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Assessment of Lateral Impact Effects on Carbon Steel Battened Built-up Columns Using Finite Element Analysis

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Abstract

The study presents a comprehensive finite element (FE) analysis of the structural response of battened-up carbon-steel columns subjected to combined axial and lateral low-velocity impact loads (ILs). The study demonstrated that 120 numerical models were created using ABAQUS/Explicit and analyzed four critical design elements: web stiffener shapes, cross-sectional shapes, edge stiffener shapes, and axial load ratios. The confirmation of the numerical models showed that they accurately predicted both overall and local failure. The parametric study shows that CDV (double V-shaped) web-stiffened columns had the highest total axial reaction capacity, reaching a maximum marginal load that is 87.4% higher than that of C-shaped columns. Edge stiffeners, especially type-3 double-edge stiffeners, improved the column's behavior under lateral ILs by increasing stability and load-carrying capacity by 71.4%; thus, local buckling was also deferred. Axial load ratios had a major effect on the impact performance of the columns, with the highest ratio always increasing the columns' capacity, depending on the stiffened design type. The cross-sectional shapes may change the performance features of the columns, either positively or negatively, depending on the arrangement; in well-stiffened designs, enhanced benefits have been reported. This research has been instrumental in advancing the optimization of battened built-up columns under dynamic and accidental loading scenarios.

Keywords

Battened built-up columns, Carbon steel, Impact loading (IL), Axial load ratio, Web stiffeners, Edge stiffeners

1. Introduction

Some of the countless controversial points in structural engineering over the last few years have probably been the use of built-up columns in steel design. Their low weight-to-strength ratio and the abundance of design options are just a few reasons for this controversial issue. Basically, these columns consist of steel shapes such as angles, plates, and channels, joined together by stiffeners or battens. Therefore, these columns have proven to be the most popular for constructing buildings, bridges, and industrial structures. It is quite necessary to know how these columns behave when subjected to various load conditions, IL in particular, to be able to guarantee their safety and keep the structures made of them intact after such events as vehicle collisions, blasts, or falling objects (Iskander et al., 2021). It is very important to assess the performance of steel-built-up columns under IL because, if the columns fail, the failure mechanisms can be complex. These failure mechanisms will most likely be local buckling, fracture, and progressive collapse, and will be of a completely different nature than those encountered in the case of static or quasi-static loads (H. Wang, Huo, Elchalakani, et al., 2021; H. Wang, Huo, Liu, et al., 2021; Zeng et al., 2022). Without a doubt, as demand for infrastructure grows and safety standards become stricter, the need to develop robust design methodologies and reliable predictive models is becoming increasingly important. Apart from that, the impact resistance of built-up columns is what ultimately determines how safe the rest of the structure will be and whether it will be able to survive accidental or deliberate impact scenarios (W. Zhao et al., 2020). Whatever the situation, whether the steel columns are under IL or not, there has been a lot of debate about them; in particular, built-up columns have been neglected. For the most part, the available investigations have been concentrated on the trait of solid and hollow steel sections beneath loading conditions with an impact component, while on the other hand, the effect of various assembly configurations, such as shape alterations of the investigated section and different arrangements of stiffening, has been less studied. In addition, the interaction effects of the parameters on impact response have not been considered, and hence, there seems to be a lack of understanding of the dynamic behavior of built-up columns (Cui et al., 2021; Xiang et al., 2020; Y. Zhu et al., 2020). This study is part of the present research aimed at closing this gap by determining how different configurations affect structural performance under impact conditions.

1.1 Literature Review

Research on battened built-up CFS columns has mainly focused on axial compression behavior, stability, failure modes, numerical modeling,

and structural design. Experimental and numerical investigations of battened built-up columns were done by Daaban et al. (Dabaon et al., 2015c, 2015a) revealed the governing role of the interaction between the slenderness of individual chords, overall slenderness of the column member, the chord spacing, the batten configuration, and different buckling modes. The finite element models used in the studies were critical tools for predicting the axial resistance and failure modes of battened built-up columns. Further research on the problem included investigations into various types of chords and their stability characteristics. Anbarasu (Anbarasu, 2020) conducted an experimental and numerical investigation of the behavior of battened built-up columns assembled from four lipped angles and found that chord slenderness and overall slenderness have a significant impact on the axial resistance and failure modes of the structure. Further, (Anbarasu et al., 2020) introduced an improved design of battened built-up columns of lipped angles, considering chord slenderness, batten spacing, and overall geometry of the member. Dar et al. (M. A. Dar et al., 2020) studied the impact of chord compactness and slenderness on the axial compression behavior of battened CFS columns and found that the slender chord may buckle prematurely, leading to a restriction of composite action development. Finally, Dar et al. (M. A. Dar et al., 2021) conducted monotonic axial compression tests and developed validated finite element models that can predict axial resistance, load-displacement response, and various buckling modes. Interactions within different segments of the chords have also received considerable scholarly interest. In Rahnavard et al. (Rahnavard et al., 2021), the composite behavior of battened built-up cold-formed steel (CFS) columns is analyzed numerically, identifying batten spacing, fastener configuration, chord separation, connection stiffness, and slenderness ratio as important factors affecting shear transfer and composite behavior. Experimental studies of battened built-up columns by Dar et al. (A. R. Dar et al., 2022) revealed that the accuracy of the existing design formulas cannot be considered satisfactory since they give different predictions depending on chord compactness and column slenderness. Accordingly, Dar et al. (M. A. Dar et al., 2022) developed an efficient design formula for CFS battened built-up columns, which considers unbraced chord slenderness, total slenderness of the column, and chord interaction. Further research has made additional progress in the field of experimental, numerical, and design-oriented studies of battened built-up columns. Columns made of two σ -shaped sections were studied by Rahnavard et al. (Rahnavard et al., 2023), revealing that geometry, batten configuration, and connection detailing have a great effect on composite action, axial capacity, and buckling performance. In Li et al. (Q.-Y. Li et al., 2023), experimental and numerical studies of several CFS battened columns were carried out in order to investigate the effects of member slenderness, transverse chord spacing, and longitudinal batten spacing on

axial capacity, deformations, and failure modes of such columns. Comparison with existing design formulations showed that prediction accuracy varies with section geometry and chord interactions. Similarly, the works of Craveiro et al. (Craveiro et al., 2023) are devoted to the analysis of the structural behavior of battened CFS columns, with particular attention to the effects of chord geometry, connection detailing, and batten configuration on composite behavior and buckling resistance. Besides, Meza et al. (Meza et al., 2023) emphasized the importance of modeling material nonlinearities, initial geometrical imperfections, connector performance and local-distortional-global buckling interaction in numerical models of built-up CFS columns. Alternative connection and stiffening systems have also been investigated to improve the axial performance of built-up members. Sadid et al. (Sadid et al., 2024) introduced hooped battens that connect both the webs and flanges of the chord sections, thereby providing greater restraint than conventional battens connected only through the flanges. Their validated numerical investigation showed that hooped battens can reduce the effective buckling length of slender plate elements and enhance the axial strength and stability of the built-up system. The relative performance of conventional and hooped-batten systems was found to depend strongly on unbraced chord slenderness and overall column slenderness. Deniziak et al. (Deniziak et al., 2024) further examined stress distribution in bolted built-up CFS columns and showed that the spacing and arrangement of interconnections influence stress transfer and the degree of interaction between the component sections. More recently, Dai (Dai, 2026) extended the numerical investigation of battened CFS members to beam-columns under axial and eccentric loading, and demonstrated that cross-sectional geometry, steel grade, plate thickness, batten configuration, and loading eccentricity interact to determine member capacity and failure response. Collectively, these studies have established that the axial behavior of battened built-up CFS columns is controlled by chord compactness, plate slenderness, unbraced chord slenderness, overall member slenderness, batten spacing and rigidity, fastener arrangement, cross-sectional geometry, initial imperfections, and the degree of composite action. The commonly reported failure mechanisms include local, distortional, and flexural buckling, as well as interactions among these instability modes. Although these investigations have resulted in improved modeling and design procedures, they have predominantly considered monotonic concentric or eccentric compression rather than combined axial and lateral impact loading. In parallel, extensive experimental and numerical research has examined the impact of behavior of other structural column systems. Concrete-filled steel tubular (CFST) columns have received particular attention because the interaction between the steel tube and concrete core provides enhanced confinement, stiffness, composite action, and energy-dissipation capacity. Wang et al. (W.-D. Wang et al., 2022) investigated CFST column-to-composite beam connections under static and impact loading and identified their characteristic failure modes and dynamic increase factors. Li et al. (Gen Li et al., 2023) evaluated the deterioration of impact resistance caused by localized pitting corrosion, whereas Zhu et al. (X. Zhu, Kang, et al., 2021) investigated cruciform-reinforced CFST columns and identified the outer steel tube as a principal energy-dissipating component. Kang et al. (Kang et al., 2021) developed and experimentally validated a computationally efficient numerical framework for predicting the impact response of CFST members. Other studies have examined the effects of material strength, cross-sectional configuration, repeated impact, and dynamic constitutive behavior on CFST columns. Guochang Li et al. (Guochang Li et al., 2024) investigated high-strength CFST columns and demonstrated the importance of cross-sectional dimensions and steel-tube thickness in controlling impact resistance. H. Zhao et al. (H. Zhao et al., 2023) and Gao et al. (Gao et al., 2023) examined the impact and repeated-impact behavior of round-ended and square CFST columns, respectively. Yan et al. (Yan et al., 2023) assessed dynamic constitutive models for predicting impact response, while H. Chen et al. (H. Chen et al., 2023) investigated the development of inertia forces in CFST columns subjected to drop-weight impact. These studies collectively demonstrate that the impact response of CFST members depends on impact energy, axial load, section geometry, material strength, contact behavior, strain-rate effects, and the interaction between the steel tube and concrete core. Impact-related studies on conventional and strengthened steel columns have similarly identified axial load level, impact velocity, cross-sectional geometry, local strengthening, and residual deformation as important response parameters. Arian and Al-Husainy (Arian et al., 2024) reviewed impact-induced failure mechanisms in conventional steel columns, while Zhang et al. (Zhang et al., 2024) investigated locally strengthened stainless-steel columns and demonstrated that localized reinforcement can improve energy absorption and reduce impact-induced deformation. Jiang et al. (Jiang et al., 2023) examined the combined effects of axial compression and impact velocity on H-section steel columns, whereas R. Wang et al. (R. Wang et al., 2022) investigated impact damage and post-impact residual strength. K. Chen et al. (K. Chen et al., 2023) developed a component-based framework for simulating the quasi-static and dynamic behavior of composite beam-

to-column connections. Wang et al. (H. Wang, Huo, Liu, et al., 2021) performed impact tests on welded unreinforced flange-bolted web and bolted unstiffened extended end-plate composite connections and demonstrated the contribution of concrete slabs to energy dissipation and rotational capacity. Research on reinforced concrete (RC), steel-reinforced concrete (SRC), and hybrid structural columns have identified additional mechanisms governing impact resistance. Zhu et al. (X. Zhu, Zhao, et al., 2021) conducted impact tests on RC and composite columns and showed that steel encasement improved impact performance relative to conventional RC members. Zhou et al. (Zhou et al., 2024) compared internal and external steel-tube strengthening methods for RC columns and found that internal strengthening provided superior impact resistance. Liu et al. (Liu et al., 2021) investigated carbon-fiber-reinforced polymer strengthening of circular RC columns and reported improvements in impact resistance and a transition from shear-dominated toward more ductile flexural behavior. Zeng et al. (Zeng et al., 2022) examined SRC columns subjected to repeated impact and demonstrated that the transverse reinforcement ratio and axial compression ratio influence both impact response and residual mechanical performance. In FRP-metal composite systems, Kadhimi and Jawdhari (Kadhimi et al., 2025) identified the potential of fiber-reinforced polymer strengthening to reduce impact-induced damage and improve the impact resistance of steel members. Despite these advances, comparatively few studies have examined battened built-up steel columns under lateral impact loading. Cui et al. (Cui et al., 2021) conducted experimental tests and developed validated ABAQUS models for built-up battened columns subjected to lateral impact. Their investigation demonstrated the importance of impact energy and boundary conditions in controlling deformation, failure response, and energy absorption. Nevertheless, the combined effects of cross-sectional geometry, web-stiffener configuration, edge-stiffener arrangement, cross-sectional dimensions, and axial load ratio have not been systematically investigated. Furthermore, existing design-oriented research on battened built-up CFS columns has primarily addressed static axial compression. Consequently, it remains unclear whether established observations regarding chord compactness, unbraced chord slenderness, composite action, batten restraint, and local-global buckling interaction remain applicable when the columns are simultaneously subjected to axial compression and lateral impact. A systematic investigation is therefore required to determine how these geometric and loading parameters interact and govern the load-carrying capacity, deformation response, and failure mechanisms of battened built-up columns under combined axial and lateral impact loading.

1.2 Research Gap

Past researchers have shown that factors such as chord slenderness, battens' spacing, connections, the geometrical form of the cross-section, and the effects of local and global buckling influence the axial behavior of battened built-up cold-formed steel columns. On the other hand, most impact tests have been conducted on CFST, RC, SRC, traditional steel, and hybrid columns. Yet little is known about the behavior of battened built-up steel columns under simultaneous axial compression and lateral impact loading. It is particularly unknown how web stiffener geometry, edge stiffener layout, section geometry, and axial load ratio affect the axial reaction and deflection behavior.

1.3 Novelty

Earlier research has examined the effects of cross-section geometry, batten spacing, joints, slenderness ratio, etc., on the behavior of such columns, but studies on the impact response of such structures have been limited to conventional and composite steel columns only. In contrast to that, the interactions between the stiffening elements, edge elements, dimensions of the cross-sections, and axial pre-compression of such columns under lateral impact are still not adequately understood. This study explains the mechanisms by which the parameters affect the axial reaction, stress distribution, and deformation of the structure. From a methodological point of view, a unified FE model is used in conjunction with experimental validation of impact and axial buckling behavior.

2. Materials and Methods

2.1 Numerical Modeling Strategy

This analysis involved a three-phase approach. In the first phase, the model's dynamic impact performance was assessed by comparing its results with those from tests on preloaded axially hollow steel pipes. The second phase involved assessing the axial strength and buckling behavior of battened, built-up, cold-formed steel columns using compression tests. The third phase involved applying the results from the first two phases to assess the performance of battened built-up carbon-steel columns

considered in parametric analysis. This was done without further calibration.

Model Geometry and Element Discretization

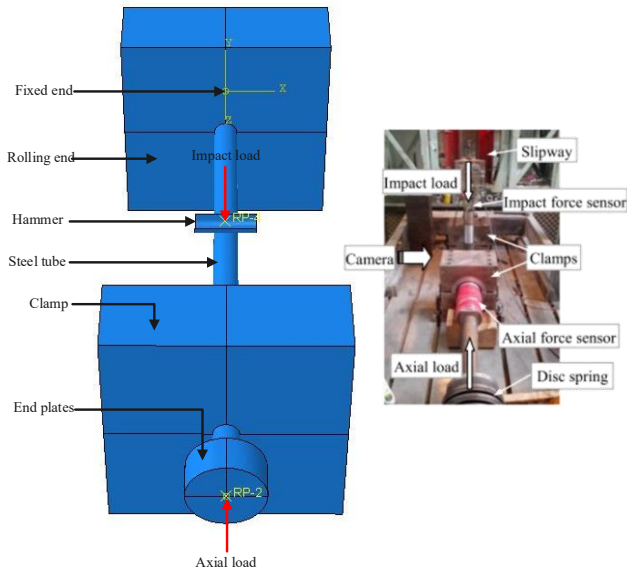


Fig. 1 Configuration of Experimental (W. Li et al., 2019) and Numerical Models for UHSS Hollow Tubes Under Lateral IL.

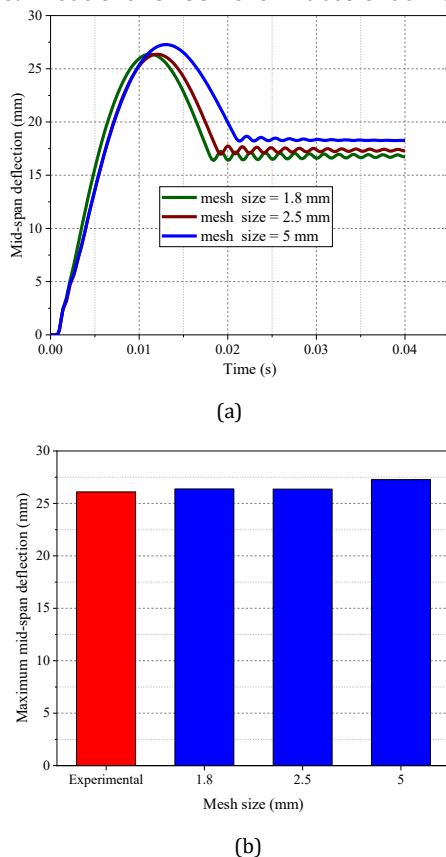


Fig. 2 Mesh-sensitivity assessment using element sizes of 1.8, 2.5, and 5 mm: (a) comparison of mid-span deflection-time histories and (b) comparison of maximum mid-span deflection with the experimental result.

Abaqus/Explicit was utilized to create a detailed, high-resolution FEM that was subsequently appointed to reproduce the dynamic response of a cylindrical shell of UHSS exposed to lateral impact. The cylindrical shell was depicted as a hollow cylindrical tube, normalized along the axis of symmetry, with a height of $Z = 730$ mm and a base of $Z = 600$ mm. The model geometry was described by a discrete mesh of structured quadrilateral shell elements (S4R) that were radially oriented in rings and then axially stacked to obtain a continuous cylindrical surface. This kind of meshing technique guarantees that the nodes are properly connected, and it is also possible to take into account various deformation modes, such as local indentation, post-buckling, and stress wave propagation. Figure 1 below illustrates the experimental configuration

and the Abaqus numerical model. A mesh-sensitivity study was conducted to evaluate the influence of element size on the predicted dynamic response. Three characteristic mesh sizes, 1.8, 2.5, and 5 mm, were examined using the same geometry, material properties, loading conditions, contact definitions, and boundary conditions. Figure 2(a) compares the mid-span deflection-time histories obtained using the three meshes. The 1.8 and 2.5 mm meshes produced closely similar response curves, including the initial deformation rate, peak deflection, unloading response, and subsequent oscillations. The 5 mm mesh predicted slightly higher maximum and residual deflections, indicating reduced accuracy due to the coarser discretization. Figure 2(b) compares the maximum mid-span deflections with the experimental result. The 1.8 mm and 2.5 mm meshes showed close agreement with both the experimental response and each other, while reducing the mesh size from 2.5 mm to 1.8 mm resulted in only a minor change in the predicted maximum deflection. Therefore, a characteristic mesh size of 2.5 mm was adopted for numerical analyses because it provided an appropriate balance between prediction accuracy and computational efficiency. Dynamic studies were conducted utilizing Abaqus/Explicit, with an overall simulation duration of 0.04 seconds. The solver autonomously established a stable time increment, initially approximately 3.6×10^{-7} s, which subsequently decreased to approximately 10^{-8} – 10^{-9} s as the study progressed. Bulk viscosity coefficients of 0.06 (linear) and 1.2 (quadratic) were employed to mitigate high-frequency oscillations. Artificial and hourglass energies remained consistently insignificant relative to internal energy, hence guaranteeing numerical stability.

Material Properties and Strain Rate Influence

The shell material was conceptualized as UHSS exhibiting time-sensitive elasticity. The single-layer steel material of the cylindrical shell was modeled with a bilinear elastic-plastic constitutive behavior having an elastic modulus in the range of 200–210 GPa and a Poisson's ratio of 0.3. The inelastic trait was simulated using isotropic thickening, with a plastic modulus set at 1% of the elastic modulus (0.01Es). The Cowper-Symonds equation (Eq. 1) was employed to characterize the ratio of deformation sensitivity of the material, enabling the definition of the dynamic yield stress (DYS) as follows:

$$\sigma_{y,dyn} = \sigma_y \left(1 + \left(\frac{\dot{\epsilon}}{C} \right)^{1/p} \right) \quad (1)$$

$\sigma_{y,dyn}$ represents the DYS, $\dot{\epsilon}$ denotes the ϵ , while C and p are fitting elements, often ranging from 40 to 50 and 5 to 6, respectively, for structural steels. This formulation accurately depicts the increase in yield strength with elevated dynamic loading. Figure 3 illustrates the stress-strain curve of UHSS steel.

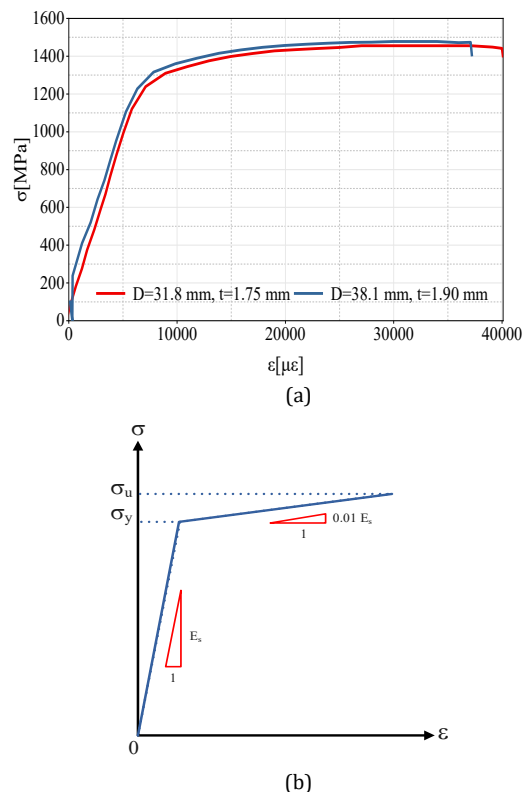


Fig. 3 Stress-strain characteristics of UHSS tubes: a) The engineering uniaxial tensile response obtained experimentally, b) A simplified bilinear model capturing elastic and plastic hardening behavior.

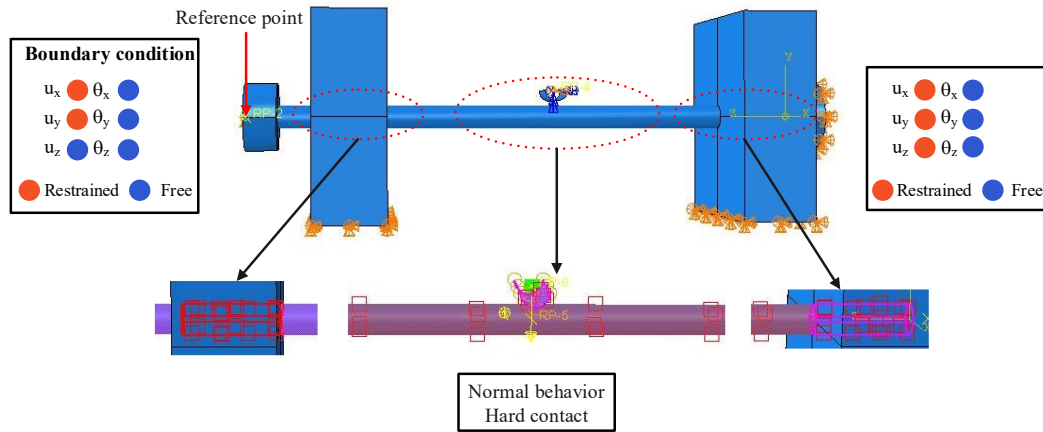


Fig. 4 Idealized boundary conditions and contact interactions between hammer, shell, and clamps.

IL and Initial Conditions

The dynamic loading model was represented by a stiff crusher composed of 4-node shell elements (R3D4) with an assumed flat velocity. Lateral deformation of the metal was caused by the pressure of the influence on the middle area of the cylindrical case. A preloaded axial force (AF) was implemented via a linear spring connector with a stiffness of $k = 1.1 \text{ kN/mm}$; this preloaded AF was essential for mitigating the axial compressive forces observed in physical demonstrations; specifically, the preloaded force was sustained through adapter constraints or multi-point constraints (MPCs) during the simulation. Gravitational forces were disregarded, as they were considerably less significant than the dynamic effect.

Boundary Conditions and Constraints

To mimic the test, both ends of the tubular shell were restrained from any movement or rotation. The fixed zones were shown through C3D8R brick elements representing the rigid supports. The shell's outer surface, which was attached to a rigid reference plate, was loaded by an axial spring load. This reference rigid plate maintained a constant axial compressive force throughout the whole impact operation. The column boundary conditions are displayed in Figure 4.

Contact Interaction Definition

The interface between the shell, the impactor, and the supports was defined using surface-to-surface contact formulas (see Figure 4). In the perpendicular direction, a rigid-union model was implemented to prevent permeation, while in the tangential direction, a frictionless technique was used to reduce the inertial effect. This contact was implemented via a penalty mechanism, guaranteeing numerical stability with negligible impact on accuracy. Mesh refinement in the contact zone was used to accurately capture stress concentrations and the initiation of localized damage.

2.2 Validation of the Numerical Model

This research employs two numerical validation methods to assess the functionality of battened built-up columns under axial load and of circular hollow cross-sections under IL, respectively.

Validation Model I: Axially Preloaded Circular Hollow Tubes under Lateral Impact

To confirm the FEM for IL, experimental data were compared with those reported by Li et al. (W. Li et al., 2019). The two source samples, T-1 and T-2, were initially tested by exposure to low-velocity lateral IL using a falling-weight impact device. The two samples were solid cylinders with a round hollow cross-section, possessing identical outer diameters of 31.8 mm, a wall hardness of 1.75 mm, and a beneficial stretch of 480 mm. They experienced a constant axial load of 0.3, corresponding to a preloaded AF of 32.9 kN. A 72 kg hammer was exposed to low-velocity IL by being dropped from several heights. The T-1 specimen was exposed to an impact from a peak of 1.00 m, resulting in a starting impact velocity of 4.427 m/s and an IE of 706 J. The T-2 was struck from a peak of 1.38 m, resulting in a starting impact velocity of 5.202 m/s and an IE of 974 J. The pair is subject to fixed-sliding boundary requirements, as stipulated by the empirical configuration. A review of geometry and loading characteristics is shown in Table 1. The numerical forecasts presented in Table 2 and Figure 5 exhibit a strong correlation with the peak mid-span deflection (Δm) and the peak mid-span rotation (Δr), with discrepancies of under 2% for T-1 and around 8% for T-2. The remaining deflections varied, with T-1 exhibiting 17% and T-2 displaying 1%. The difference is due to intrinsic changes in boundary condition stiffness, damping during deformation, and strain recovery in the experimental testing, which were all simplified in the numerical model. Malfunction types from FE studies were contrasted with those from the assessments, as shown in Figure 6, providing additional evidence that global bending was the main failure mode, accompanied by localized indentation at the impact location. The numerical framework reproduced the experimental inward cross-sectional deformation and local buckling, with similar deformation patterns in the cross-section, stress concentration, and cross-section flattening. FEM's capacity to predict structural behavior under lateral IL is clearly illustrated by the strong agreement between the empirical and numerical findings. It is also observed that the acceptable gaps between the experimental and numerical data fall within engineering tolerances, validating the predictive FEM for additional parametric analyses and predictions.

Table 1. Dimensional characteristics of validation specimens (W. Li et al., 2019).

Specimen	Outer Diameter (D) [mm]	Wall Thickness (t) [mm]	Effective Span Length (Le) [mm]	Axial Load Ratio (n)	Preloaded AF (N_0) [kN]	Drop Height (H) [m]	Initial Velocity (V_0) [m/s]	IE (E) [J]	Impact Impulse (I) [kg-m/s]
T-1	31.8	1.75	480	0.3	32.9	1.00	4.427	706	318.8
T-2	31.8	1.75	480	0.3	32.9	1.38	5.202	974	374.6

Table 2. Comparability of numeric findings with experimental observations.

Metric (mm)	T-1 (Experimental)	T-1 (Numerical)	T-1 (Exp./Num. Ratio)	T-2 (Experimental)	T-2 (Numerical)	T-2 (Exp./Num. Ratio)
Δm	26.1	26.3614	0.99	35.5	32.59	1.08
Δr	15.7	18.9777	0.83	25.4	25.0906	1.01
δr	10.4	7.3837	1.4	10.1	7.5048	1.34

Table 3. Evaluation of numerical results against experimental data.

Specimen	Test results (kN) (Dabaon et al., 2015b)	Failure mode (Test) (Dabaon et al., 2015b)	FE results (kN)	Failure mode (FE)	Percentage difference, %
B2B25-300	$P_{Test} = 109.9$	Flexural+Distortional	$P_{FE} = 112.7$	Flexural+Distortional	2
B2B50-300	$P_{Test} = 119.1$	Flexural+ Local	$P_{FE} = 112.6$	Flexural+ Local	6

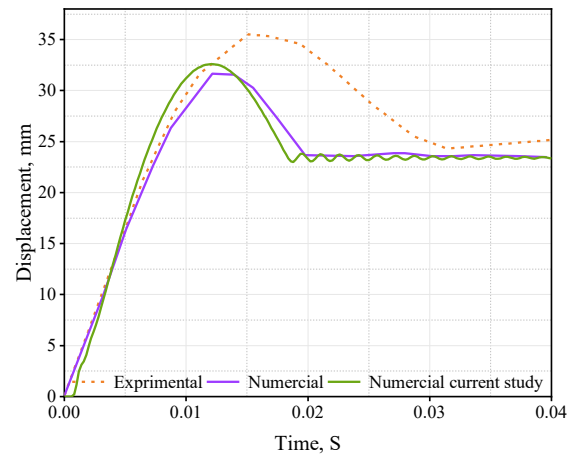
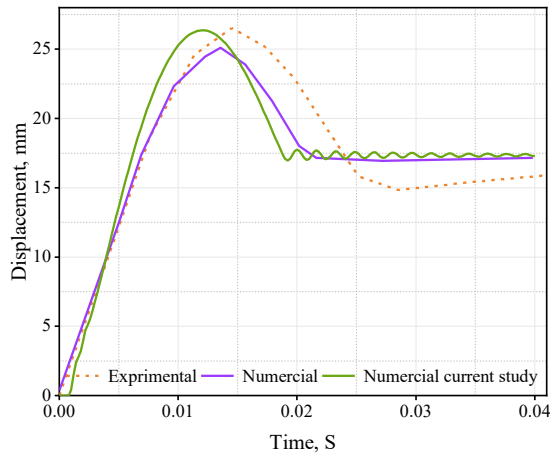


Fig. 5 Validation of numerical models: (a) T-1 and (b) T-2 (W. Li et al., 2019).

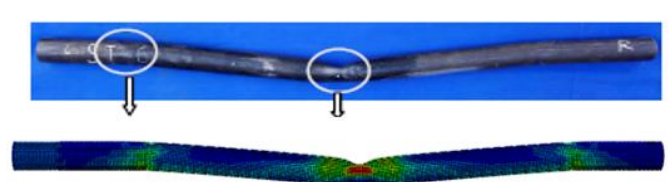
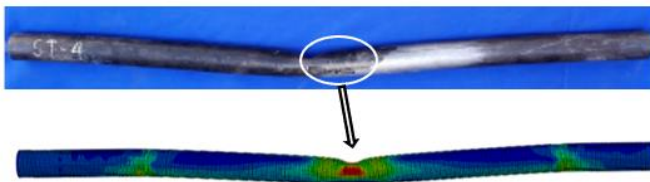


Fig. 6 Evaluation of the malfunction types identified in the specimens: (a) T-1 and (b) T-2 (W. Li et al., 2019).

Validation Model II: Battened Built-Up Columns under Axial Compression

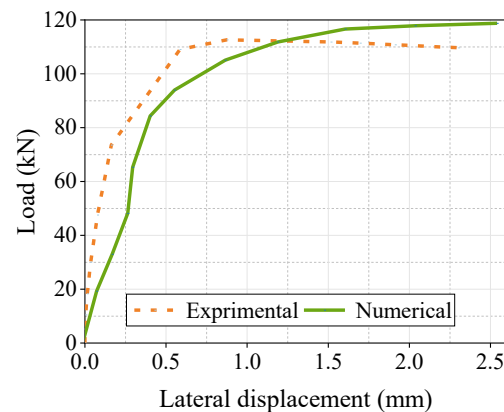
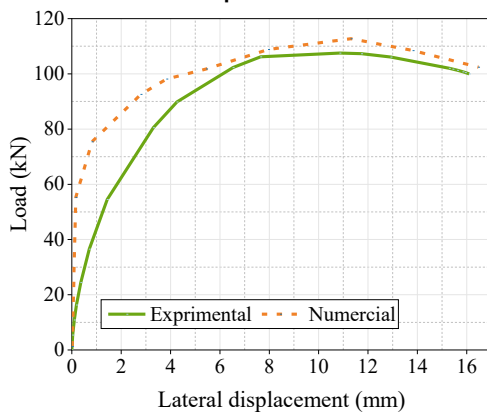


Fig. 7 Assessment of numerical model accuracy (Dabaon et al., 2015b).

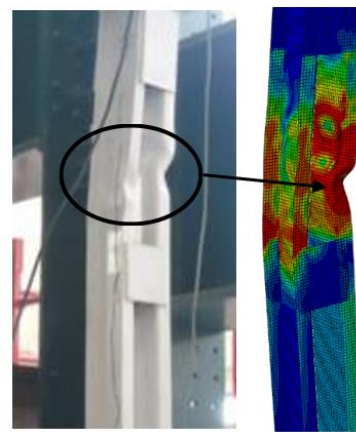
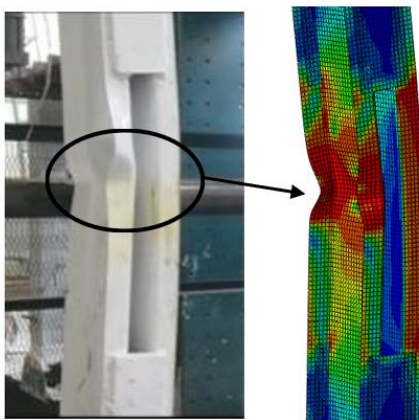


Fig. 8 Investigation of specimen failure behaviors: a) B2B25-300, b) B2B50-300 (Dabaon et al., 2015b).

The numerical simulations conducted for battened built-up cold-formed steel (CFSC) columns subjected to axial load were corroborated by comparing predictions with experimental outcomes (Dabaon et al., 2015b, 2015d). Table 3 and Figure 7 depict the relationship between experimental and numerical capacity estimates, yielding an average ratio of $P_{test}/P_{FE} = 1.02$ and a coefficient of variation of 0.039. Thus, the FEM can be regarded as a valid tool for estimating the axial load-carrying capacities of battened built-up columns. The initial identification of failure mechanisms involved mainly flexural buckling (F) and local buckling (L).

A close relationship between the experimental and numerical failure mechanisms is shown in Table 3. In both cases, the main failure mode was flexural buckling of the two samples, B2B25-300 and B2B50-150. Consistent with the experimental and numerical results, the thin B2B25-300 column underwent elastic flexural and distortional buckling. With the increase in the inter-channel spacing in the B2B50-300 column from 25 mm to 50 mm, the failure mode was a combination of flexural and local buckling. The failure mechanism was dominated by the slenderness of the individual channels, even if the overall slenderness of the column was still

a factor. The experimental and numerical deformation patterns for the B2B25-300 and B2B50-300 specimens exhibited strong correlation, especially in their buckling behavior along the y-axis, as illustrated in Figure 8. The study validates the FEM as a reliable visual representation of the structural performance of battened CFSC under axial loading.

2.3 Parametric Study

Finite Element Analysis was conducted systematically to evaluate the behavior of battened-built-up carbon-steel columns subjected to simultaneous axial compression and lateral impact loading. The modeling assumptions used in the simulations were validated by the two validation analyses. The methodology for applying impact loading, modeling the impactor, and performing dynamic analysis, as well as axial preloading before impact, was adopted from W. Li et al. (W. Li et al., 2019). The built-up column geometry and the modeling assumptions regarding element formulations, meshing techniques, batten-to-chord connection, geometric imperfections, boundary conditions, and axial loading were taken from Dabaon et al. (Dabaon et al., 2015b). If required, the modeling assumptions have been modified to match the geometrical and loading configurations used in the present parametric study. The actual carbon-steel material properties used in the parametric models were obtained from Zhang et al. (Zhang et al., 2024), as shown in Figure 9 and Table 4. Four parameters were considered for analysis: web stiffener geometry, cross-sectional dimension series, edge stiffener geometry, and axial load ratio. Five types of cross-sections were investigated: an unstiffened C-shaped cross-section was chosen as the reference configuration; a cross-section stiffened with a

sigma stiffener (CS); a cross-section stiffened with a V stiffener (CV); a cross-section stiffened with a double V stiffener (CDV); a cross-section stiffened with a U stiffener (CU). Every composite column was made of two cold-formed steel chord sections connected via batten plates. Figure 10 and Table 5 present geometrical characteristics and sizes of the investigated configurations. Every section had an overall depth of 240 mm and a constant plate thickness of 1.97 mm. A two-dimensional series of cross-sections was analyzed. In the first series, the cross-section dimensions were $B = 60$ mm, $w_1 = 15$ mm, and $w_2 = 105$ mm. In the second series, the cross-section dimensions were $B = 75$ mm, $w_1 = 18.75$ mm, and $w_2 = 101.75$ mm. The length of the edge stiffener was 20 mm, and the characteristic depth of the web stiffener was 60 mm. The model identification is presented in Figure 11. For example, the designation CS1-1-0.5 means the cross-section is stiffened with sigma stiffeners, dimension series 1, edge stiffener geometry type 1, and an axial load ratio of 0.5. The axial load ratios investigated were 0.0, 0.2, 0.5, and 0.7. Axial load ratio can be expressed as the ratio of the pre-applied axial compressive force to the reference axial capacity of the corresponding column. Rigid impactors with a mass of 70 kg were used in all parametric models. The transient behavior resulting from the combined effect of the axial preload and the lateral impact was simulated using ABAQUS/Explicit. The impact and contact assumptions were kept constant across all models to ensure that any observed numerical differences in response could be traced primarily to the geometric/loading parameters considered. The main response parameter was the maximum total axial reaction obtained from the time-history graph of the axial reaction. The parametric study was deliberately restricted to include only a comparative study focusing on strength.

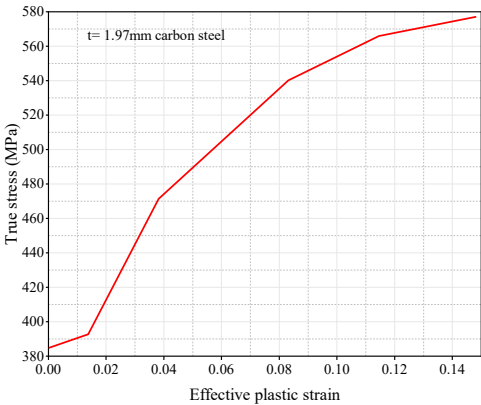


Fig. 9 True stress–effective plastic strain curve (Zhang et al., 2024).

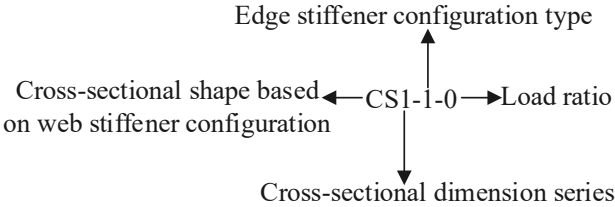


Fig. 11 Model labeling

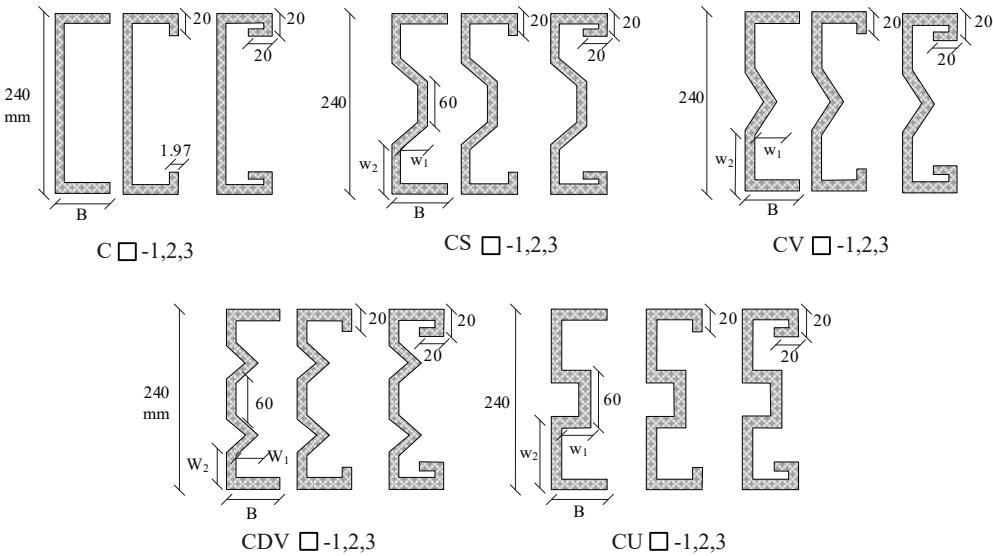


Fig. 10 Cross-sectional geometries and dimensions of the C-, CS-, CU-, CV-, and CDV-shaped battened built-up columns, showing the two-dimensional series, web-stiffener configurations, and edge-stiffener arrangements.

Table 4. Mechanical properties of steel (Zhang et al., 2024).

Steel	E_s , GPa	f_y , MPa	f_u , MPa
1.97 mm	210.0	385.2	507.9

Table 5. Cross-sectional dimensions of the battened built-up columns used in parametric investigation.

Cross-sectional configuration	Series	B (mm)	w_1 (mm)	w_2 (mm)	Plate thickness (mm)
C, CS, CU, CV, CDV	1	60	15	105	1.97
C, CS, CU, CV, CDV	2	75	18.75	101.75	1.97

3. Results and Discussion

3.1 Effect of Parameters on the Peak Axial Load of Models Subjected to Combined Impact and Axial Loading

Web stiffener configuration

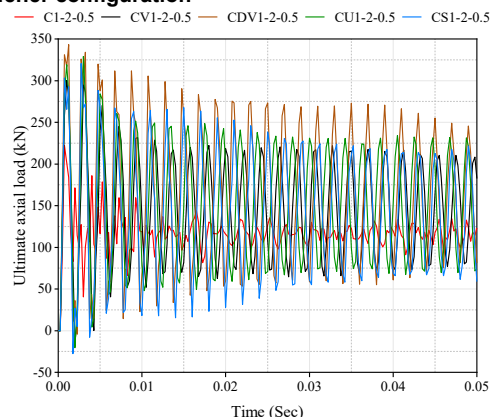


Fig. 2 Axial load-time curve of numerical analysis with different web stiffener configurations.

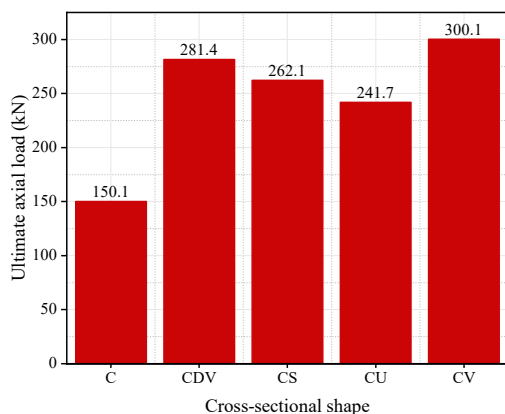


Fig. 3 Effect of web-stiffener configuration on the peak total axial reaction of Series 1 built-up columns with type-1 edge configuration and an axial load ratio of 0.5.

The presence of web stiffeners significantly affects the axial response of battened built-up carbon steel columns. In Figure 12, the axial reaction-time curves of the five analyzed cross-sectional structures: C, CS, CV, CU, and CDV are shown. To study the influence of the web stiffener shape, all the structures under consideration have Series 1 sizes, Type-1 edge stiffener arrangements, and an axial loading ratio of 0.50. The C-shaped column without web stiffeners, designated C1-1-0.5, showed the minimum peak total axial reaction of 150.12 kN and was therefore taken as the base structure. As shown in Figure 13, incorporating shaped web stiffeners enhanced the peak response. Thus, the values for the structures CS1-1-0.5, CV1-1-0.5, CU1-1-0.5, and CDV1-1-0.5 were 262.10 kN, 300.07 kN, 241.72 kN, and 281.45 kN, respectively, which are 74.6%, 99.9%, 60.9%, and 87.4% greater than that of the reference structure. The improved response observed in the stiffened cases may be associated with constraining out-of-plane displacement of the web and cross-sectional deformation. By providing stiffeners, the web plate is divided into smaller segments, enabling more of the cross-section to carry axial and impact loads. Unlike the unstiffened C-shaped case, the stiffened cases exhibited greater resistance to local web deformations, resulting in a localized response and a lower peak axial load. In all tested cases, the maximum peak response was observed for CV and CDV. The inclined stiffeners provided effective restraint to the web and direct paths for transferring forces from the web sections to the adjoining flanges. The CV case had a slightly better response than the CDV case, demonstrating that adding stiffener folds to a specific configuration does not yield a proportional improvement in response. The stiffness and efficiency of the stiffeners depend on their geometry and their interactions with other plate segments.

Cross-Sectional Dimension

The effect of changing cross-sections on the axial reaction behavior of battened built-up carbon steel columns was determined by comparing Series 1 and Series 2 sections. The results of the study for axial reaction-time histories of the models are illustrated in Figure 14. In all models used

in the study, the axial load ratio is 0.50, and edge-stiffener configurations of Types 1 and 3 were considered to assess the interaction between the two variables. From Figure 15, the effect of changes in the dimensional series on web stiffener configurations is highly dependent. On unstiffened C-columns, the highest total axial reaction decreases slightly from 150.12 kN to 145.63 kN on the Type-1 configuration, a decrease of 3.0%. Similarly, in the Type-3 configuration, there is a 2.8% decrease in peak reaction from 257.22 kN to 250.10 kN. The results show that increasing the cross-section dimensions of specific sections does not necessarily improve the behavior of unstiffened open sections. If the web section is not adequately restrained, the wider plate will increase vulnerability to deformation and distortion. The CS-shaped columns proved quite sensitive to changes in cross-sectional dimensions. For the Type-1 case, the highest total axial reaction grew from 262.10 kN to 276.17 kN, which corresponded to the 5.4% increase. As for the Type-3 case, the highest total axial reaction increased from 363.70 kN to 374.37 kN, or 2.9%. It may be noted that the sigma-shaped web stiffener seems to provide enough confinement to allow the changed cross-section to take part in the force transfer. The CV-shaped columns showed little sensitivity to dimensional change. Specifically, the Type-1 reaction decreased from 300.07 kN to 296.74 kN, a 1.1% decrease, and the Type-3 reaction decreased from 348.23 kN to 343.92 kN, a 1.2% decrease. Such a moderate change suggests that the response of the CV cross-section is mainly controlled by its current V-shaped web stiffness, rather than by the change in dimension itself. Some moderate positive changes occurred for the CU-shaped columns. For the Type-1 configuration, the highest total axial reaction increased from 241.72 kN to 248.34 kN, or 2.7%, and for the Type-3 configuration, from 385.88 kN to 395.45 kN, which corresponds to 2.5%. Thus, the U-shaped stiffener allowed some contribution of the additional dimensions into the total force transfer process. The highest sensitivity to dimensional change was achieved for the CDV-shaped columns. Namely, the Type-1 configuration increased from 281.45 kN to 307.88 kN, or 9.4%, and the Type-3 configuration increased from 392.70 kN to 427.11 kN, or 8.7%. Thus, the double V-shaped web stiffness helped mitigate distortions within the cross-sections and allowed additional plates to contribute to force transfer, resulting in the largest increase in peak axial reactions for the series-2 configurations. Concluding, it is possible to say that the effect of cross-sectional dimensions on the behavior of the columns was configuration dependent. In particular, the CS, CU, and especially the CDV-shaped columns have improved with the change in dimensions, while the C- and CV-shaped columns have shown minor negative changes. Such results show that dimensional change can be efficient only when the stiffness of the web and flange components is sufficient to mobilize the extra material.

Edge stiffener configuration

The effect of edge-stiffener design on the axial reaction of battened built-up carbon-steel columns was investigated using the axial reaction-time history curves shown in Figure 16. The three types studied include Type 1, without any edge stiffeners; Type 2, with one edge stiffener; and Type 3, with two edge stiffeners. Comparisons were made for the considered cross-section designs and sizes at an axial load ratio of 0.50. The numerical results show that the application of edge stiffeners typically increases the peak total axial reaction. For the Series 1 C-shaped columns, the Type 1 case yielded a peak reaction force of 150.12 kN. The application of one edge stiffener increased the response to 222.06 kN, representing a 47.9% increase. Using the two edge stiffeners in the Type 3 yielded a response of 257.22 kN, representing a 71.4% increase relative to Type 1. A similar trend was observed for the Series 2 C-shaped columns, with the Type 2 configuration showing a 62.0% increase compared with the Type 1 counterpart, as shown in Figure 17. This increased response is due to the restraining effect of the edge stiffeners on the flange rotations and deformations. In the absence of the edge restraining effect, the slender flanges are more likely to deform locally, and thus their effective role in carrying the combined axial and impact actions becomes limited. Application of one edge stiffener improves the stability of the flanges, and when two edge stiffeners are used, a restraining effect is obtained at both flanges, and more flange widths can be involved in the response. The improvement level depended on the interaction effect between the edge stiffener arrangement and the web stiffener geometry. The CS and CDV stiffener arrangements demonstrated very clear superiority with the type-3 arrangement. In these cases, the joint restriction from the web and the edge stiffeners reduced cross-section distortion and promoted better stress distribution between the web and flange portions. This explains why the type-3 arrangement yielded the maximum peak total axial reaction among the edge-stiffener arrangements. In conclusion, it is evident that edge stiffeners have great potential to improve the performance of battened columns. The type-3 arrangement showed the highest response among the cases studied; nevertheless, its effectiveness may be considered only with respect to the mentioned parameters – geometries, axial load ratio, boundary conditions, and the impact case.

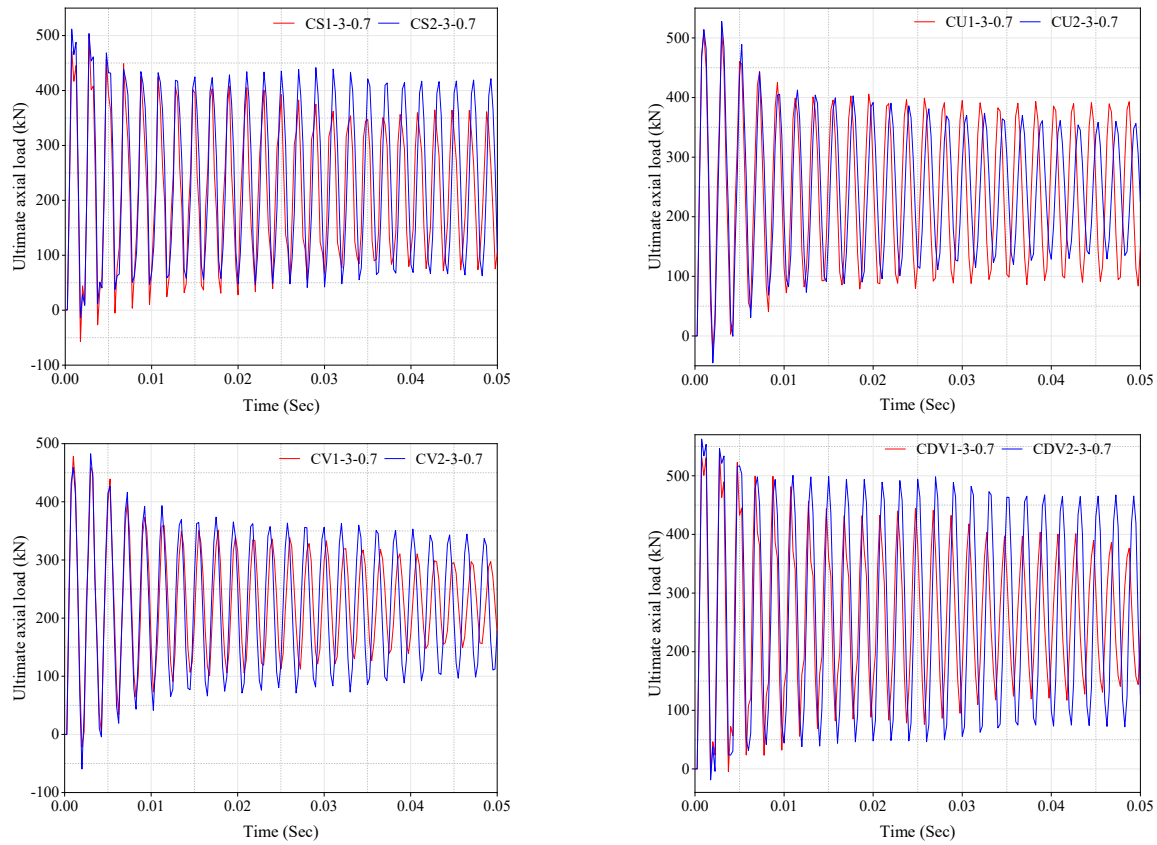


Fig. 4 Axial load-time Curve of numerical analysis with different cross-sectional dimensions.

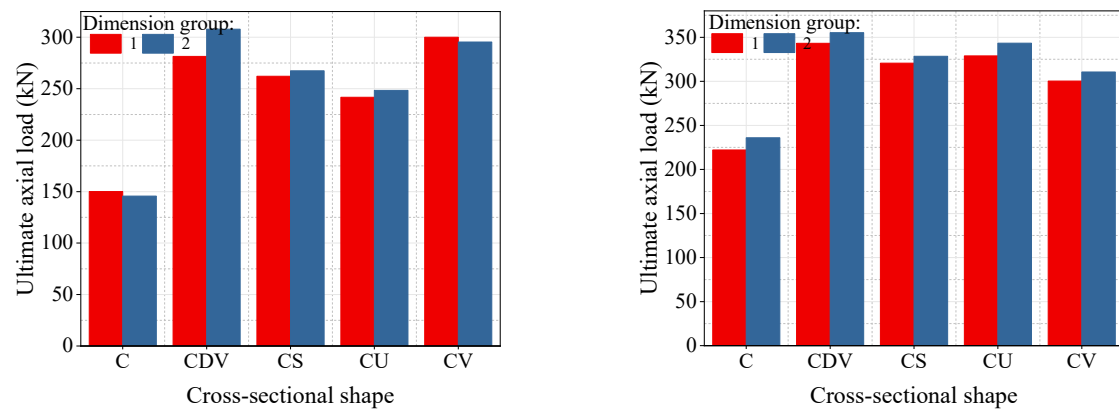
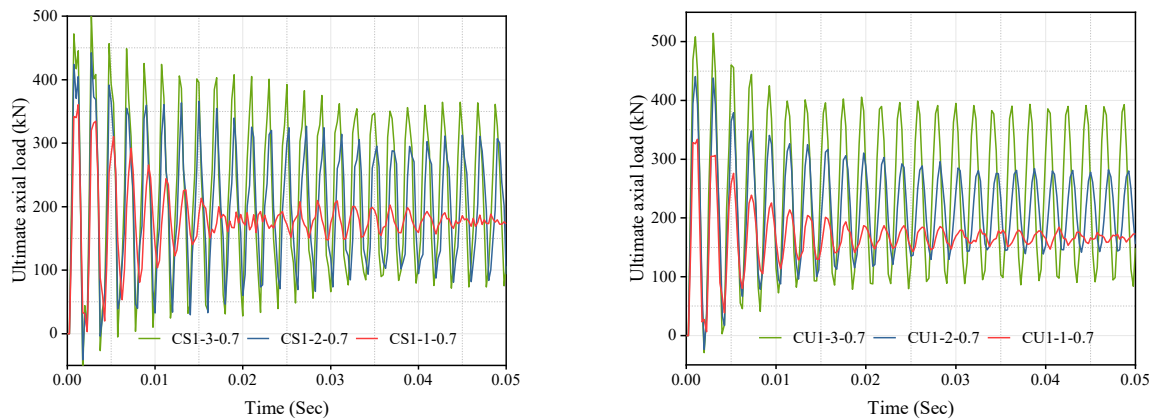


Fig. 5 Comparison of the peak total axial reactions of Series 1 and Series 2 columns for different cross-sectional geometries and edge-stiffener configurations at an axial load ratio of 0.5.



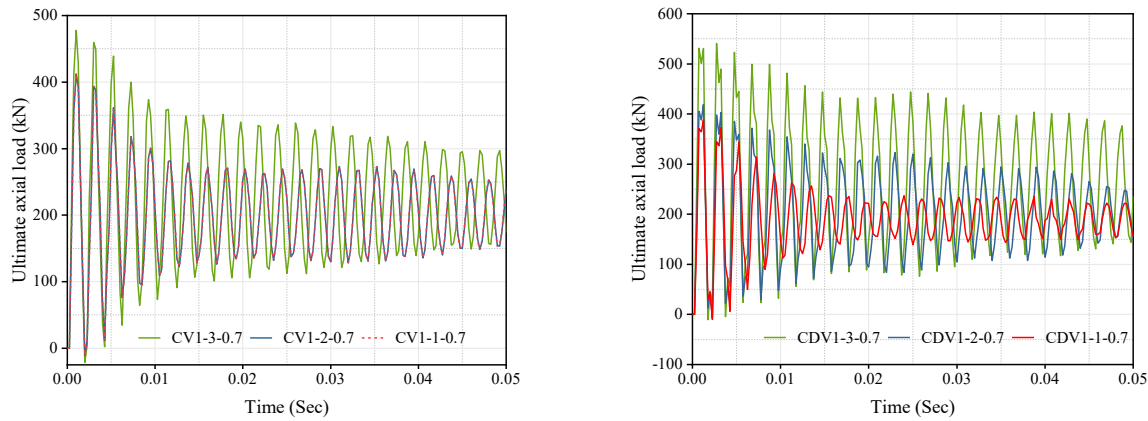


Fig. 6 Axial load-time Curve of numerical analysis with different stiffener configurations.

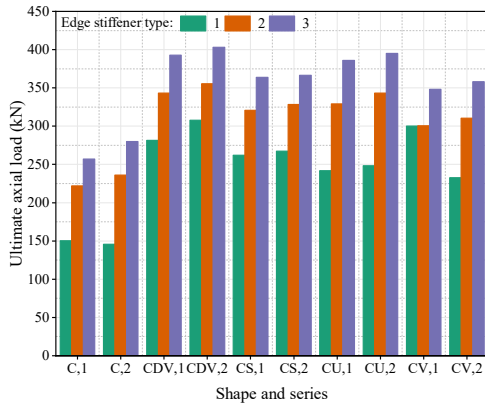


Fig. 7 Effect of type-1, type-2, and type-3 edge-stiffener configurations on the peak total axial reaction of the investigated built-up column geometries under combined axial compression and lateral impact.

3.2 Behavior of Columns at Different Axial Load Ratios

The influence of the axial load ratio on the behavior of battened carbon-steel built-up columns is shown through the time-history plots of axial reaction plotted in Figure 18. Four axial load ratios, including 0.0, 0.2, 0.5, and 0.7, have been considered in the study. It has been found that peak total axial reaction increases with axial preload, but the magnitude of this increase depends on the geometry of the web stiffeners, the edge stiffener configuration, and the section sizes. It must be noted here that this trend should not be interpreted as an increase in the inherent axial capacity of the columns. As the peak total axial reaction has been reported here, it includes both the pre-applied compressive load and the transient reaction due to the lateral impact. Hence, a column with a larger axial load ratio begins the impact scenario with a higher initial axial force, with the impact response added to the pre-load. Hence, an increase in the peak reaction reflects the history of loading but does not indicate an increase in the column's load-carrying capability or stability. From all the configurations studied, the C-shaped columns have shown the lowest peak values (Figure 19). In the case of selected C-shaped column, the peak total axial reaction has increased from 18.55 kN for an axial load ratio of 0.0 to 209.14 kN for the ratio of 0.7. Despite the increase in numerical value owing to the presence of larger pre-load, the section became more susceptible to local deformations and cross-section distortions due to the increasing compressive preload, owing to the lack of web stiffening and lower flange restraint. The CS- and CU-shaped specimens had higher peak total axial reactions than other configurations at intermediate axial load ratios. For example, the peak total axial reactions of Type-3 CS- and CU-shaped models were 374.37 kN and 395.45 kN, respectively, at an axial load ratio equal to 0.5. The sigma- and U-shaped stiffeners restrained the out-of-plane deformations of the web and allowed a greater portion of the cross-section to participate in the transfer of the combined actions. The CV-

shaped columns exhibited increasing peak reactions under axial load. However, the peak responses of the CV-shaped configurations were lower than those of the CDV-shaped configurations. The double V-shaped stiffener restrained the web in a larger area and created several inclined paths of force transfer between the web and flanges. As a result, the CDV specimens usually developed the highest peak total axial reactions among the analyzed configurations. The verified CDV peak reactions increased from [insert the value and model designation at an axial load ratio of 0.0] to 427.11 kN for the Type-3 specimen at an axial load ratio of 0.5. Thus, the influence of axial load ratio is governed by two factors that interact with each other. The first is the increase in the initial axial force, which in turn increases the peak total reaction. The second factor is the reduction in the stability margin due to increased axial compression, thereby increasing the specimen's sensitivity to local deformation, cross-sectional distortion, and second-order effects. Specimens with efficient restraint of the web and edges could redistribute the combined actions effectively and maintain the cross-section's participation under increasing preload. In general, the CDV, CU, and CS-shaped configurations responded most intensely to the combined loads, while the unstiffened C-shaped columns were the most sensitive to local deformation. These dependencies are characteristic only of the geometry and the applied loading conditions.

3.3 Failure Modes under Combined Axial Compression and Lateral Impact:

Figure 20 shows characteristic deformed shapes and distributions of von Mises stress of the studied columns. Since no fracture criterion or deletion of failed elements was involved in this analysis, the failure modes referred to the deformation and instability patterns that dominated at the end of the analysis. From Figure 20(a), the unstiffened C-shaped column exhibited the largest local deformations and cross-sectional distortions near the impact location. The CU, CS, CV, and CDV exhibited more restricted deformations due to the stiffened webs, which reduced the plates' unsupported width and increased force transmission through the section. Also, the inclined folds in the CV and CDV columns contributed to the stress transfer paths through the impact region. Figure 20(b) shows that changes in the cross-sectional dimensions did not affect the basic failure pattern of the CS-shaped columns. However, both columns exhibited localized indentations and plate distortions, while Series 2 had a wider stress distribution, indicating greater participation of the section. Figure 20(c) represents the effects of edge stiffeners. The Type-1 model exhibited more pronounced flanges and web distortions, whereas the Type-2 and Type-3 configurations showed more controlled deformation. The Type-3 configuration provided the maximum flange restraint and minimized the rotation of free edges. The effects of axial load ratio are shown in Figure 20(d). For small axial preloads, the behavior was primarily governed by localized impact-induced deformations. As the ratio increased, compression led to greater plate buckling and cross-sectional distortion. Thus, although the peak total axial reaction increased with the axial preload, the residual stability margin decreased. Generally, the basic behavior is caused by the interaction of localized impact indentations and the instability of thin-walled plates. Web and edge stiffeners helped to minimize the deformation zones and enhanced the stress distribution, while the higher axial preload made the structure more prone to compression-induced buckling.

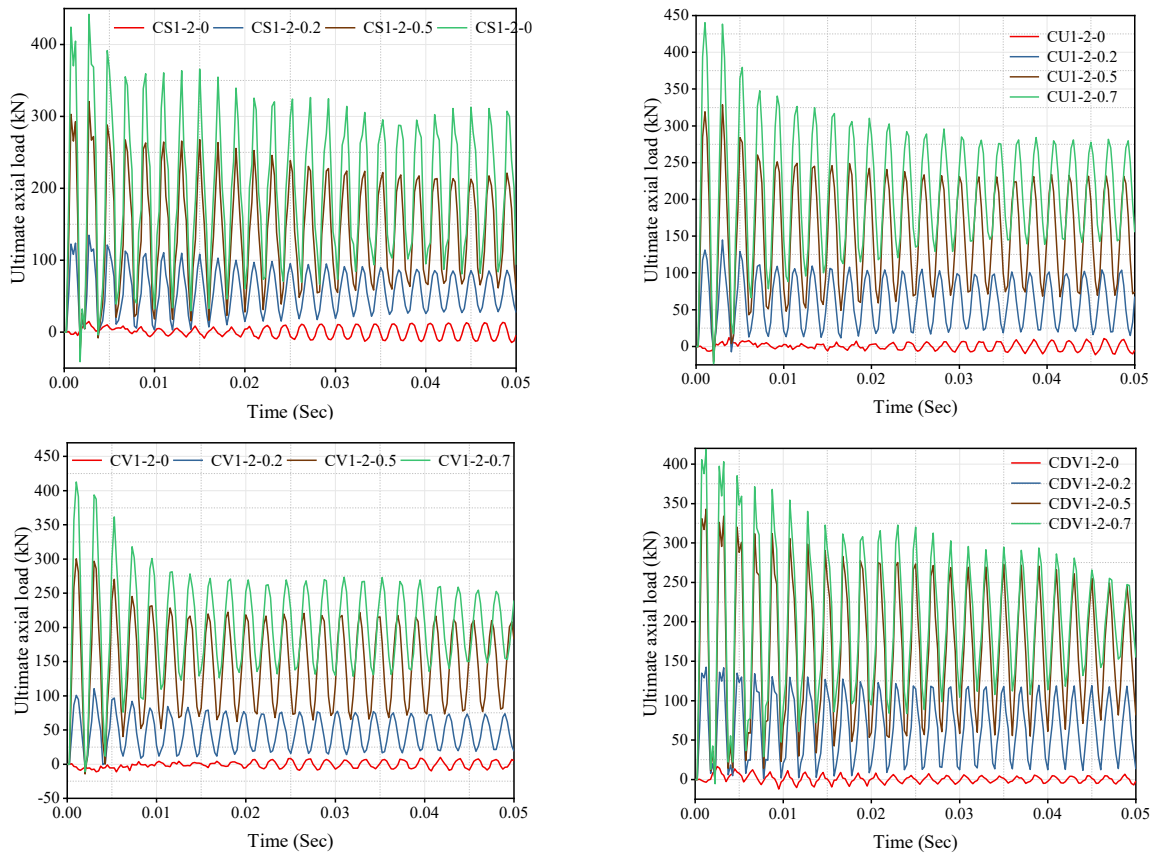


Fig. 8 Axial load-time Curve of numerical analysis with different load ratios.

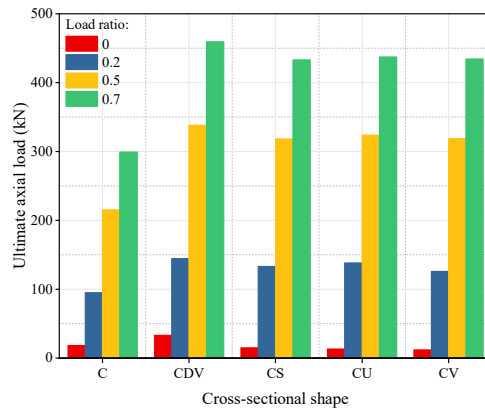
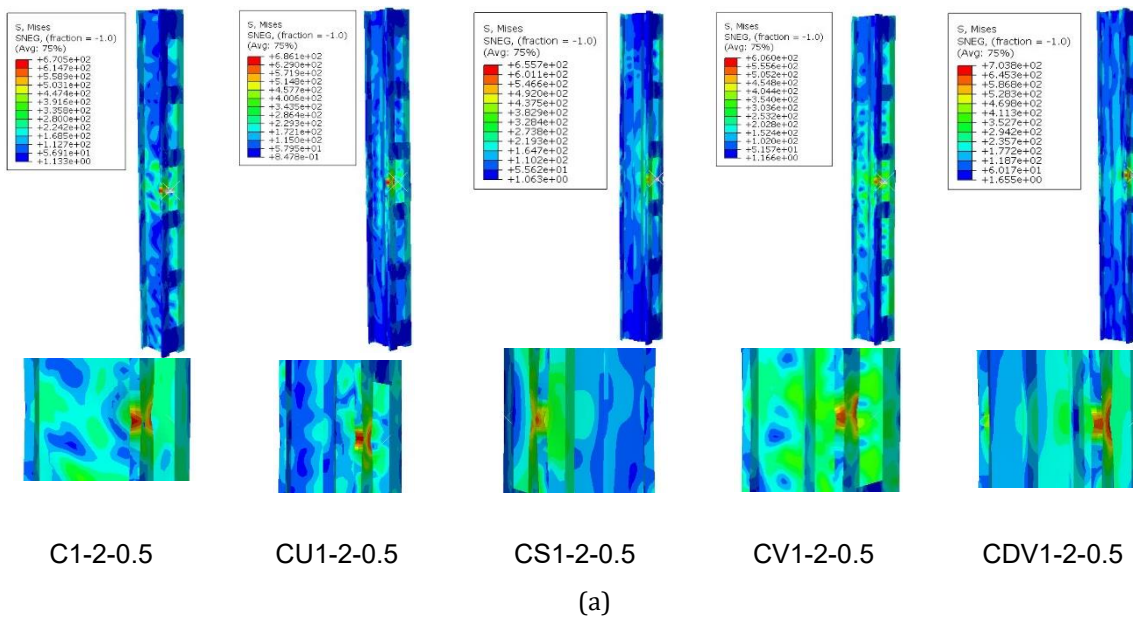


Fig. 9 Peak total axial reaction of the investigated built-up column configurations at axial load ratios of 0.0, 0.2, 0.5, and 0.7 under the adopted lateral impact scenario.



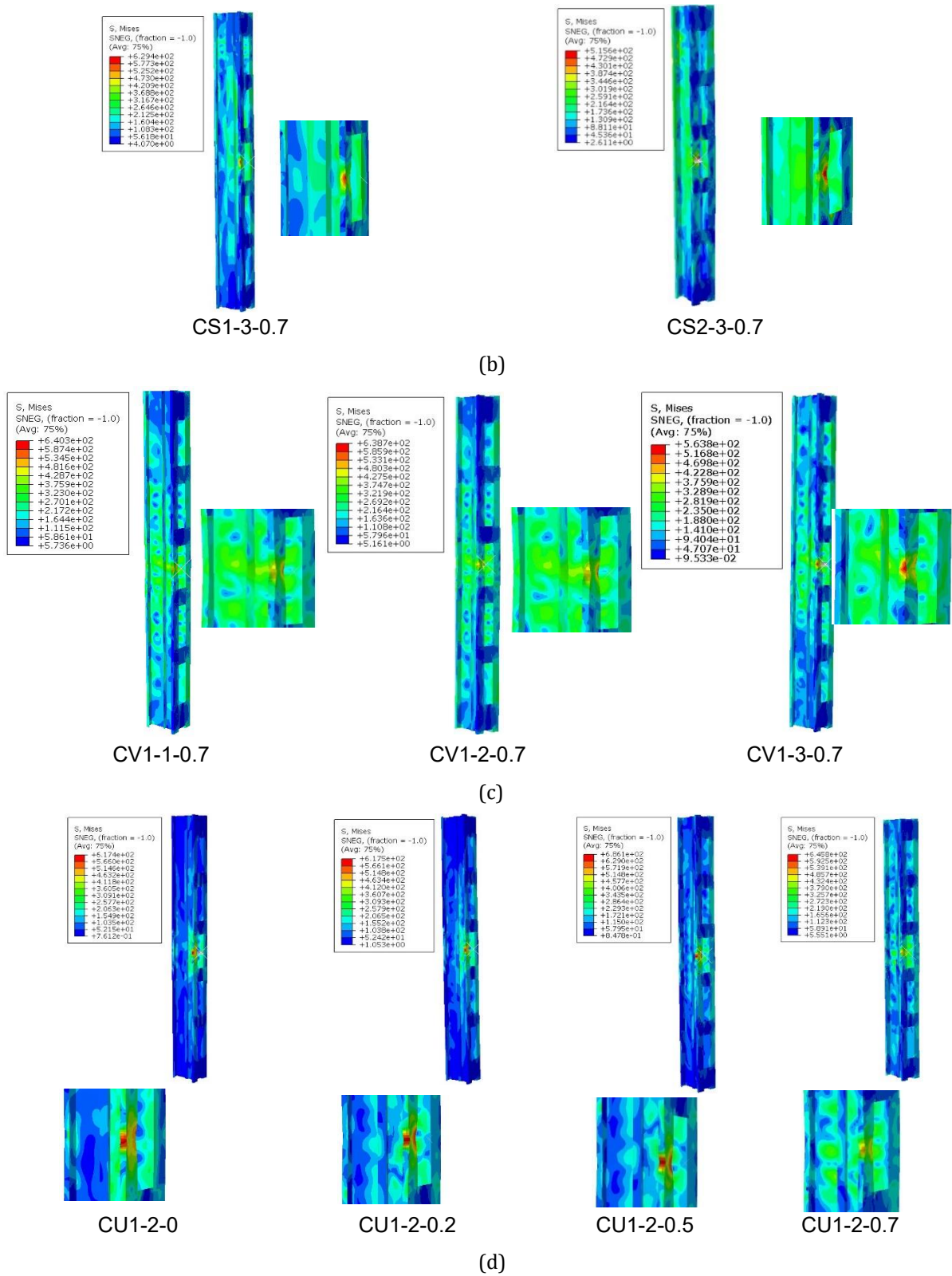


Fig. 20 Representative deformed shapes and von Mises stress distributions of battened built-up carbon-steel columns under lateral impact loading: (a) web-stiffener configurations, (b) cross-sectional dimensions, (c) edge-stiffener configurations, and (d) axial load ratios

4. Conclusions

Systematic finite element analysis of 120 cases was conducted to investigate the performance of stiffened composite carbon steel columns under combined axial compression and low-velocity lateral impact loading. The effects of web-stiffener geometry, cross-section size, edge-stiffener geometry, and the axial load ratio were considered in the study. Peak total axial reaction was the primary response variable, along with interpretation of deflection and von Mises stress contours. The geometry of the web-stiffener had a considerable effect on the behavior of stiffened sections. In Series 1 with Type-1 configurations at an axial load ratio of 0.5, CS, CV, CU, and CDV geometries increased the peak total axial reaction by

74.6%, 99.9%, 60.9%, and 87.4%, respectively, compared to the unstiffened C-shaped reference configuration. The stiffer-section configuration had the largest response among these four stiffened-section types. Stiffened sections had superior performance due to a smaller web width without stiffeners, better restraint of out-of-plane web deformation, and more efficient load distribution. The effect of the web-stiffener geometry on performance was found to be independent of the stiffener's fold count. The effect achieved using edge stiffeners was significant in limiting flange rotation and localized distortions. The use of the Type-2 and Type-3 configurations in the Series 1 C-shaped column led to a 47.9% and 71.4% increase in the peak total axial reaction, respectively, compared to the Type-1 configuration. The Type-3 configuration provided resistance

to rotation at both flange edges and allowed greater cross-sectional area participation in the force-transmission process. In engineering practice, web and edge stiffeners must be viewed as interacting elements because adequate restraint of the web may be insufficient to prevent localized flange distortions when subjected to simultaneous axial compression and lateral impacts. The effect of cross-sectional dimensions showed pronounced dependency on the configuration. The transition from Series 1 to Series 2 resulted in an increase in the peak total axial reaction of the Type-1 CDV and CS models by 9.4% and 5.4%, respectively, while the corresponding C-shaped model saw a decrease in the peak total axial reaction of approximately 3.0%. On the other hand, the peak total axial reaction of the Type-3 CDV model increased by 8.7% to reach 427.11 kN. Therefore, one can conclude that increasing the cross-sectional dimensions is beneficial only when there is sufficient restraint of the web and flanges to engage the new area. An increase in the axial load ratio led to an increase in the peak total axial reaction, since the latter included the already applied compressive load. However, it is important to stress that this does not reflect any increase in the inherent capacity for stability against, or resistance to, axial impact loads. Greater axial compression reduced the stability margin and increased sensitivity to second-order, local buckling, distortional, and overall instabilities. The failure mode contours demonstrated that the primary failure mode was the combination of local indentation due to impact with web and flange instabilities. Web and edge stiffeners limited the area of deformation, prevented cross-sectional distortions, and facilitated a more even distribution of stresses, while greater axial load increased the effect of compression-assisted local instability. The numerical results provide guidelines for selecting appropriate cross-sections and stiffeners under these loading conditions. The CV and CDV web-stiffener arrangements proved effective in providing improved restraint and force-transmission capabilities; moreover, Type-3 edge stiffeners are also beneficial. Nevertheless, the numerical results do not suggest that more complex stiffeners or larger cross-section sizes will always lead to greater effectiveness. The relative slenderness of plates, stiffener orientation, flange restraint, axial preload, and their interactions should be considered simultaneously during configuration selection. This research is limited to the specific geometry, material, impactor type, boundary and connection conditions, and peak total axial reaction as the only comparative response measure. No fracture, damage propagation, element deletion, connection separation, and post-impact residual resistance have been considered additional impact performance measures. Therefore, one should treat the numerical results obtained as indicative trends rather than universal design provisions. Additional studies on the effects of batten spacing, connection stiffness and slip, plate thickness, steel grades, the location and intensity of impacts, repeated impacts, and geometric imperfections should be conducted in the future. Moreover, experiments and numerical analyses of post-impact residual strength should be conducted before developing any design equations or acceptance criteria.

Conflict of interests

The authors declare no competing of interests.

Authorship Contribution Statement

Kun GUO: Writing-Original draft preparation, Conceptualization, Supervision, Project administration.

Data Availability

On Request

Declarations

Not applicable

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Statement

The manuscript has been read and approved by all the authors; the requirements for authorship, as stated earlier in this document, have been met, and each author believes that the manuscript represents honest work.

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