



A Numerical and Experimental Investigation of a Steel Column Reinforced with A CFRP Laminate Under the Effect of Geometric Imperfections

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ABSTRACT:

The presence of geometrical imperfections in steel columns results in the intensification of buckling and a reduction in their compressive capacity, which also leads to a change in post-buckling behavior. Accordingly, in several regulatory frameworks, the extent of this imperfection is typically constrained to a maximum of 0.001 of the length of the member, expressed as the lateral deviation at the mid-height of the compression member. One of the modern systems that is currently under consideration by various engineering groups, including those specializing in civil, mechanical, and aerospace engineering, is the use of FRP family materials, such as GFRP, CFRP and AFRP. Due to the limitations of heat treatment and welding in steel columns under loading, engineers can utilize the mechanical properties of this material to enhance structural stability. This article aims to evaluate the effect of imperfections of varying magnitudes through nonlinear analysis and experimental testing of several specimens. Subsequently, the capacity of the compression member was evaluated using specimens reinforced with a carbon fiber layer. The findings of this study indicate that a column with a mid-span imperfection equal to 0.001 of its length shows a 35.3% increase in compressive capacity when reinforced with three layers of carbon fibers. Furthermore, it was observed that if the initial imperfection increases to up to twice the permitted value, the column's load-bearing capacity decreases by approximately 10%.

KEYWORDS:

Steel column, Load-Bearing Capacity, Post-buckling, Imperfection, CFRP.

1. Introduction

In a compressive member such as a column, the force applied to it may be sufficiently large to cause the member to become unstable, a phenomenon known as buckling of the column. This phenomenon leads to the sudden lateral deformation of a structural member under a compressive load, occurring before it reaches its maximum compressive strength. Various forms of this phenomenon can be seen, such as the bending of a column under compression or the wrinkling of a plate under shear. In other words, when the load is gradually applied to a structure and the amount of load increase reaches a critical level, that member will suddenly experience large deformations in the

structure, which may cause the complete loss of the load-bearing capacity of the member. In fact, prior to failure caused by compressive yield stress, the phenomenon of buckling occurs.

In recent years, with the increasing development of technology and the introduction of novel materials, researchers have made significant advancements in utilizing and combining these materials with others and effectively extracting their performance characteristics. FRP, or Fiber Reinforced Polymer, represents a novel material used in civil engineering for the repair, reinforcement, and retrofitting of a variety of structures. This composite material is made of two parts. The first part is the matrix, and the other part is the fibers. The matrix comprises chemical materials, including epoxy and polyester resins,

which are reinforced with fillers and additives to enhance mechanical and chemical properties. The role of fibers in fiber-reinforced polymer (FRP) is to provide sufficient mechanical strength. In contrast, the matrix does not have a mechanical bearing role and is instead responsible for protecting the fibers against corrosion, environmental factors, and damage. In addition, the transfer of load in FRP is done with the support of the matrix, facilitating the transfer of shear force between fibers. The matrix can also be used to regulate local fiber buckling under pressure, and fibers constitute the largest volume of FRP.

The application of fiber-reinforced polymer (FRP) materials, including glass-fiber-reinforced plastic (GFRP), carbon-fiber-reinforced plastic (CFRP), and aramid-fiber-reinforced plastic (AFRP), is expanding rapidly across a diverse range of industries. Researchers and engineers are utilizing these materials in heavy installations, water and marine structures such as dams and canals, and in retrofitting of engineering infrastructures such as road and rail bridges, water and chemical tanks, silos, and cooling towers.

The use of fiber-reinforced polymers (FRPs) in various industries is increasing. These materials are used in heavy installations as well as in water and marine structures such as dams and canals. They also include retrofitting in engineering infrastructures such as road and rail bridges, water and chemical tanks, silos, and cooling towers, and it is also expanding daily. The material offers additional advantages, including the ability to function without interruption, the prevention of damage to other parts of the structure, and the ability to continue using the building without interruption. Furthermore, the material resists corrosion in areas with plaster and soil, which is an essential consideration in many construction projects. Moreover, any human or environmental factors that cause structural defects or lack of proper performance, such as design flaws, inadequate bending and tensile strength, structural cracks, increased load-bearing capacity, changing structural application, increased gravity and lateral loading, demonstrate the significance of utilizing this material.

In recent years, researchers have investigated the combined behavior of various elements with these materials, which researcher can use to study the buckling behavior of thin-walled structures utilized with CFRP (Bhetwal, Krishna Kumar and Seishi Yamada, 2012), the steel shear wall reinforced with CFRP (Sahebjam & Showkati, 2016), the behavior of plate girder reinforced with CFRP (Ardalani, Showkati, Teymourlouei & Firouzsalar, 2017), strengthen cylindrical shells with CFRP rings (Khatuni & Showkati, 2019), some research findings like Schnerch et al, (2006) emphasize that the strengthening of steel structures with FRP requires

proper surface preparation, appropriate adhesive selection, and careful detailing of strip terminations to ensure effective load transfer and resistance against corrosion. Cyril Thomas Antony Raj et al, (2023) report that the application of carbon fiber-reinforced polymer (CFRP) in the strengthening of steel structures leads to an increase in natural frequency and damping ratio, resulting in a significant enhancement of the dynamic behavior and vibrational characteristics of the honeycomb beams (CPE) investigated in this study. Investigating the effect of increasing layers on the load-bearing capacity of steel columns by Boudaghi and Showkati, (2023). Çelik Aİ et al, (2024) demonstrate that reinforcement of cylindrical steel tanks using CFRP sheets has been shown to significantly reduce buckling and enhance their seismic performance. Finite element analyses indicate that this approach effectively controls stresses and deformations, thereby improving the structural stability of the tanks.

Recent experimental studies on composite steel-concrete members have shown that their structural performance is strongly affected by loading conditions, confinement, and environmental effects. Pachideh and Gholhaki (2020a) reported stable cyclic behavior and high energy dissipation capacity in CFDST columns under cyclic loading. In addition, FRP confinement was found to significantly enhance strength and ductility while improving post-peak behavior in concrete-filled steel tube columns Pachideh and Gholhaki, (2020b). Furthermore, Pachideh et al. (2021) demonstrated that temperature rise can reduce stiffness and load-bearing capacity while intensifying nonlinear response in CFDST members.

These findings highlight the sensitivity of composite members to environmental and thermal conditions, which is further supported by recent research showing that elevated temperatures and reaching the maximum adhesive layer temperature can significantly reduce the load-bearing capacity of CFRP systems, while heat-resistant coatings, particularly hybrid types, can mitigate these adverse effects (Deng et al., 2025).

To provide a clear overview of the research methodology and the sequence of the study, a flowchart of the research process is presented in Fig. 1.

2. The relationship between buckling and geometric imperfections

All metals can have defects during construction, transport, or installation. Engineering science classifies these imperfections into two categories, geometric and mechanical, each of which is further subdivided into local (member) and system (structural) imperfections. Such imperfections are then categorized. Imperfections significantly affect

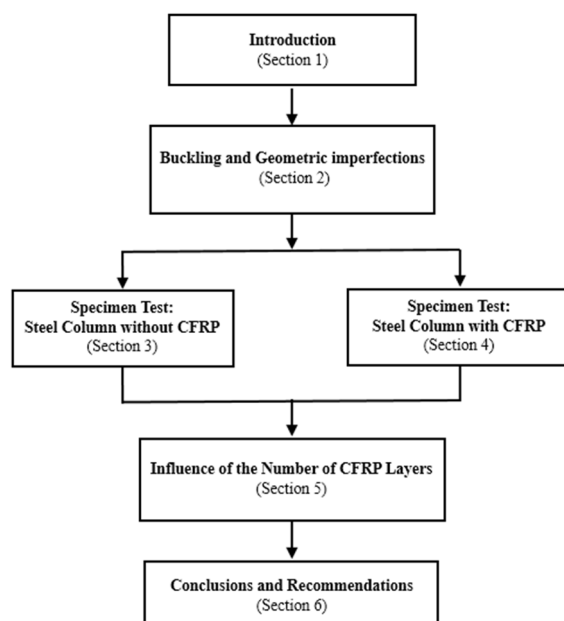


Fig. 1. Flowchart of the research methodology and overall study procedure

the capacity and stiffness of compression members, such as columns, influence the buckling and post-buckling behavior, and alter their response to dynamic loads, fire, and seismic events. For these reasons, various standards set a limit on the maximum allowable amount of initial imperfections (ANSI/AISC 360-22) and (Eurocode 3). In the event of any significant seismic activity, which causes minor damage to the structure, imperfections inevitably occur. In addition, different types of columns, such as thin, medium, or short, are affected differently by imperfections or manufacturing defects. The results demonstrate the significance of accurate construction and implementation of steel columns, which reduces the risk of structural failures and enhances their flexibility capacity. It is crucial to recognize that throughout the design process, engineers must consider the effects of imperfections and incorporate measures to reinforce and eliminate their adverse effects. Additionally, they must assess the dynamic behavior and failure modes of steel columns to ensure their ability to withstand extreme events and minimize the extent of potential catastrophic failures.

In recent years, the development of advanced analytical and numerical tools, including finite element analysis and artificial intelligence algorithms (Tahir ZU and Mandal P, 2017) has facilitated significant advancements in structural engineering; their understanding and ability to predict the effects of imperfections have greatly enhanced the safety and reliability of structures. These tools can be utilized to enhance the optimization of designs, improve the efficacy of evaluation techniques, and facilitate the decision-making processes related to steel structures, particularly considering the behavior of columns.

Furthermore, these tools can improve the performance and lifespan of steel structures by developing design guidelines and suggesting retrofitting strategies, reducing the risk of structural failure, and increasing flexibility in facing different loading conditions; the end users of the structure are the ultimate beneficiaries. For example, the introduction of neural network as a new method in various sciences to solve complex problems, which, like the human brain with several rounds of training, provides a general function as an answer to non-linear problems such as buckling and post-buckling behavior of columns and predicting their critical load. In recent years, the number of published articles related to imperfections in steel columns has steadily increased, indicating a growing interest in this subject. These trends reflect both the growing interest in this field and the ongoing efforts to enhance the performance of steel columns.

Researchers have investigated several aspects related to imperfections in steel columns. These include the effects of various imperfections, local geometric imperfections, residual stresses, and others. The sensitivity of steel columns to imperfections varies with the slenderness ratio of the column as well as the type of imperfection, which has been investigated (Brown and Davis, 2015).

Additionally, Gupta and Patel, (2012) tested a variety of methods and approaches for modeling imperfections in steel columns, including geometric imperfections, material imperfections, and residual stresses. Their findings indicated that accurate imperfection modeling is crucial for predicting the behavior of steel columns. This is an important point that merits further investigation. Smith and Johnson, (2010) published a review of the various techniques used to reduce the imperfections of steel columns. The authors reviewed a number of methods, including strengthening, bracing, and post-tensioning, in order to identify the most effective approach for reducing the effects of imperfections while also considering the advantages and limitations of each technique. Imperfections affect the reduction of the load-bearing capacity of the column under axial load by Boudaghi and Showkati, (2023). Ali İhsan Çelik et al, (2024) indicated the effect of the initial imperfection on the stainless-steel shell, showing that the buckling reduction factor approaches unity as the shell slenderness ratio decreases.

Radwan and Kövesdi (2023) highlighted the influence of combined local and global imperfections on the buckling behavior of box-section columns. Quan et al. (2024) developed GMNIA-based equivalent geometric imperfection models for steel beam-columns and demonstrated their significant effect on predicted buckling resistance. In addition, recent studies have shown

that increasing imperfection amplitude leads to a noticeable reduction in buckling capacity, while geometric uncertainties further amplify instability in slender members (Liu et al., 2025).

3. Specimen test of a steel column without CFRP

In this research, the 20×20×2mm box section with a length of 1000mm was selected based on the capacity of the available laboratory equipment in the Structural Department of Urmia University, as well as to ensure accurate control of initial geometric imperfections and enable a reliable evaluation of the behavior of both unstrengthened and CFRP-strengthened specimens. The specimen

was used as a compression member with fixed-fixed boundary conditions. The section was made of steel St 37-2 (S235JR) with the desired mechanical characteristics. A cross-sectional analysis assessed its thickness and compactness.

In order to extract information from the setup system and create a load-displacement curve, the specimen (column) was meshed in dimensions of 20*20mm. Two LVDT devices were installed and tested: one positioned under the load cell and the other in the center of the column. The load was applied at a constant rate of 20 N/s to ensure static loading conditions.

Table 1 and Fig. 2 show the test specimen's geometric and physical characteristics and placement in the setup system in two directions during the test: the north-south and east-west axes

Table 1. Geometrical and physical characteristics of the test specimen

Length (mm)	Width (mm)	Thickness (mm)	Height (mm)	Weight (Kg)	A-sec (mm ²)	I (mm ⁴)	r (mm)	CC*	SR*	K
20	20	2	1000	1.256	1.44e+2	7.9e+3	7.4	8	67.6	0.5

*CC: Compression control; SR: Slenderness ratio

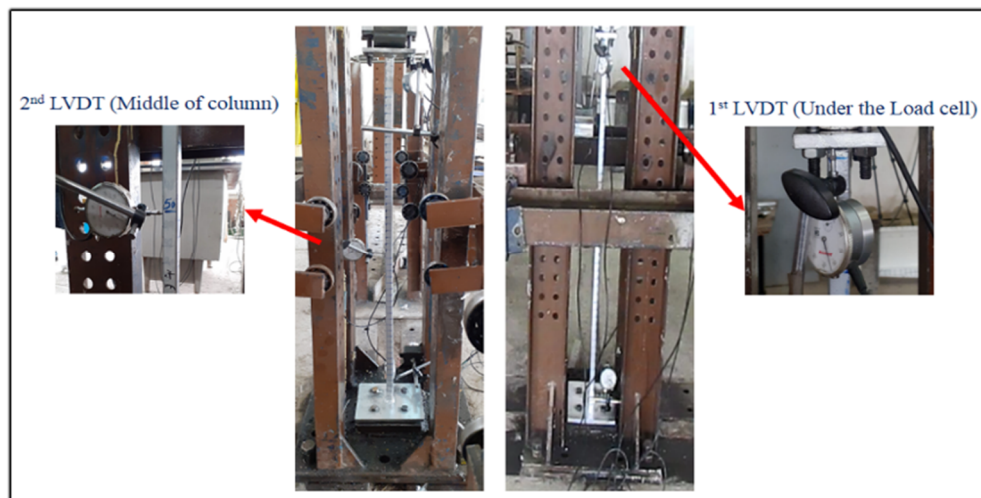


Fig. 2. The test specimen into the test setup and the placement of the LVDTs

3.1. The numerical modeling and analysis

ABAQUS (Smith M, 2016) software was used to determine the critical load of the column (compression member) and to model the specimen.

The specimen was modeled with fixed ends, and the model in the software was defined using the Shell element type and the steel's non-linear properties.

To reduce computation time, an optimized mesh size of 3mm was selected for S4R elements, as presented in Table 2.

Initially, a load of one newton was applied to excite the system.

Table 2. Mesh size testing

Mesh Size(mm)	Load(N)	Time(S)
1	37234.87	196
2	37096.42	296
3	37131.2	657
4	37204.11	1506
5	37388.68	6012

Once the buckling modes were obtained, the first three modes were observed in Fig. 3.

The maximum allowable initial imperfection of 1mm was assigned to Mode 1, which is the dominant mode of the column, in order to evaluate its effect on the load-bearing capacity.

Subsequently, the Riks analytical model, as illustrated in Fig. 4, is utilized to assess non-linear

deformations and extract the load-displacement curve.

In the next phase, the study investigates how imperfections affect the load-bearing capacity of the column.

Imperfections 50% below the limit (0.5mm), as well as 50% above (1.5mm) and twice that (2mm), will be introduced into the column. The maximum capacity of the column is then extracted from the load-displacement curve.

3.2. Finding out

Fig. 5 compares the load-displacement curves for a steel column with several imperfections.

Fig. 6 presents the results of a nonlinear analysis demonstrating the reduction in the load bearing-capacity of the steel column as imperfections increase (imperfections in 27 points).

Additionally, Table 3 shows the maximum load bearing-capacity of the steel column under different levels of imperfections.

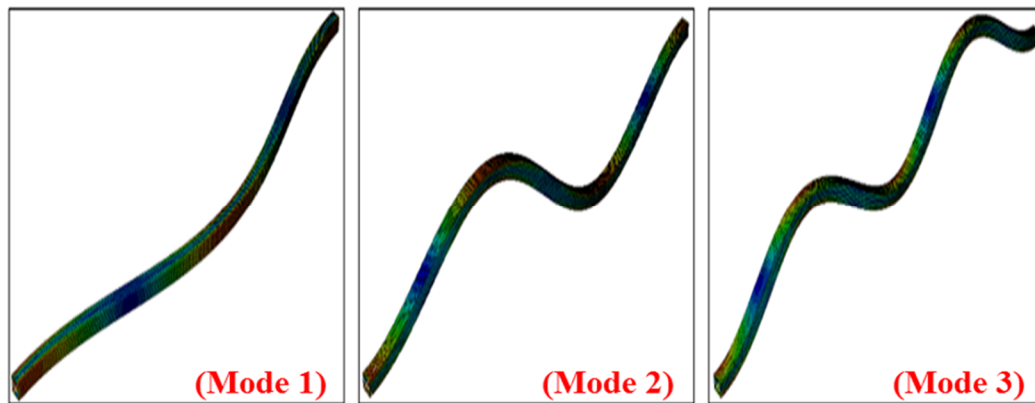


Fig. 3. Eigenvalue analysis of the first three buckling modes of the column

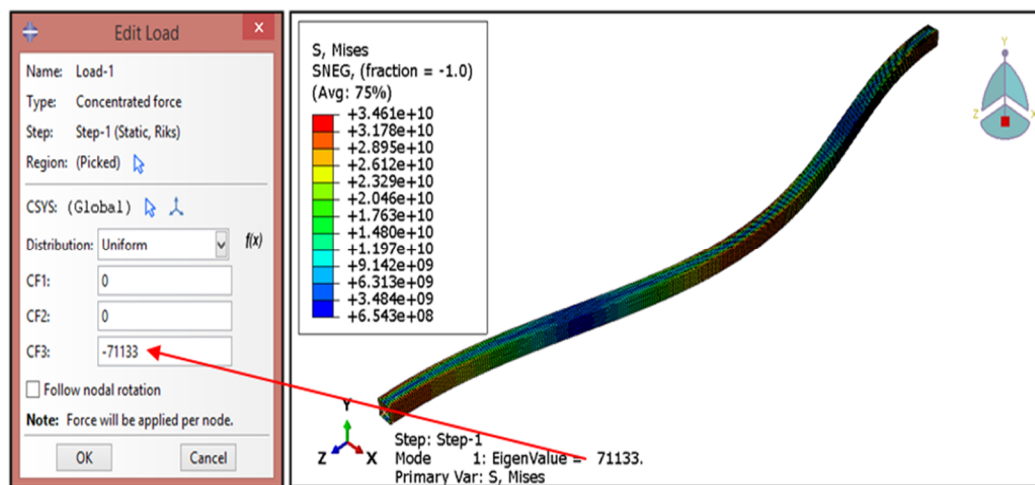


Fig. 4. Buckling of the first mode load in a nonlinear analysis

Table 3. Numerical reduction of load-bearing capacity with increasing imperfection

Steel Column (Mesh Size=3mm / Length=1000mm)								
Imperfection (mm)	0.2	0.5	0.8	1	1.2	1.5	1.8	2
Riks (N)	37210	35710	34410	33204	32900	31940	31060	30420

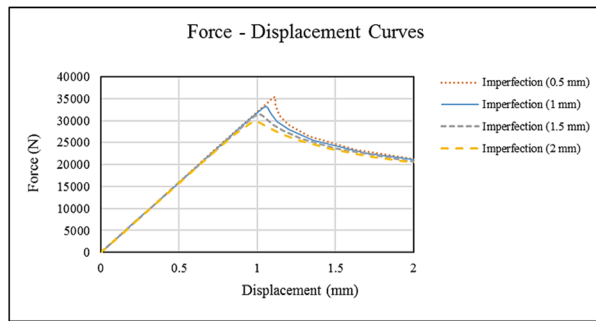


Fig. 5. Load-Displacement curves for various imperfections

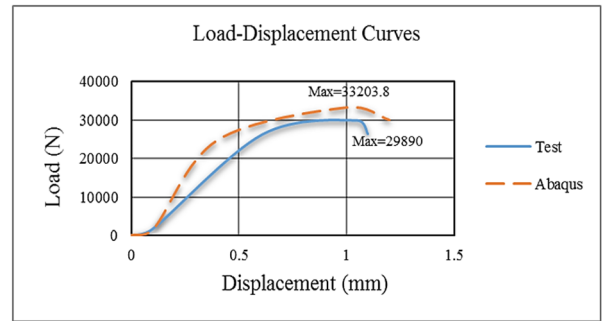


Fig. 7. Experimental and numerical load-displacement curves

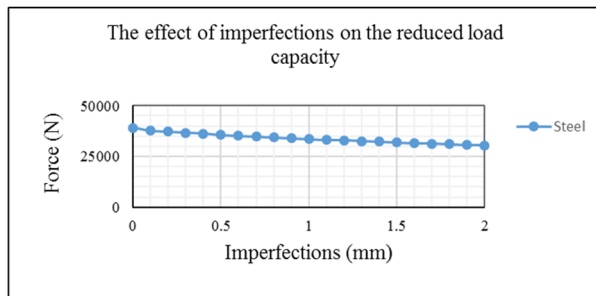


Fig. 6. Steel column imperfections reduce load-bearing capacity

3.3. Experimental and numerical comparison of the load-displacement curves of the specimens

By evaluating the data obtained from the specimen test and nonlinear analysis, it can be seen that the maximum force value obtained from the software is approximately 11.09% higher than the value obtained from the experimental specimen test. Fig. 7 illustrates the load-displacement curves of the specimen.

4. Specimen test of a steel column with CFRP

4.1. Specifications of the CFRP test specimen and test method

In order to prepare a CFRP-strengthened test specimen with the exact specifications as the previous one, the test specimen was sand-blasted (Fig. 8-a and 8-b)) to improve the adhesive performance.

The adhesive was made from a two-component combination of resin and epoxy hardener (Fig. 8-c) for bonding CFRP to the steel column (Fig. 8-d) and (Fig. 8-e)). Then the specimen was placed in the test setup at Urmia University, as shown in Fig. 9-a.

Therefore, the information obtained from the system could be used to create a load-displacement curve.

Fig. 9-b illustrates the deformation of the test specimen after being removed from the test setup.

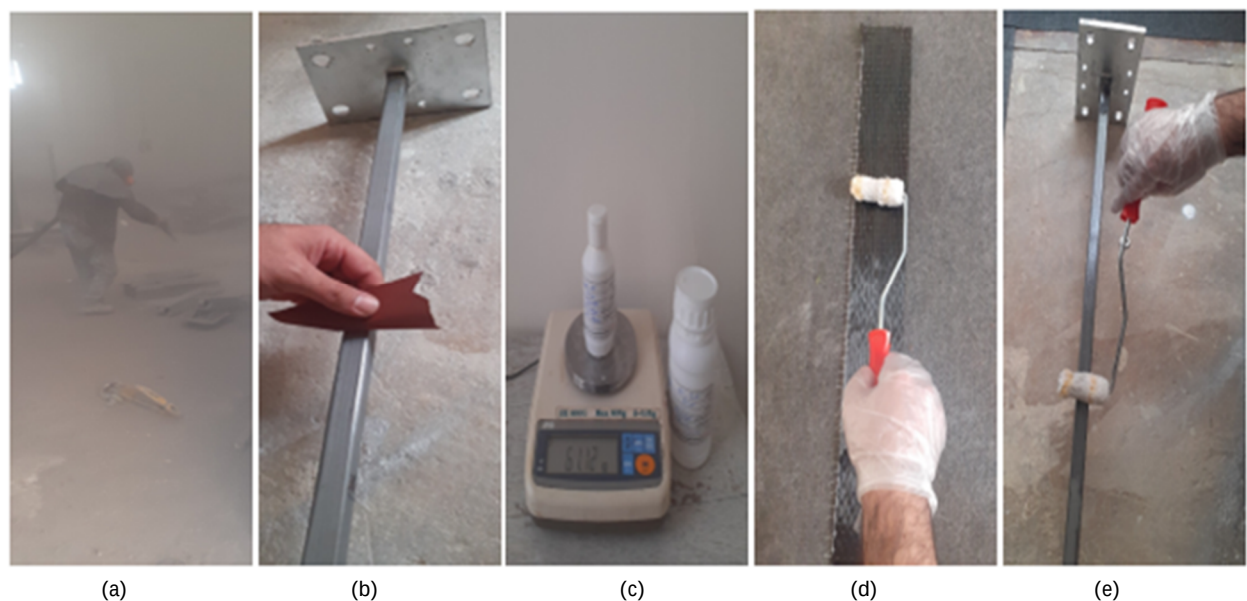


Fig. 8. a) Sand-blast, b) Surface cleaning, c) Preparation of a two-part adhesive, d) Coating the CFRP surfaces with adhesive, e) Bonding the CFRP layer to the steel column

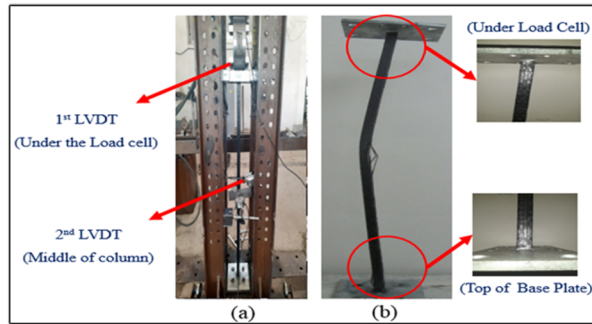


Fig. 9. a) The specimen test into the test setup, **b)** Deformation of steel column

4.2. Numerical modeling test specimen reinforced by CFRP

In this study, the ABAQUS software was used to perform non-linear analysis and to determine the critical load of a column reinforced with CFRP, in accordance with the methodology previously outlined for the test specimen.

The mechanical characteristics of the steel material and the method of modeling the column element are consistent with those of the previous test specimen.

The thickness of the CFRP is 0.17mm, and its mechanical specifications were provided by the manufacturer, as shown in Fig. 10 and Table 4.

The method of modeling the test specimen in ABAQUS software is based on shell elements, utilizing the Tie option in the Interaction module, with all connections shown in Fig. 11.

The meshing is identical to that of the steel section. Following the acquisition of the buckling modes and the application of the buckling load with an initial imperfection of 0.001 of the member length (1mm), which represents the dominant mode, the load-displacement curve can be extracted from the Riks analytical model.

We can also see the good correspondence of the images in the buckling area and the regions connected to the load cell and the support Fig. 12, which corresponds to the maximum stress obtained by the nonlinear analysis with the deformation areas of the tested specimen shown in Fig. 13.

4.3. The Behavior of experimental and numerical CFRP reinforced specimen

It can be observed from the load-displacement curve presented in Fig. 14 that the maximum force obtained from the test specimen with CFRP is approximately 13.20% lower than that predicted by nonlinear analysis. Additionally, Table 5 displays the maximum load-bearing capacity of the steel column with CFRP under various initial imperfections.

	E1	E2	Nu12	G12	G13	G23
1	230000000000	15000000000	0.2	27000000000	27000000000	7000000000

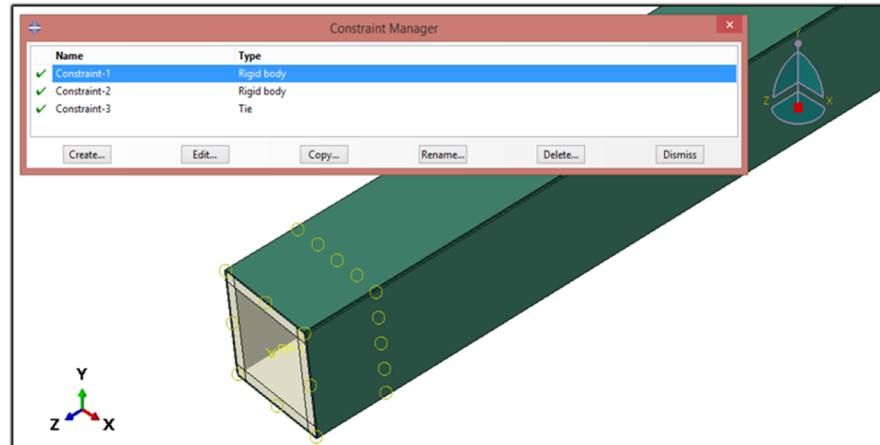
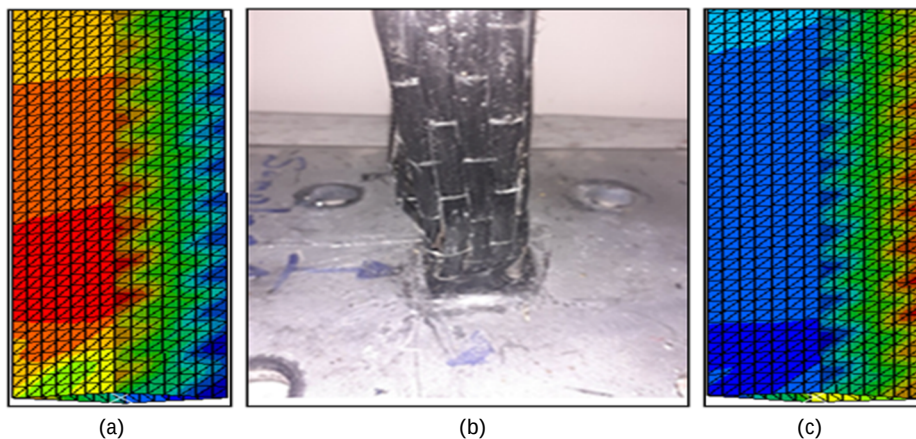
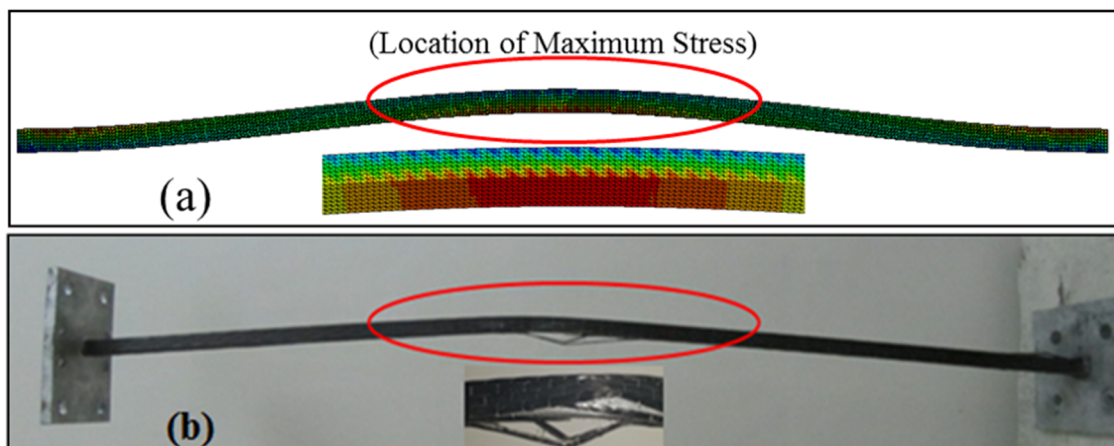
Fig. 10. CFRP mechanical specifications

Table 4. Parameters for Hashin Damage behavior

Longitudinal Tensile Strength (Mpa)	Longitudinal Compressive Strength (Mpa)	Transverse Tensile Strength (Mpa)	Transverse Compressive Strength (Mpa)	Longitudinal Shear Strength (Mpa)	Transverse Shear Strength (Mpa)
4950	2400	1800	1000	500	500

Table 5. Numerical reduction of load-bearing capacity with increasing imperfection in the CFRP specimen

Steel Column with Full CFRP (Mesh Size=3mm / Length=1000mm)								
Imperfection (mm)	0.2	0.5	0.8	1	1.2	1.5	1.8	2
Riks 1 Layer (N)	119500	117800	38020	37130	36490	35180	34540	33960

**Fig. 11.** Tie CFRP to steel column**Fig. 12.** Similarity of steel column deformation above base plate in: **a)** non-linear analysis with, **b)** the test specimen**Fig. 13.** Similarity deformation of buckling areas in: **a)** non-linear analysis, **b)** the test specimen

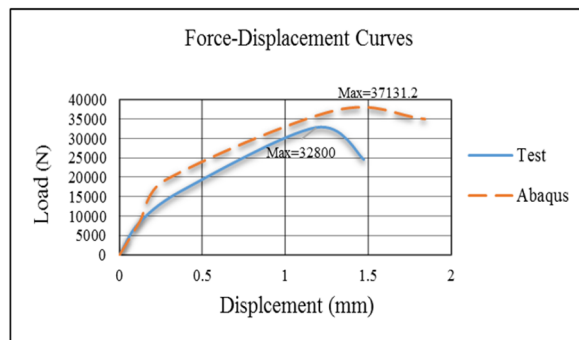


Fig. 14. Load-displacement curve for CFRP test specimen with nonlinear analysis

4.4. Scale Effect Validation

To evaluate the applicability of the proposed strengthening method to practical structural members, a full-scale steel column with a cross-section of 100×100×10mm and a length of 5000mm was numerically modeled.

The results indicated that the load-bearing capacity of the specimen strengthened with five CFRP layers increased by approximately 8.5% compared with the unstrengthened reference column.

5. Influence of the Number of CFRP Layers

Fig. 15 shows that as the number of CFRP layers increases, the capacity of the column increases. The results obtained from nonlinear numerical analysis are presented in the following approximate order: one layer of CFRP: 37131 N, two layers of CFRP: 40950 N, three layers of CFRP: 44949 N.

According to the diagram in Fig. 4, the maximum load of the steel column without the CFRP layer was 33203.8 N.

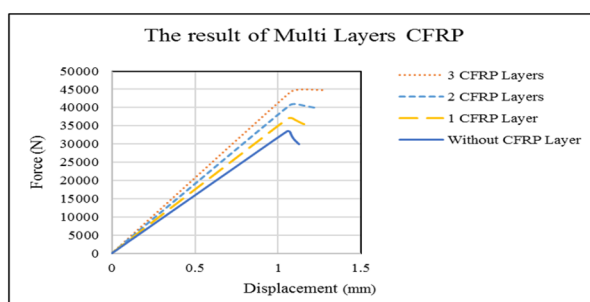


Fig. 15. Increase in the load-bearing capacity of the steel column by adding CFRP layers

6. Conclusions and Recommendations

In various standards, the maximum amount of imperfection for the column is limited to 0.001 of the member length. In this article, nonlinear numerical analysis is used to investigate the effect

of varying imperfection values on the behavior and load-bearing capacity changes of the member under axial compressive force. The results are then compared with experimental data obtained from the specimen test. Subsequently, the effect of carbon fiber-reinforced polymer (CFRP) on the steel column was investigated. This study involved a numerical and experimental analysis of the behavior and load-bearing capacity changes of the member under the influence of axial compressive force and different initial imperfection values.

1) A 50% reduction of the imperfections relative to allowable value resulted in an approximate 6.6% increase in the compressive capacity of the column.

2) A 50% increase in the imperfections relative to allowable value resulted in an approximate 5.2% reduction in the compressive capacity of the column.

3) A 100% increase in the imperfections relative to allowable value resulted in an approximate 9.7% reduction in the compressive capacity of the column.

It should be noted that:

The results clearly demonstrate that the compressive capacity of the steel column is highly sensitive to the magnitude of the initial geometric imperfection. A 50% reduction in the imperfection level below the allowable value leads to an increase in load-bearing capacity, which can be attributed to a more stable structural response and reduced lateral deformations. In contrast, increasing the imperfection level by 50% and 100% above the allowable value results in a gradual reduction in compressive capacity, due to increased lateral instability and earlier buckling initiation. Overall, geometric imperfections play a governing role in reducing the stability and buckling resistance of steel columns by increasing their susceptibility to lateral deformations. Conversely, reducing the imperfection level improves the effective stiffness and enhances the member's ability to sustain higher loads prior to global instability.

4) The effect of 0.001 of the member imperfection was also evaluated by comparing the specimen test results with the results of the nonlinear numerical analysis obtained using a single layer of CFRP:

- The numerical nonlinear analysis results were 11.09% higher than those obtained in the specimen test for the steel section without CFRP.
- The numerical nonlinear analysis results were 13.2% higher than those obtained in the specimen test for the steel section with CFRP.
- The specimen test results for the steel section with CFRP indicate a 9.7% increase in strength compared with the steel section without CFRP.
- The specimen test results for the steel section with CFRP indicate an 11.8% increase in

strength compared with the steel section without CFRP.

It should be noted that:

As shown in Figures 11 to 14, a good agreement is observed between the experimental and numerical (ABAQUS) responses, confirming the reliability of the numerical model. Minor discrepancies can be attributed to inevitable differences between idealized numerical assumptions and real experimental conditions. These include micro-scale damage in the CFRP matrix and fibers, adhesive quality, environmental effects during handling and installation, as well as fabrication, assembly, and support connection imperfections. In addition, initial seating effects and equipment slack at the early stage of loading may have contributed to slight differences in the response of the experimental specimens.

5) By utilizing a single layer of CFRP with 0.001 of the member length imperfection, a comparison of the experimental results with the results of the nonlinear analysis is illustrated as the following:

- The column's load-bearing capacity is observed to increase by 11.8% when a single layer of CFRP is utilized.
- The column's load-bearing capacity is observed to increase by 23.3% when two layers of CFRP are utilized.
- The column's load-bearing capacity is observed to increase by 35.3% when three layers of CFRP are utilized.

It should be noted that:

The obtained results clearly indicate that CFRP strengthening leads to a progressive increase in the load-bearing capacity of the column. This improvement is primarily attributed to the additional confinement and stiffness provided by the CFRP layers, which effectively reduce lateral deformations and delay the onset of buckling.

6) In conclusion, based on the obtained results, the use of a single CFRP layer is recommended as an efficient and practical strengthening strategy for steel columns subjected to axial compression with initial geometric imperfections. The results indicate that the member can sustain imperfections up to 100% of the allowable value (2mm), while its load-bearing capacity within the allowable imperfection range remains nearly comparable to that of the unstrengthened condition (Tables 3 and 4). This demonstrates that CFRP enhances the effective flexural stiffness, reduces the sensitivity to initial imperfections, and consequently improves both load-bearing capacity and structural stability. Therefore, this technique can be considered a cost-effective solution for enhancing the performance of steel members in engineering applications.

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