Blast performance and residual strength of concrete-filled cold formed (CFCFST) built-up column

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**Abstract:** This paper presents the concrete-filled cold-formed steel tubular built-up column behaviour under blast loading. The blast-induced damage and the residual strength of the CFCFST column have been presented with the varied intensity of the blast. The probable influence of infilled concrete grade has been investigated. The performance of the CFCFST column with eccentricity has been presented under the blast threat. A 3D numerical model of a full-scale CFCFST built-up composite column has been presented, considering geometric imperfections, fasteners, and material nonlinearity. The cold-formed steel hollow sections are made with two C-sections and two U-sections using self-drilling screw/fastener. The blast performance and their residual have also been studied and compared with the conventional RC column after validating the numerical model with experimental results. It was found that the induced damage and concrete disintegrations were less in the CFCFST column due to the confinement effect. Also, the rate of decrease in the residual strength of the CFCFST column was less in the case of CFCFST thus preventing progressive collapse effectively.

**Keywords:** CFCFST, Numerical model, Blast load, Residual strength, eccentricity

1. **Introduction**

With the increase in the number of explosions and blast threats worldwide, the vulnerability study of the building under blast is getting considerable attention[1][2][3]. Conventional structures are not designed to resist blast load, and thus researchers are more focused on making the building safer for occupants under blast attacks[4]. The concrete structure shows concrete spalling and even fully blown away at higher intensity of blast load. Because of this, the study of a structure's residual capacity after blast-induced damage becomes crucial. The dislodging of concrete can be effectively minimized by using a composite structure and applying an external cover like a concrete-filled steel tubular structure. These members are widely recognized for their excellent structural performance and have been applied in the construction industry worldwide. Due to composite action, the covering steel tube provides better confinement to infilled concrete and increased compressive and shear strength. Also, the local buckling of thin-walled steel sections is minimized due to infilled concrete. However, CFST structural elements are suffering from a variety of deteriorations, including cracking, yielding, and large deformation caused by factors like fire, environment, and corrosion [5]. However, with the benefits of better confinement and increased concrete strength, the behaviour of CFST columns under blast loading needs to be investigated [4]. In general, CFST columns under blast loading may undergo global flexural damage and shear damage as well as localized damage. Flexural damage and shear damage of the column are mainly attributed to the deformation and internal force of the whole member, whilst the localized damage is dominated by the failure of infill concrete and steel tubes in the vicinity of the explosion[6][7].

A numerical investigation of blast performance of 500 mm x 500 mm 10 mm CFST column was presented [8] which showed that the damage in the infilled concrete was more dominant on the back face of the column. Moreover, the CFS section in the CFST circular column showed a localized creator formation on the front face[9]. Remennikov and Uy (2014) [10] conducted a close-range blast test at a scaled distance of 0.08 m/kg^1/3 on the 100 mm x 100 mm 5mm CFST column and CFS hollow column with a charge weight of 2.6 kg TNT. It was reported that the 5mm CFST column failed to split in half.

However, the behaviour of the CFST column under sustained loading needs an hour. Since, in the real scenarios, CFST columns in existing structures are under sustained loading due to service load. Also, the existing literature lacks in providing insight into blast-induced damage and the behaviour of built-up CFST columns under sustained loading.

# Numerical and material modeling

A three-dimensional numerical model of the CFCFST column size 150 mm x 150 mm x 3000 mm is developed in ABAQUS[11]. Firstly, the CFS section is modeled using a shell element, S4R, where, two CFS-C and CFS-U sections are used to make CFS hollow column as shown in Fig. 1. Self-drilling screws are modeled at each corner to connect CFS sections. The infilled concrete is modeled using brick elements with reduced integration, C3D8R . Interaction between the CFS section and concrete is assigned using a penalty contact algorithm with friction 0.3 as suggested in the literature[12]. Two-step loading is applied on the column; such as, in step one, an axial load of 10% of axial strength is applied followed by blast load. In the second step, axial compression is applied in a quasi-static manner. The boundary conditions on the CFCFST column in both steps are shown in Fig. 1(b). The concrete compressive behaviour is modeled as per Eurocode 2[13], see Fig. 2(a). The concrete tensile behaviour is simulated as per relation in Fig 2(b). The calibrated value of plastic parameters for the concrete model has been taken from previous work[14]. The CFS section is modelled using the two stages Ramberg-Osgood [15] model as shown in Figure 2(c). The material properties of the steel bar are as in Table 1. The material properties of CFS sections are taken from [12].

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| (b)  (a) |

Fig 1. (a) FE model of CFCFST column and blast locations for two cases (b) BC and sections

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| (b)  (a)    (c) |

Fig 2. (a) compressive behavior of concrete, (b) tensile behavior of concrete, (c) stress-strain behavior of CFS section

# Material Model

Concrete is modelled with the concrete damage plasticity model which is based on the concept of continuum damage mechanics. The inelastic behavior of the concrete structure is defined based on scalar damage elasticity in combination with isotropic tensile and compressive stress-strain properties.

# Concrete compression

The compressive behavior of concrete in the structure is evaluated using a compression stress-strain model that provides a scalar damage parameter (*d*c) for stiffness reduction. The concrete under compression passes through three stages such as linear elastic, strain hardening, and softening as shown in Fig. 2(a). The variation of stress in concrete with strain has been considered per Eurocode 2 as per Eq 1. Detailed material models from Eqs. 2-4 are explained in[16].

(1)

*E* = (1-*d*c) Ecm (2)

(3)

(4)

Where, η , κ , *d*c = 1- (/), is an elastic strain in the undamaged material which equals to σc/Eo. is strain corresponding to stress .

* 1. **Concrete Tension behavior**

The concrete tensile behaviour is modelled as per Eqns. 5-7. Concrete tensile behavior shows linear elastic up to ultimate axial capacity and then, tension softening starts till ultimate cracking strain as shown in Fig 2(b). The softening phase of the tensile stress-strain curve depicts crack initiation and its progression which attributes material stiffness degradation using the tensile damage parameter, *d*t as per Eq. 5 along with, cracking strain and plastic strain as Eqns. 6-7.

*E* = (1-*d*t) Eo (5)

(6)

(7)

Where is the elastic strain in the undamaged material which equals σtu/Eo as shown in Fig. 3(c). is strain corresponding to the onset of material stress . The infilled concrete and its plasticity parameters and CFS section properties are listed in Table 1[16].

Table 1. Concrete and CFS section properties

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| Concrete | |
| Grade | M20-M40 |
| Plasticity parameters | Numerical values |
| Dilation angle (ψ) | 370 |
| Stress ratio (σbo /σco) | 1.16 |
| Shape factor (*K*c) | 0.667 |
| Eccentricity (ϵ) | 0.1 |
| Viscosity (μ) | 0.005 |
| CFS | |
| Young’s module, Es, (Pa) | 206000 |
| Yield strength (MPa) | 306 |
| Ultimate strength (MPa) | 424 |

# Results and Discussion

The CFCFST column with M20 infilled concrete (pristine column) was analyzed under compression and the results in terms of damage pattern and load-deflection behaviour were compared with test results [12] as shown in Fig 3. The buckling of CFS sections had a good correlation with the test. Also, the predicted axial capacity of the CFCFST column was 925 kN compared with the test result of 935 kN, which showed a 1.6% error. Also, the buckling and opening of the outer CFS-U section is well predicted from the presented numerical model.

After validation of the presented numerical model, the sequential failure modes are analyzed at different axial compressions as shown in Fig. 4. Before the ultimate axial capacity, the CFS section shows wrinkle formation throughout the length of the column as seen at point-A in Fig. 4. Whereas, there was no failure in infilled concrete. At the ultimate capacity, at point B, concrete crushing is observed in approximately 15% of the concrete section. From point B to C, concrete crushing progresses and consequently, the bulging of the CFS section becomes localized and increases near concrete crushing. After point C, the rate of decrease in the axial capacity decreases. This is due to the confinement of the concrete by the CFS section which prevents the concrete from bulging out.

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Fig. 3. Comparison of predicted numerical results with experimental result [12]

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Fig. 4. Behaviour of CFCFST column under axial compression and sequential failure modes

This built-up CFCFST column of 150 mm x 150 mm x 3000 mm is applied to a blast load with 25 kg TNT at a 500 mm standoff distance (scaled distance 0.17 m/kg^1/3). Wherein, column (M20) is bearing a sustained axial compression with an axial load of 10% of their nominal axial capacity. The impulse generated with the above blast case is shown in Fig. 5(a). The axial capacity of the CFCFST column decreased from 925 MPa to 571 MPa subjected to a blast at an intensity of scaled distance of 0.17 m/kg^1/3, which shows a decrease of 38.2%. With the same blast intensity, and increase in infilled concrete grade from M20 to M40, the axial capacity of the CFCFST column increases from 571 MPa to 800.4 MPa only.

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Fig. 5. (a) Overpressure for 25 kg TNT with a stand of distance 500 mm, (b) Influence of infilled concrete strength

The given CFCFST column has different faces based on CFS sections overlapping, and let’s say it is blast face A (BFA) and blast face B(BFB) as shown in Fig. 6(a). On the BFB face, the outer two U sections are connecting, which shows two unconfined edges of sections. Also, this face is vulnerable to opening up as observed in Fig. 3 under compression. The blast-induced behaviour may vary with this face. Therefore, the probable influence of blast face on the axial capacity of the CFCFST column and its damage behaviour has been studied, considering blast intensity with a scaled distance of 0.17 m/kg^1/3. With the same intensity of blast on BFB, the induced stress is observed to be 308 MPa in CFS sections as compared to 329 MPa in case of BFA. Also, the stress concentration in CFS sections is very localized in the case of BFB as shown in Fig. 6(a). This is due to comparatively less stiff outer CFS U sections and easy to open up. Consequently, the blast-induced damage in the infilled concrete is also localized as compared to that in the case of BFA as shown in Fig. 6(b). Moreover, the blast-induced damage is propagated more in-depth in the case of BFB. This leads more a decrease in the axial capacity of the CFCFST column as shown in Fig. 6(c).

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Fig. 6. Influence of blast face on (a) damage behaviour in CFS, (b) infilled concrete, (c) axial capacity

# Conclusions

A numerical investigation of damage behaviour and axial capacity of concrete-formed built-up columns has been discussed. The influence of infilled concrete grade on blast behaviour has also been discussed. Axial capacity and blast-induced damage have been discussed considering blast at two differently configured faces in the column. A simplified 3D numerical model and the procedure for axial capacity investigation under blast load have been discussed showing a two-step procedure. Some important conclusions are drawn below,

1. The CFCFST column experiences wrinkle formation throughout the length of the CFS section under axial compression before ultimate axial capacity. Also, the failure at the ultimate capacity is caused by concrete crushing.
2. The axial capacity of the CFCFST column (150 mm x 150 mm x 3000 mm) infilled with M20 concrete was decreased by 38% under blast with a scaled distance of 0.17 m/kg^1/3.
3. Increasing the infilled concrete grade increases the axial capacity.
4. In the case of blast at face B, the stress in CFS sections is comparatively lower and localized as compared to that in the case of blast on face A. Also, the blast-induced damage in the infilled concrete was localized but propagated more in-depth.

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