dimensional models are used to model a quarter of CFST columns as shown in Fig. 2. The three dimensional eight nodes solid element with reduced integration C3D8R is used to model the concrete core and the steel tube while the R3D4 is used to model the indenter and the steel clamp. To provide accurate results, many models with different mesh sizes have been tried to find out the moderate element size with reasonable computational time. To simulate the experimental test conditions, the clamp was restrained in all direction to provide a fixed case while the tube end was free in the axial direction of the columns and fixed with the other directions. The indenter was restrained against all degree of freedom except for the vertical displacement. Symmetric boundary conditions were applied on the symmetric plans.

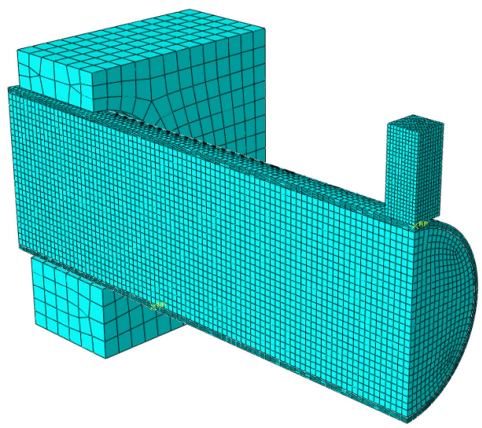


Figure2. Finite element mesh of CFST

Materials modelling

The stress-strain curve of the steel tube is assumed to be elastic perfectly plastic, the elastic modulus and Poisson’s ratio were 200 GPa and 0.3 respectively. The (*Plastic option) in ABAQUS is used in steel material model

The Concrete Damage Plasticity available model in ABAQUS 6.13 is used in this study to describe the behaviour of the confined concrete in CFST columns under impact loading with both tension stiffening and compression hardening definition. Both of the elastic and plastic parts are included for the concrete model.

The confined concrete stress-strain models described by [Hu et al. (2003)] is used in this study. [Ellobody et al. (2006) and Dai and Lam (2010)] were adopted this model in their numerical analysis and the finite element results showed a good agreement with the experimental work data. The difference between the stress strain relationship for confined and unconfined concrete is showed in Fig. 3

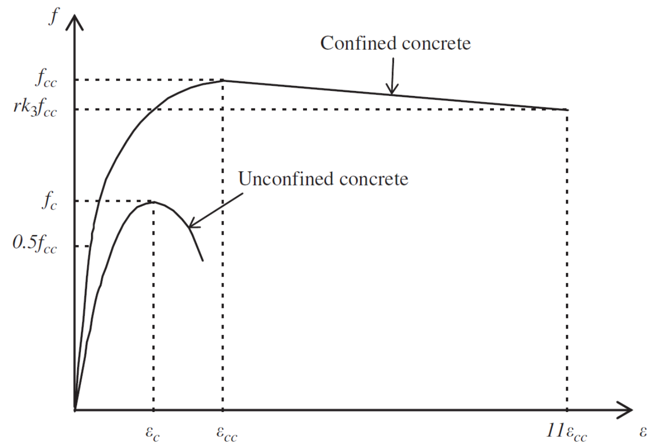


Figure 3. Stress-Strain relationship for confined and unconfined concrete (Dai and Lam, 2010)

Where f_{ck} is the cylinder compressive strength of unconfined concrete which is equal to eighty percent of the unconfined cube strength $0.8f_{ck,\ cube}$. While f_{cc} is the cylinder compressive strength of confined concreter. ε_{ck} and ε_{cc} are the corresponding strain for f_{ck} and f_{cc} respectively. The axial compressive strength for confined concrete structural hollow section can be predicted by the proposed relationship between f_{cc} and f_{ck} [Mander and Priestley (1988)].

$$f_{cc} = f_{ck} + k_1 f_l \tag{1}$$

$$\varepsilon_{cc} = \varepsilon_{ck}\left(1 + k_2 \frac{f_l}{f_{ck}}\right) \tag{2}$$

[Richart et al. (1928)] suggested the value of the constant k_1 and k_2 to be 4.1 and 20.5 respectively and the strain of unconfined concrete ε_{ck} can be taken 0.003 [ACI (1999)]. Based on the formulas proposed by [Hu et al. (2003)], the lateral force f_l value can be predicted:

$$f_l/f_y = 0.043646 - 0.000832(D/t) \qquad for\ 21.7 \leq D/t \leq 47 \tag{3}$$

$$f_l/f_y = 0.006241 - 0.0000357(D/t) \qquad for\ 47 \leq D/t \leq 150 \tag{4}$$

Where D is the outer tube diameter, t is wall thickness of the tube and f_y is the yield strength of the tube. [Hu et al. (2003) and Ellobody et al. (2006)] suggested the proportional limit stress for the linear part in the confined concrete stress-strain curve (elastic) to be $0.5f_{cc}$. The modulus of elasticity for the confined concrete E_{cc} can be predicted by the [ACI (1999)] empirical formula which expressed as $E_{cc} = 4700\sqrt{f_{cc}}$ MPa [Dai and Lam (2010)]. The nonlinear portion of the curve represents the compressive strength f between the elastic limit $0.5f_{cc}$ and the maximum compressive strength f_{cc}. [Saenz (1964)] suggested formula to predict f:

$$f = \frac{E_{cc}\varepsilon}{1+(R+R_E-2)\left(\frac{\varepsilon}{\varepsilon_{cc}}\right)-(2R-1)\left(\frac{\varepsilon}{\varepsilon_{cc}}\right)^2+R\left(\frac{\varepsilon}{\varepsilon_{cc}}\right)^3} \tag{5}$$

Where

$R_E = \frac{E_{cc}\varepsilon_{cc}}{f_{cc}}$,$R = \frac{R_E(R_\sigma - 1)}{(R_\varepsilon - 1)^2} - \frac{1}{R_\varepsilon}$,$R_\sigma = R_\varepsilon$=4

The start of the third portion of the strain-stress curve is f_{cc} while its end is f_u. ε_u =11ε_{cc} is the correspondence strain at $f_u = rk_3 f_{cc}$ [Hu et al. (2003); Ellobody and Young (2006b); Ellobody et al. (2006); Dai and Lam (2010)]. For the circular steel tube section with $21.7 \leq \left(D/_t\right) \leq 150$, the value of the parameter k_3 can be obtained from the proposed by [Hu et al. (2003)].

$$k_3 = 1 \qquad for\ 21.7 \leq \left(D/_t\right) \leq 40 \tag{6}$$

$$k_3 = 0.0000339\left(D/_t\right)^2 - 0.0100085\left(D/_t\right) + 1.3491 \quad for\ 40 \leq \left(D/_t\right) \leq 150 \tag{7}$$

According to [Giakoumelis and Lam (2004); Ellobody and Young (2006b); Ellobody et al. (2006); Dai and Lam (2010)] the value of r with compressive cube strength of 30 MPa can be taken as 1.0 while with compressive strength of 100 MPa as 0.5, a linear interpolation used with compressive strength between 30 MPa and 100 MPa.

The tension stiffening for the concrete is defined as a displacement using the model proposed by [Li et al. (2002)] as shown in Fig. 4

$$\sigma = f_t\left\{1 - exp\left[-\left(\frac{0.05}{w_c/_{w_{ccr}}}\right)^{1.3}\right]\right\} \tag{8}$$

Where *ft* is the concrete tensile stress and it is obtained from the equation:

$$f_t = 0.34\sqrt{fc'} \tag{9}$$

Where and *fc'* is the compressive strength of concrete.

The w_c and w_{ccr} are the crack width and the critical crack width respectively. 1.5 mm is taken for the critical crack width in this study. The adopted concrete Poisson's ratio is 0.2.

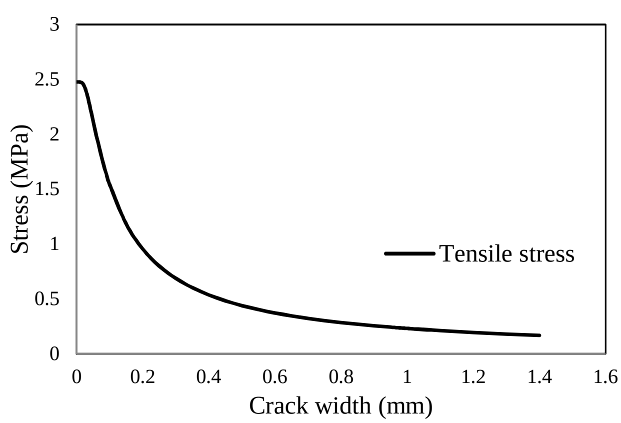
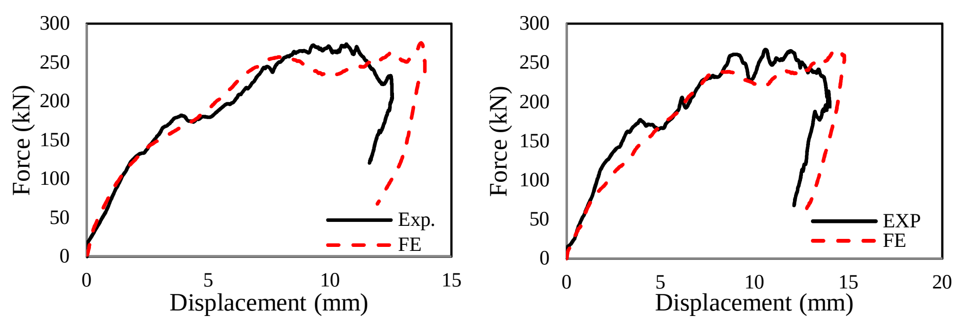


Figure 4. Concrete material behavior model in tension

The surface to surface contact was defined between the indenter and the steel tube and between the steel tube and the clamp with hard contact option and coefficient of friction 0.01 and 0.1 for the interaction between the indenter and the tube and between the clamp and steel tube respectively. To model to interaction between the concrete core and the steel tube a pressure contact was defined. The coefficient of friction adopted in this study was 0.2.

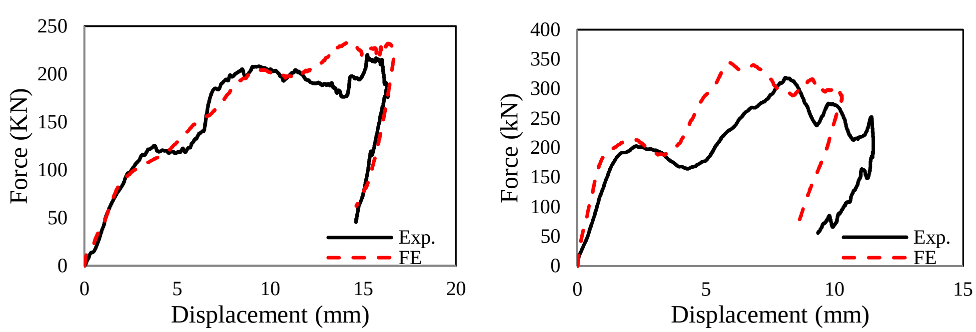
Results and discussion

The results of the numerical analysis for CFST columns with different indenter are compared with those obtained from the experimental tests and the curves of the impact force versus local indentation for these specimens are plotted against the experimental results in Fig. 5, 6 and 7. The deformed shapes for these columns are also examined. In General it can be seen that the numerical results show good agreement with the experimental data. For the short columns tested with (BI) in Fig 5 (a) the difference between the results was only 2.2 % and 8.4% for the peak force and local displacement respectively while the difference for the columns tested with medium indenter was 0.81% for the peak load and 5.58% for the local displacement as shown in Fig. 5 (b). The impact force for short CFST column tested with SI using the finite element analysis was 232.31 kN at a local displacement 16.67 mm compared with the experimental values of 220.13 kN and 16.36mm as shown in Fig 6 (a). In terms of the local displacement, stiffer results were obtained from the numerical analysis compared with the experimental data for the short columns tested with FI which were 9.89 mm and 11.1 mm for the numerical and experimental results respectively. However the maximum difference between the peak forces obtained from the finite element analysis and the one evaluated from the experimental test was 7.37% as shown in Fig. 6 (b).



(a) (b)

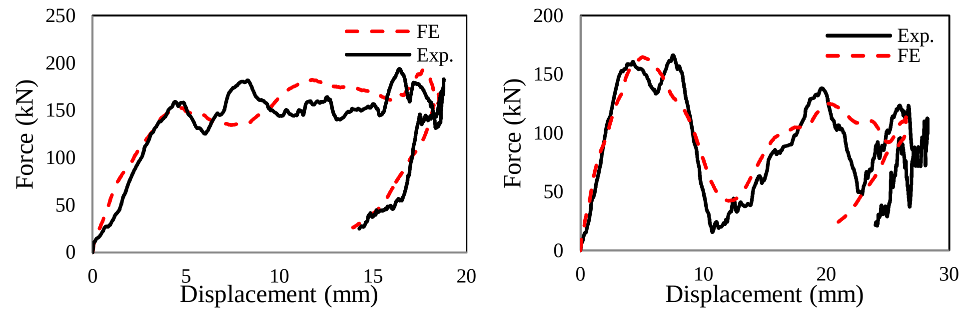
Figure (5) Load-deflection curve for the short CFST column with (a) BI (b) MI



(a) (b)

Figure (6) Load-deflection curve for the short CFST column with (a) SI (b) FI

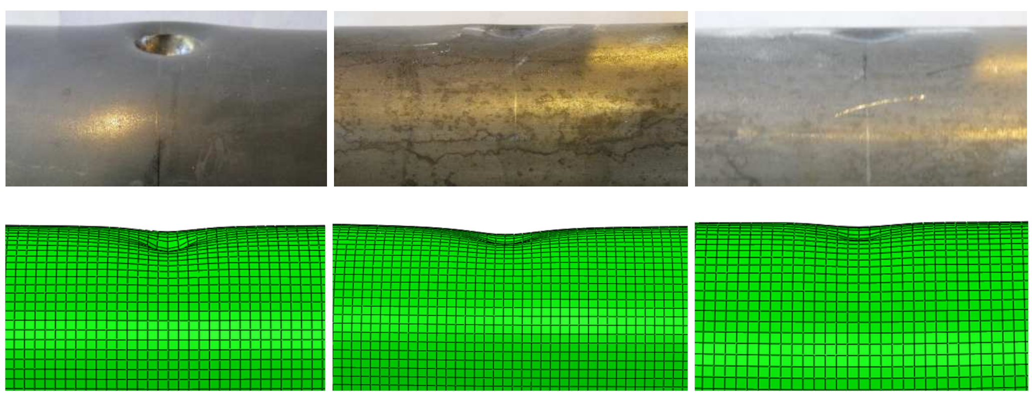
Fig. 7 (a) and (b) show the good agreement between the experimental and numerical results for the medium and long CFST columns respectively. The experimental and numerical peak force and the local displacement for medium CFST columns were 193.68 kN, 18.78mm and 187.87 kN and 18.54 respectively. The numerical simulation for the long CFST columns was able to capture the beak force reduction which resulted from the vibration of the tested columns during the test with same natural frequency of the whole system tested as shown in Fig. 7 (b).



(a) **(b)**

Figure (7) Load-deflection curve for the short CFST column with (a) medium tube (b) long tube

From the comparison between the failure mode of the experimental test and numerical model for the short, medium and long CFST columns, the numerical failure modes were in good agreement with those obtained from the experimental tests as can be seen from Figs. 8 (a), (b) and (c).



(a) (b) (c)

Figure (8) Experimental and numerical failure mode (a) Short tube (b) Medium tube (c) Long tube

5 Conclusions

The paper presents the numerical analysis of CFST columns under lateral impact loading. The concrete was molded using an equivalent stress-strain curve for the confined concrete while the steel tube was molded as elastic-perfectly plastic material. The predicted impact force, local displacement and the failure mode using the finite element analysis were compared with those evaluated from the experimental tests of the CFST columns. The comparison between the numerical experimental and finite element results showed a very good agreement for both the force-displacement curves and the deformed shape.

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