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ANALYSIS OF CONCRETE FILLED STEEL TUBE (CFST) COLUMNS SUBJECTED TO LATERAL IMPACT LOADING

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ABSTRACT

Concrete Filled Steel Tubes (CFST) are widely being used for building bridge piers, transmission towers, high rise buildings, seismic resistance buildings etc. There might be some accidental loads and impact occurring during the life of the structure. The following work has been carried out to analyze the CFST columns under lateral impact loading. A study on drop hammer impact test at mid-span of CFST column is used for required input data. The analysis is based on the dissipation of kinetic impact energy by formation of plastic hinges in the column. The analysis is carried out using MATLAB R2018b. Analysis results for force & displacement are compared with experimental values; with Eurocode EN1991-1.7 for impact load; with non linear FEM models using Abaqus/CAE 2018. Analysis results are further studied for various parameters.

KEYWORDS: *CFST column, lateral impact, MATLAB, plastic analysis.*

1. INTRODUCTION

A number of structural constructions are employing the use of CFST for building bridge piers, transmission towers, high rise buildings, seismic resistance buildings etc. When CFST is used in a structure as a column element, it mainly experiences axial load; and sometimes accompanied with bending moment. There might be some accidental loads and impact occurring during the life of the structure.

Extensive studies have been made regarding failure of CFST column under axial loads. The effects of flexure, buckling, bearing capacity etc have been studied for axial loads, but very few studies and experiments were carried out to study the behavior of CFST columns under lateral impact load. In recent years, few studies have been made on the impact behavior of CFST columns.

The following work has been carried out to analyze the CFST columns under lateral impact loading. An experimental study on drop hammer impact test at mid-span of CFST column is used for required input data [1]. The analysis is based on the dissipation of kinetic impact energy by formation of plastic hinges in the column. Max deflection & max impact force is studied for the experimental data available. The analysis is carried out using MATLAB R2018b. Analysis results for force & displacement are compared with experimental values; with Eurocode EN1991-1.7 for impact load; with non linear FEM models using Abaqus/CAE 2018. Analysis results are further studied for various parameters like length of tube, diameter & thickness of tube, grade of steel & concrete, mass & height of drop hammer, shape of indenter etc

1.1: Impact Load

Impact is said to occur when a mass strikes another mass with certain velocity. It can also be illustrated as a large quantity of force acting in a small duration of time. It is a single cycle dynamic load and the analysis is quite complex due to rapid increase in strain[2]. Since impacting body and the targeted body are in contact, it brings in the concept of 'conservation of energy' and also 'conservation of momentum'. At the time of contact, impact energy will produce instant stress waves at the targeted area and the structure is supposed to withstand the induced strains and deformations.

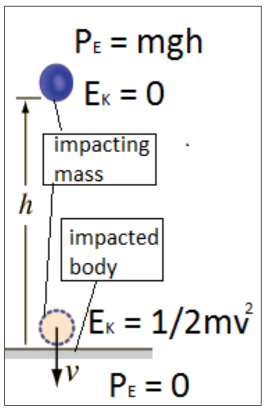

Fig1: Drop weight impact- Conservation of energy

The law of conservation of energy states that 'kinetic energy (E_K) remains equal to the potential energy (P_E)' as depicted in Fig 1. After impact, there are generally two responses in the structure. (a)Local response (spalling, perforation, indentation etc) due to stress wave at the point of impact; (b)Overall response (deformation) in the whole structural member. [3]

1.2: Plastic Analysis

Plastic analysis is carried out for the present study as it is more rational and has a quicker approach. A structure can sustain higher quantity of load than the load at yield. To determine the actual collapse load, plastic analysis proves useful. It summarizes that 'a structure will only fail when it has lost all its redundancies'. For this type of analysis, the cross section of an element is essential. Plastic hinges are assumed to be formed in an element when the section can rotate freely once the plastic moment capacity exceeds.

2. LITERATURE REVIEW

A three dimensional non linear FEM analysis using Abaqus/Explicit was done and the results were validated against experimental values. Load-displacement curves & deformation modes were studied by Shakir et al[4]. The results showed that increase in tube length increases lateral displacement and decreases impact force. Further studies were made which including Carbon Fiber Reinforced Polymer (CFRP) & use of recycled aggregate in the concrete. The study concluded that both normal & recycled aggregate have similar deformation mode and similar impact resistance.[1]

A drop hammer test at mid-span of CFST was conducted by Wang et al to study residual deformation mode and time history of impact loads[5]. Parameters such as displacement, duration & stability of impact were studied at different axial load levels. It was concluded that CFST columns behave in a ductile manner under impact. Axial load level has significant effect on impact force.

An experimental analysis was made to study the residual axial bearing capacity of CFST specimens after impact. The effect of varying thickness of tubes & heights of tubes was taken into account. Failure mode, load-displacement curves, load-strain curves etc were extensively studied. The study showed that bearing capacity increases with increased D/t ratio. [6]

3. EXPERIMENTAL ARRANGEMENT

3.1: Test set up

A drop hammer impact test was conducted at the mid-span of CFST columns by Shakir et al[1] and this data has been used for further analysis in this study. Fig 2 shows the illustration of the experimental set up. Eighty four hollow and concrete filled specimens were studied.

3.2: Material properties

The density of concrete is 2627kg/m^3, the 28-day cube compressive strength of concrete was found to be 56 MPa. W/C ratio of 0.46 was adopted for mix proportion. Cold formed circular steel tubes with yield strength 450MPa & ultimate strength 542 MPa are used. Elastic modulus of steel was 200 GPa with Poisson's ratio 0.3.

3.3: Specimen properties

The outer diameter (D) 114.3 mm & thickness (t) 3.6 mm are taken. The specimen is cut into 3 different lengths of tube: 686 mm (6D), 1029 mm (9D) and 1543 mm (13.5D) for S, M, and L i.e. short, medium & long tubes respectively. Two different sections of indenters were used: Spherical with 3 diameters 60 mm (BI), 40 mm (MI) and 20 mm (SI); flat indenter (FI) with 60 X 60 mm square section. Maximum height of rig (H) was 2.6m and masses were 106, 106.5, 107 and 107.5 kg for SI, MI, FI, and BI respectively. 'h' refers to hollow & '0' refers to filled tubes.

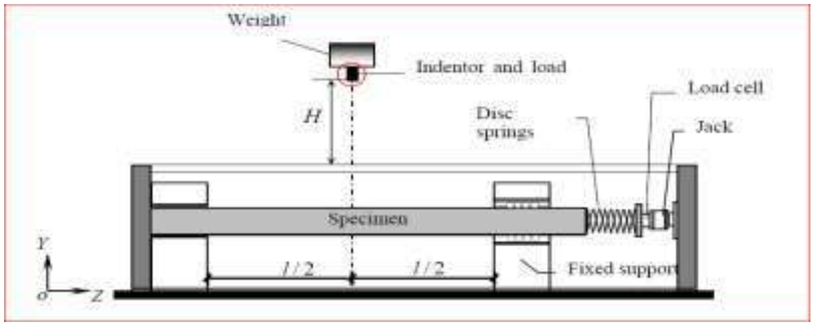

Fig2: Schematic view of test set up

3.4: Experimental data

Tube ID	Outer dia, D(mm)	Length L (mm)	L/D	Mass M (kg)	Displacement δ (mm)	Impact force F(kN)
S0	114.3	686	6	106.5	19	217.3
M0	114.3	1029	9	106.5	18.8	193
L0	114.3	1543	13.5	106.5	28.2	166
S-h	114.3	686	6	106.5	52.2	84
M-h	114.3	1029	9	106.5	57.1	98.7
L-h	114.3	1543	13.5	106.5	68.7	64.7
S0-SI	114.3	686	6	106	16.4	220.1
S0-MI	114.3	686	6	106.5	14	266
S0-BI	114.3	686	6	107.5	12.9	286.3
S0-FI	114.3	686	6	107	11.2	319

Table1: Experimental data

4. ANALYSIS

MATLAB R2018b is used to obtain the maximum displacement & impact force. The problem statement is initially defined & the objectives are outlined. The codes including functions, conditions & loops are scripted in MATLAB editor with proper syntax. Fig 3 shows a MATLAB editor window. Respective formulae & data are input in matrix and vector form wherever necessary.

Bambach [7] proposed a formula for impact force including shape factor for indenters, modification factors for tube length etc. These relations are in good terms with the experimental values & hence favorably used in this work. Impact force is calculated using relation (1). But this is applicable for L/D ratio between 14 and 35. For short length tubes, force can be calculated using relation (2) [1].

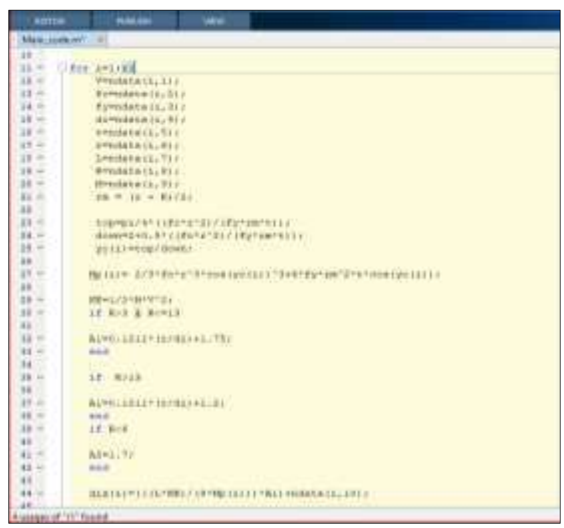

Fig 3: MATLAB editor

$$F= (6M_p/L)(N_0\delta_{max}/4M_p)^2 + (8M_p/L) \quad (1)$$

$$F=((6M_p/L)(N_0\delta_{max}/4M_p)^2+(8M_p/L)) \times B \times C \quad (2)$$

Here N_0 is fully plastic axial force (3) and B, C are modification factors (4-7)

$$N_0 = 4Dtf_y \quad (3)$$

$$B= 0.002*(L/D)^2 + 0.0179*(L/D) + 0.5416 \quad \textit{for } 3<(L/D)<14 \quad (4)$$

$$B=1.2 \quad \textit{for } (L/D) \geq 14 \quad (5)$$

$$C= 0.77209*(d_i/D) +0.69 \quad \textit{for spherical impactor} \quad (6)$$

C= 1.2 *for flat impactor* (7)

The maximum displacement δ_{max} is calculated at mid-span of fixed column. Here the local indentation is ignored and only the overall displacement is calculated. It is assumed that 3 plastic hinges are formed before actual failure for a fixed column [7]. The equations are given as

δ_{max}=((L*KE)/8M_p) x A_i (8)

Here KE & M_p are the kinetic energy & full plastic moment in the section respectively which are given in (9, 10). A_i is the shape factor. (12-14)

KE= $(MV)^2/2$ (9)

Where M, V are mass of hammer (impactor) & impact velocity respectively.

$M_p = \frac{2}{3} f'_c\, r^3_i \cos^3\gamma_0 + 4\, f_y\, r^2_m\, t \cos\gamma_0$ (10)

Where r_i - inner radius of tube, r_m – mean radius given as: $r_m=(r_i+R)/2$

γ_0 is angular location of plastic neutral axis

$\gamma_0=$
$(\pi/4)((f'_c r^2_i)/(f_y r_m t)) / (2+(0.5(f'_c r^2_i)/(f_y r_m t)))$ (11)

Shape factors for spherical impactor is given in (12, 13) and for flat impactor in (14)

A_1= 0.1211(D/d_i) +1.75 *for 3<(L/D)<13* (12)

A_1= 0.1211(D/d_i) +1.2 *for (L/D)≥13* (13)

A_2= 1.7 *for (L/D) ≤6* (14)

5. MATLAB RESULTS & DISCUSSIONS

Fig 4 gives the comparison of MATLAB expected vs. experimental results with the error percentage. Fig5&6 show the force-displacement curves for different lengths & different indenter shapes.

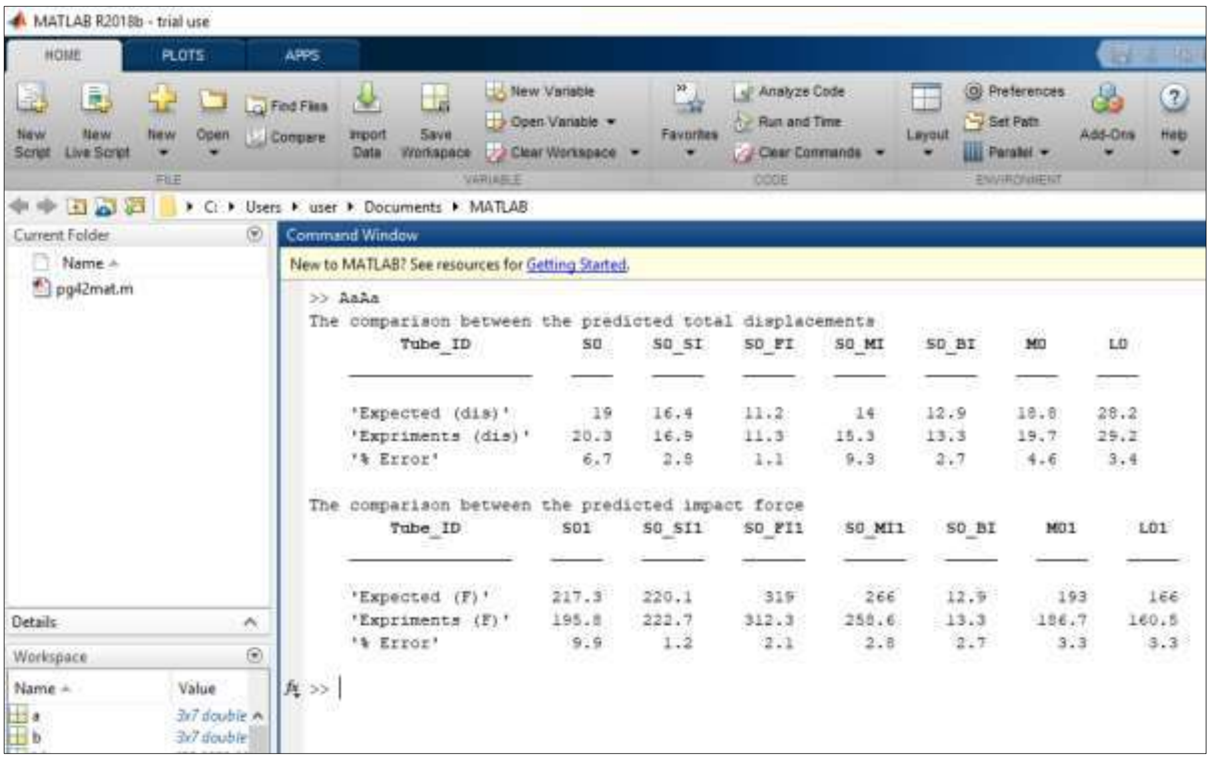

Fig4: MATLAB command window displaying results (force & displacement

Fig 5 shows that the shorter columns have higher impact force. Also the displacement is lesser compared to long & medium length columns. Fig 6 shows the effect of indenter configuration. As the indenter size increases, the force also increases. This is due to increased contact area. Since there is more area under contact, there is no puncturing effect and hence the displacement decreases. The error is within permissible limits.

6. COMPARISON WITH EURO CODE

EN 1991-1.7[10] suggests a formula for impact load (15). Here v- velocity of impactor, k- effective stiffness, m- mass of impactor. Effective stiffness (16) can be found by EN 1994-1-1[11]

F=v*√(km) (15)

$EI_{eff}=E_a I_a + 0.6 E_{cm} I_c$ (16)

Where E_a- Young's modulus of steel, E_{cm}- Young's modulus of concrete (EN1992-1-1

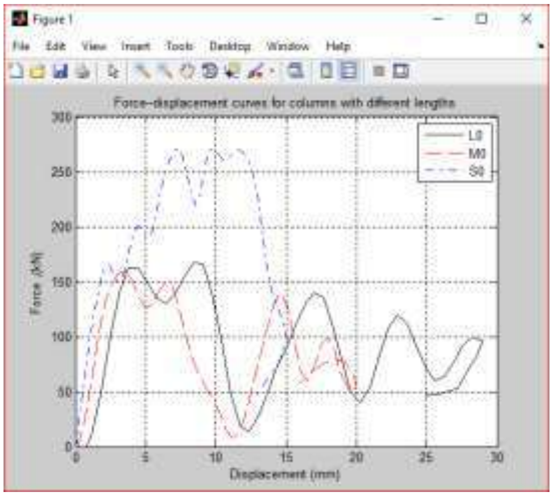

Fig 5: Force-displacement curves for different column length

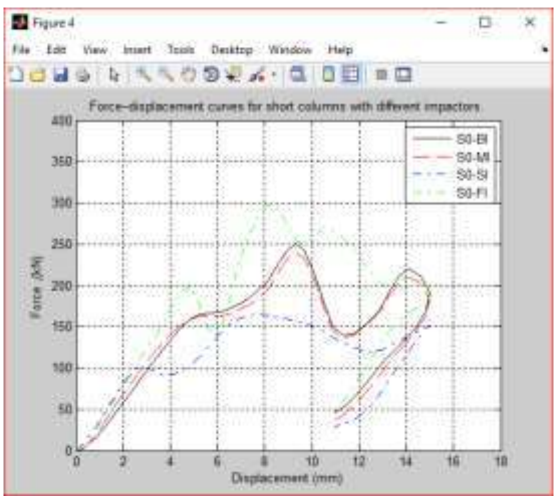

Fig6: Force-displacement curves for different indenters

table 3.1[12]), I_a- Moment of inertia of steel tube, I_c-Moment of inertia of concrete core

For circle, moment of inertia=I=Ix+Iy given as Ix=Iy=(π*R^2)/4.

Results obtained from Euro code vary between 3-30%. This is because the effect of intender shape is not taken into account.

7. COMPARISON WITH ABAQUS/CAE

A FEM model is generated to model CFST column using Abaqus/CAE 2018. Steel tube & concrete core are designed as 8 node solid brick elements with reduced integration i.e. C3D8R. The materials are designated as elastic & elasto-plastic for steel & concrete respectively [9]. Concrete damaged plasticity model is adopted along with Coulomb friction contact[6]. Fixed end boundary conditions are provided with dynamic implicit load applied at mid-span as a concentrated load. A suitable fine mesh is adopted and analyzed to obtain force & displacement values. The obtained values are in good agreement with MATLAB analysis results. These results vary between 2-18%.

Tube ID	Experiment force(kN)	MATLAB force (kN)	Euro Code force (kN)	ABAQUS Force(kN)
S0	217.3	195.8	202.22	207.5
M0	193	186.7	202.22	190.6
L0	166	160.5	202.22	156.7
S0-SI	220.1	222.7	201.75	240.7
S0-FI	319	312.3	202.7	359.8
S0-MI	266	258.6	202.22	282.5
S0-BI	286.3	294.2	203.17	300.4

Table2: Comparison of impact force with Euro code & Abaqus

Tube ID	Experiment disp (mm)	MATLAB disp (mm)	ABAQUS disp(mm)
S0	19	20.3	19.9
M0	18.8	19.7	18.26
L0	28.2	29.2	28.5
S0-SI	16.4	16.9	15.98
S0-MI	14	15.3	15.83
S0-BI	12.9	13.3	16.36
S0-FI	11.2	11.3	16.22

Table3: Comparison of displacement with MATLAB & Abaqus

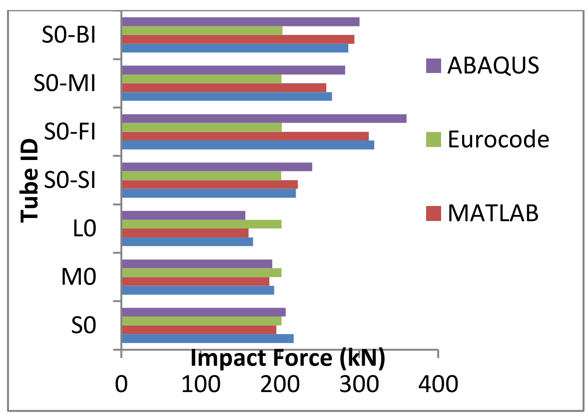

Fig7: Graph depicting comparison of impact force values

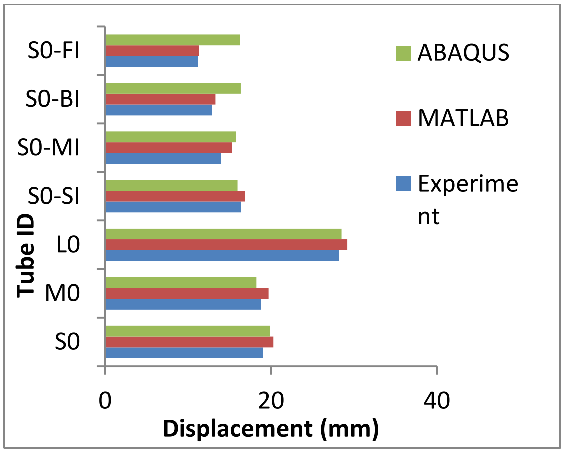

Fig8: Graph depicting comparison of displacement values

8. CONCLUSION

- The increase in tube length increases the displacement but decreases the impact force.
- The increased size of indenter increases impact resistance and reduces local indentation as well as global displacement.
- The increase in mass of impactor increases both the impact force & displacement.
- The results obtained with MATLAB & Euro code vary between 3-30%
- The results obtained with MATLAB & Abaqus/CAE vary between 2-18%

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