Numerical Study on the Structural Behaviour of Steel Column under Pitting Corrosion

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***Abstract*— This study was to identify the behavior of corroded steel columns under various loading and strengthening conditions. The study focused on the effect of different parameters on the load-carrying capacity of the columns, including the position, angle, and eccentric loading in different directions. The study also found that eccentric loading in both uniaxial and biaxial directions reduced the peak load capacity of the column, with the effect being more significant for eccentricity in the X direction. Furthermore, the study explored the effectiveness of using fiber-reinforced polymer (FRP) sheets as a strengthening technique for corroded columns, examining the impact of partial and full wrapping arrangements and the number of layers of FRP sheets. The experimental results showed that the load-carrying capacity of the columns decreased as the eccentricity of the loading and the number of layers of FRP sheets decreased, while it increased with the use of full wrapping arrangements. Additionally, the study revealed that the position and size of the corrosion notch significantly affected the load-carrying capacity of the columns. These findings have practical implications for the design and maintenance of corroded steel columns in various structural applications. Finite element software ANSYS Workbench 2022 R2 was used for analysis and to study the influence of various parameters on the load-bearing capacities.**

Keywords—Corrosion, axial behavior of steel column, Artificial notch, CFRP, ANSYS Workbench 2022 R2.

I. INTRODUCTION

Circular steel tubes are widely used in the construction of industrial and offshore structures, such as bridges, oil platforms, and power towers. For these structures to have a long lifespan, it is crucial that they are effective in corrosive environments. Despite the use of anticorrosive coatings, corrosion and degradation of steel structures is inevitable. This chapter provides an overview of different types of corrosion and their impact on steel columns. Depending on the service conditions, columns may experience uniform corrosion and/or localized corrosion. When designing thin-walled steel members, the additional thickness can be added to resist corrosion, in addition to the use of anticorrosive coatings, making uniform corrosion more manageable. However, localized corrosion is more common, unpredictable, and difficult to detect in real-life situations, leading to more serious problems. Localized corrosion in thin-walled steel structures usually begins with pitting corrosion, similar to uniform corrosion. With time, pitting corrosion can progress into localized area corrosion, and can even result in holes and cracks in the walls of the steel members.

Generally, to induce corrosion, accelerated corrosion methods are used [1]. It is difficult to do accelerated corrosion because of time constraints. So, need to adopt a new method for corrosion. In this study for the penetrating corrosion, an artificial notch is introduced. As mentioned above the notch can be a hole or crack according to the corrosion type. There are also some other methods that induce the corrosion of the specimen like thickness reduction. But the notch type was introduced recently and only a few studies are done based on this approach.

Fig. 1. Localized penetration corrosion.

II. NUMERICAL MODELLING

The finite element modeling of the notched column was carried out in the finite element software ANSYS R2. The axial behavior of the column was established by axial point loading in the software as a displacement-controlled method. The finite element model developed in this study was validated against the models in the experimental study conducted by Shan Gao et al. (2022) [2].

A. *Geometrical modeling*

The dimensions of the column and material properties of the model components were obtained from the experimental study and used for the development of the FE model. The same model was then used for validation in ANSYS R2. The circular column used had a diameter(D) of 90 mm and a height(h) of 270 mm, with a 4 mm notch width and 90 mm notch length. Three types of columns were used for the study: normal columns without corrosion, vertically notched (CRV) columns with a 4 mm notch width and 45 mm notch length, and oblique (CDO) columns with a 4 mm notch width and 90 mm notch length. These dimensions were used for validation purposes. The sample FE model was given in Fig. 2, and dimensions are established in Table I.

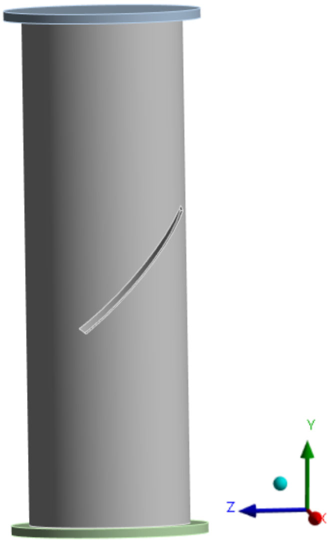

Fig. 2. Column with oblique notch modeled in ANSYS.

TABLE I. MODEL DIMENSIONS

Parameter	Dimensions (mm)
D x H x t	90 x 270 x 2
Notch length	90
Notch width	4
Notch orientation	45° (oblique) 90° (vertical)

B. *Material modeling*

Shan Gao et al. (2022) developed a constitutive model for a steel column with corrosion induced by an artificial notch. The properties of the model are presented in Table II.

TABLE II. MATERIAL PROPERTIES

Property	Value
Young’s modulus	210 GPa
Yield stress	338 MPa
Poisson’s ratio	0.3
Ultimate strength	428 MPa

The material properties provided in Table I. were utilized to develop a three Finite Element (FE) model for parametric studies. The only material used in the model was steel, with a modulus of elasticity (E_s) of 210 GPa and a Poisson's ratio of 0.3.

C. *Meshing*

20 nodded, Solid 181 shell element was used for modeling. The element has 3 degrees of freedom per node. To ensure accuracy and efficiency in the model, a mesh convergence study was conducted. Five different mesh sizes were tested, ranging from 5 mm to 15 mm. The results of the study showed that reducing the mesh size beyond a certain point did not significantly affect the accuracy of the results, but significantly increased the computation time. Therefore, a mesh size of 10 mm was chosen as it provided sufficient accuracy while keeping the simulation time reasonable. The mesh convergence study was carried out under monotonic loading to save time and effort.

D. *Loading and Boundary Conditions*

To replicate the experimental setup, the specimen was securely fixed at the bottom and subjected to axial loading on its top surface. To ensure that the necessary boundary conditions were met, a 5 mm thick plate was expertly welded to both the top and bottom ends of the column. The loading process was then implemented via displacement control in the axial or y direction, thereby ensuring consistency with the experimental procedure.

E. *Validations*

Fig. 3 and Fig. 5 display a comparison between the load-displacement curves obtained from the FE model and the experimental data for the vertical and oblique notches, respectively. The model was validated using three different experimental specimens from the study conducted by Shan Gao et al. The results show a good agreement between the experimental and computational models. Table III summarizes the variations in the overall load-carrying capacity of the specimens.

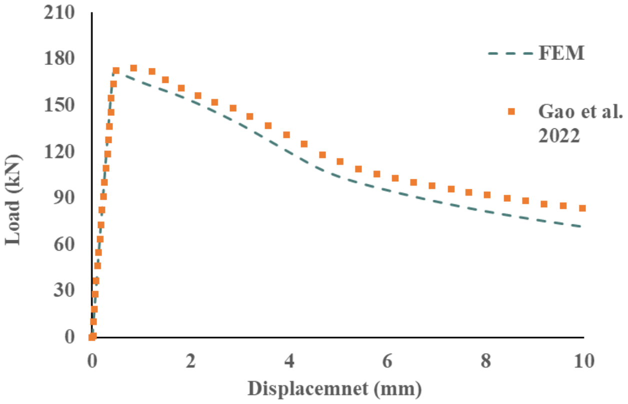

Fig. 3. Vertical notch.

The peak load obtained from the load-displacement curve for the vertical notch in the numerical model is only 1.15% different from the maximum load in the experimental results. Fig. 4 displays the failure modes of both the numerical and experimental models for the vertical notch.

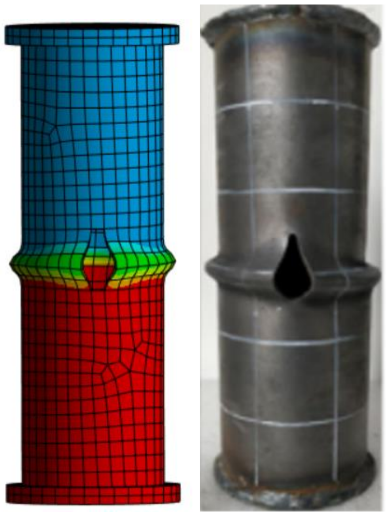

Fig. 4. Failure mode of the vertical notch.

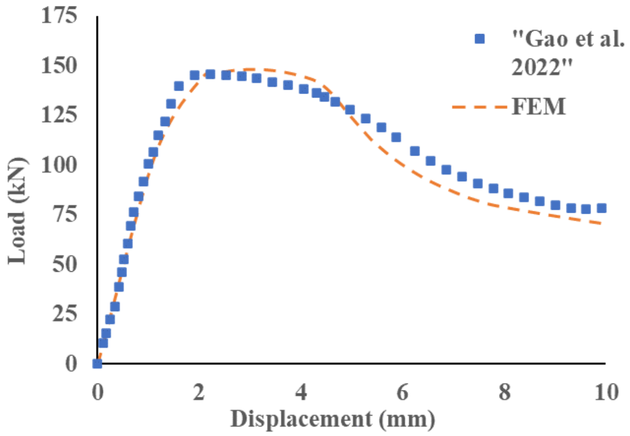

Fig. 5. Oblique notch.

The load-displacement curve for the oblique notch indicates a difference of only 1.05% from the maximum load obtained in the experimental results.

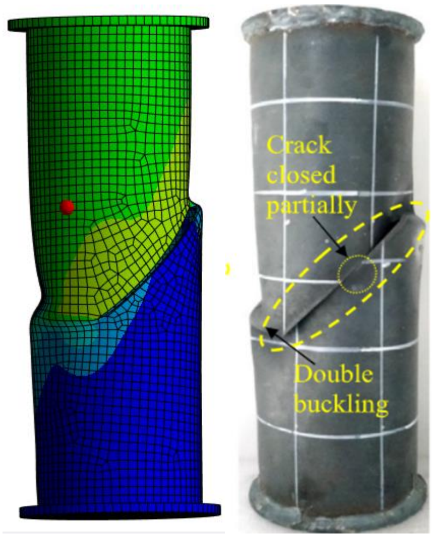

Fig. 6. Failure mode of the oblique notch.

TABLE III. COMPARISON OF FE MODEL WITH EXPERIMENT

Specimen	Peak load (Shan Gao et al.,2022) (kN)	Peak load (FEA) (kN)	Variation (%)
K-CDR	173	171	1.15
K-CDO	145.02	143.5	1.05

III. PARAMETRIC STUDY

The validated finite element model is utilized to conduct several parametric studies, including eccentric loading, varying notch angles, and exploring different strengthening techniques aimed at restoring or enhancing the strength of the structure. The primary objective of this parametric study was to investigate the impact of new types of corrosion or notches on the behavior of the column and to understand how such damage affects its structural integrity. The study focuses on identifying and analyzing the main parameters that have a significant impact on structural behavior.

A. Notch angle

ANSYS 2022 R2 was used to create various models to investigate the impact of notch angles, which were measured from the horizontal axis. The study focused on angles up to 80 degrees, and specific standards were followed. To analyze the effect of different notch angles, models with angles ranging from 20 degrees to 80 degrees were considered. The diameter and height of the specimens were kept constant at 90 mm and 270 mm respectively. The details of the test specimens are given in Table IV. After conducting a thorough numerical investigation of these models, the change in strength or ultimate load of the models was observed. The study revealed that an increase in the notch angle resulted in a corresponding increase in the peak load. The peak load exhibited greater variation initially, but this variation decreased as the notch angle increased. While the variation was not drastic, there was a noticeable change in the ultimate load at every angle. Specifically, the ultimate load increased by almost 10% from 20 degrees to 40 degrees and then increased by 10% for every 10 degrees thereafter. Overall, there was a 42% increase in the load-carrying capacity of the specimen from 20 degrees to 80 degrees. The graph plotted between the ultimate load and displacement is shown in Fig. 7.

TABLE IV. MODEL DIMENSIONS

Dimension	Angle (Degrees)
270 x 90 x 4	20
270 x 90 x 4	40
270 x 90 x 4	50
270 x 90 x 4	60
270 x 90 x 4	70
270 x 90 x 4	80

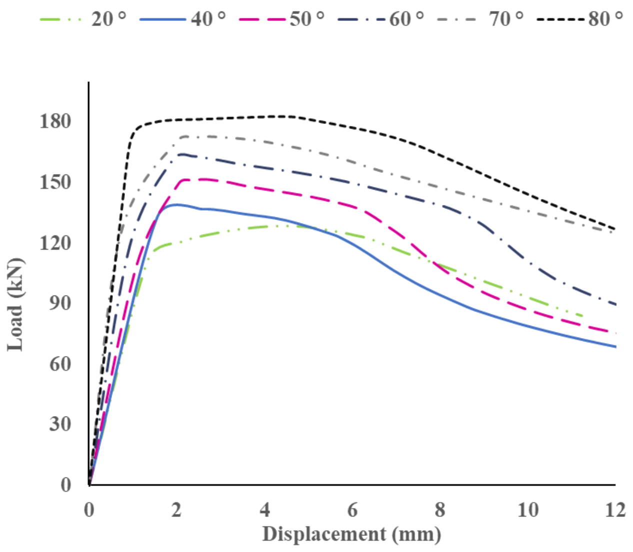

Fig. 7. Load vs Displacement.

B. *Effect of eccentric loading*

All previous study was concentrated only on the axial loading condition of corroded columns. But in real cases, the loading can't be always concentric. So, to get practically relevant results, there is a need to consider the loading condition as an eccentric case. This study investigated the behavior of the notched columns under eccentric loading conditions that include eccentricity in the X and eccentricity in the Z axis that is uniaxial eccentricity and biaxial eccentricity as load eccentricity on both X ad Z axes. A total of twelve models were used for testing, with four each for the uniaxial and biaxial specimens. The dimensional properties of these models are listed in Table V.

TABLE V. MODEL DIMENSIONS

Dimension	Eccentricity (mm)
270 x 90 x 4	5
270 x 90 x 4	10
270 x 90 x 4	20
270 x 90 x 4	30

The objective of the study was to observe the behaviour of corroded columns under eccentric loading circumstances. The study selected eccentricities ranging from 5 mm to 30 mm. Fig. 8 depicts the load-displacement curve for the uniaxial eccentricity in the Z direction. Here, Table V represents the eccentricities in both X and Z directions. As the eccentricity increases, the peak load decreases. At first, for small eccentricity, there is some variation in the load capacity when compared to the concentric case. However, this variation increases as the eccentricity increases.

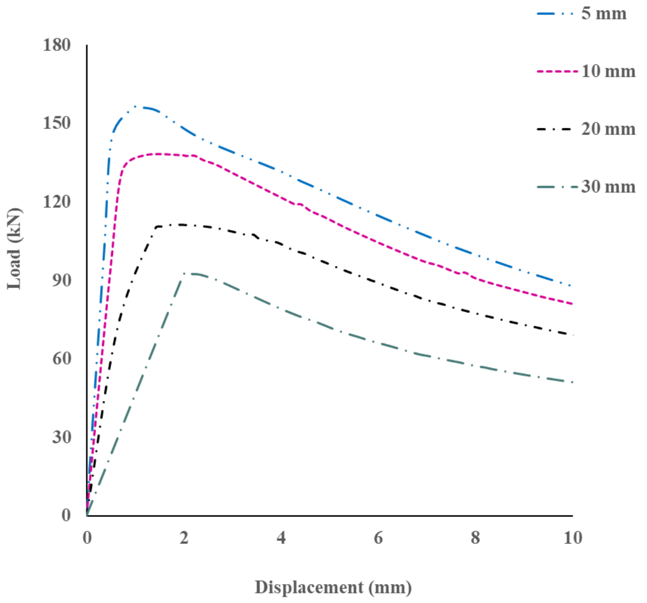

Fig. 8. Load vs Displacement.

Likewise, in the case of eccentricity in the X direction, the peak load decreases as the eccentricity increases. Fig. 9 demonstrates the behavior of the specimen. For small eccentricities, the variation is more pronounced compared to the concentric case.

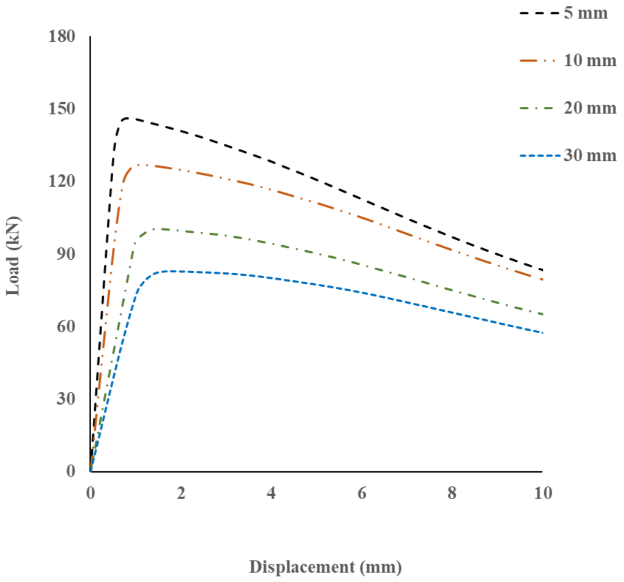

Fig. 9. Load vs Displacement.

In both uniaxial cases, the peak load decreases as the eccentricity increases. The rate of decrease is more significant in the X-direction case because the notch was in that direction. Hence, eccentricity in the X direction has a more considerable impact on the column than eccentricity in the Z direction. The peak load was decreased by 75% for the eccentricity in the X axis from 5 mm to 30 mm, while it is almost 68% for the eccentricity in the Z axis in the same range.

In the biaxial eccentricity case, the load was eccentric about both the X and Z axes. The same specimen that was used for uniaxial eccentricity was also used here, and its dimensions and details are shown in Table V. The load-displacement curve for this case is depicted in Fig. 10.

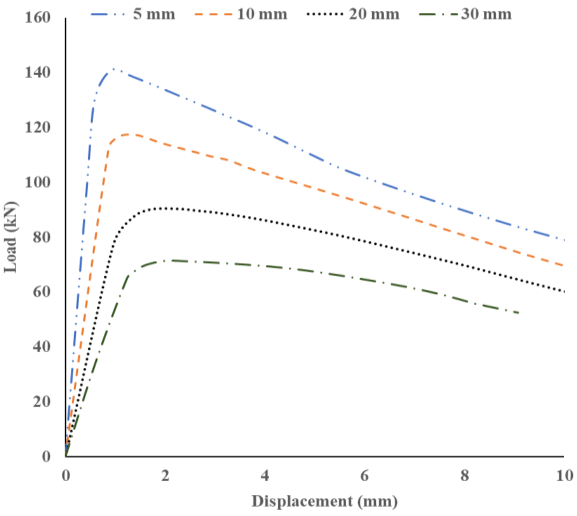

Fig. 10. Load vs Displacement.

Like the previous cases, in the biaxial eccentricity case, the peak load decreases as the eccentricity increases. However, the reduction in the peak load is more significant than in both the uniaxial condition and the concentric case. Here, a 95% reduction in peak load is observed when the eccentricity is increased from 5 mm to 30 mm. This reduction is substantial, indicating that biaxial eccentricity has a significant impact on the load-carrying capacity of the corroded steel column.

C. Strength improvement using FRP

The strength of corroded columns is a major concern because there are limited techniques available to improve their strength once they have corroded. One of the main methods used to improve the strength of corroded columns is to wrap them with FRP sheets. In this study, the use of FRP sheets was considered, with the most common type being Carbon Fiber Reinforced Polymer (CFRP) sheets. The CFRP sheets were arranged in different ways, such as full wrapping and partial wrapping, to reduce the amount of material required and minimize costs. In this study, sheets with a thickness of 0.5 mm were used. The detailed specifications and properties of the FRP sheets are listed in Table VI.

TABLE VI. MATERIAL PROPERTIES OF CFRP

Property	Value
Poisson’s ratio	0.3
Modulus of elasticity	220 GPa
Modulus of rigidity	5 GPa
Tensile strength	3000 MPa

1) Arrangments of FRP

The study initially concentrated on the arrangement of the FRP wrapping on the column. Both full and partial wrapping techniques were used, and the arrangements are depicted in Fig. 11. Three locations on the column were chosen for the FRP arrangements and a single layer of 0.5 mm CFRP was used for the wrapping, and the same dimensions and model were used for wrapping also. The load-displacement curve for the model was shown in Fig. 12.

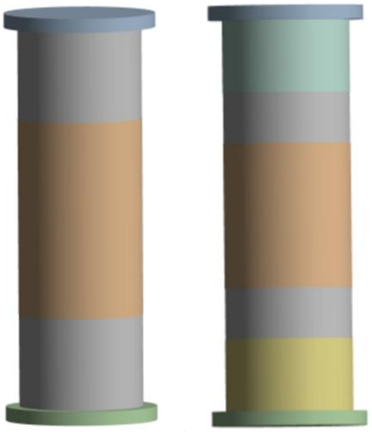

Fig. 11. Partial wrapping arrangement.

The full wrapping arrangement exhibits a significant difference in peak load when compared to the other arrangements. The partial wrappings, on the other hand, demonstrate similar strengths and behaviour. It should be noted that a single layer of partial wrapping is insufficient as a strengthening method since it provides only a marginal increase in load-carrying capacity compared to the original column without corrosion. Full wrapping provides more strength to the column as it covers the entire surface area, which results in a larger load-carrying capacity. On the other hand, partial wrapping covers only a portion of the column and hence provides less additional strength compared to full wrapping. However, partial wrapping can still be useful in some situations where full wrapping is not feasible or cost-effective, but additional layers may be required to achieve the desired strength.

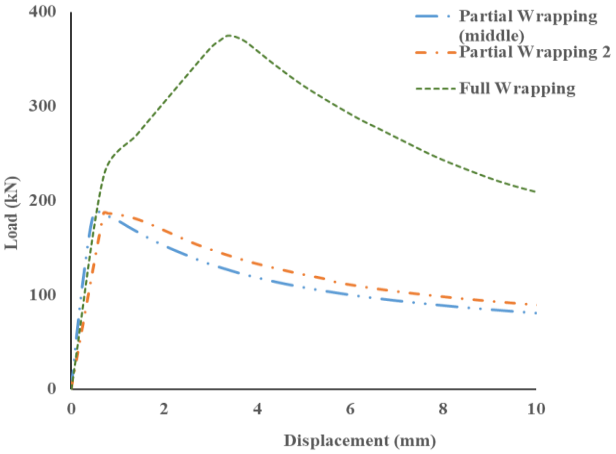

Fig. 12. Load vs Displacement.

In summary, partial wrapping can offer additional strength, but not a significant amount, and it may be beneficial to add more layers. Therefore, for the purpose of strengthening, full wrapping arrangements provide more strength to the specimen and result in a higher load-carrying capacity.

2) FRP layers

Following the completion of the arrangements, the study is now concentrating on the number of layers of the FRP wrapping. Therefore, for the full wrapping arrangement, additional layers are being added, including a single 0.5 mm layer, followed by one layer, two layers, and four layers, among others. For the study, only three different layers will be added. The load-displacement curve for this model is displayed in Fig. 13.

Increasing the number of layers of FRP wrapping increases the load-carrying capacity of the column. It is evident that increasing the number of layers also results in a gradual increase in the stiffness of the column. The addition of one layer of CFRP increased the load capacity by approximately double compared to the single unwrapped non-corroded column. The addition of two layers increased the capacity by 47% and 82% increased from two to four layers. Thus, adding more layers of FRP wrapping results in a significant increase in the strength and stiffness of the corroded column. However, it should be noted that adding more layers also increases the cost of the strengthening method.

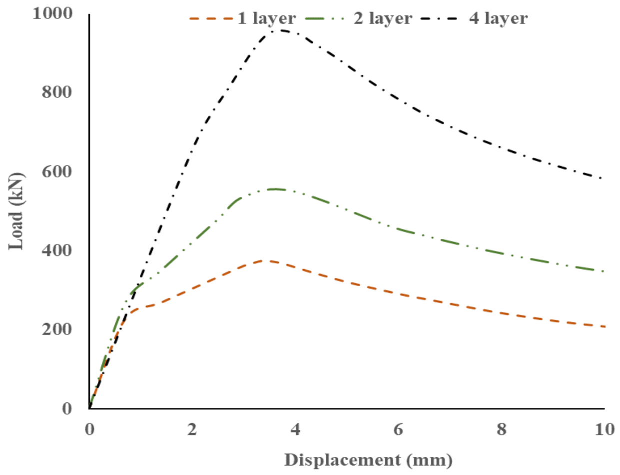

Fig. 13. Load vs Displacement.

IV. CONCLUSIONS

In this thesis, the behaviour of corroded steel columns was investigated through finite element modeling. Various parameters, such as notch angle, and eccentric loading conditions were studied to understand their effect on the load-carrying capacity of the columns. The notch angle played a crucial role in varying the strength of the columns. Additionally, eccentric loading in both X and Z directions resulted in a significant reduction in peak load, with a greater impact observed for the X direction.

The study also investigated the use of FRP wrapping as a method of strengthening corroded columns. Full wrapping arrangements were found to be the most effective, with additional layers resulting in increased load-carrying capacity. Overall, the findings of this study have significant implications for the design and maintenance of corroded steel columns. The results highlight the importance of regular inspections and maintenance to identify and address corrosion in its early stages. Additionally, the study provides valuable insights into the use of FRP wrapping as a potential strengthening method for corroded columns. In conclusion, this study contributes to the existing knowledge on the behaviour of corroded steel columns and provides important information that can be used to improve the safety and reliability of steel structures.

- The ultimate load increased by almost 10% from 20 degrees to 40 degrees and then increased by 10% for every 10 degrees thereafter. Overall, there was a 42% increase in the load-carrying capacity of the specimen from 20 degrees to 80 degrees.
- The peak load was decreased by 75% for the eccentricity in the X axis from 5 mm to 30 mm, while it is almost 68% for the eccentricity in the Z axis in the same range.
- For the biaxial eccentricity, a 95% reduction in peak load is observed when the eccentricity is increased from 5 mm to 30 mm. This reduction is substantial, indicating that biaxial eccentricity has a significant impact on the load-carrying capacity of the corroded steel column.
- Partial wrapping can offer additional strength, but not a significant amount, and it may be beneficial to add more layers. Therefore, for the purpose of strengthening, full wrapping arrangements provide more strength to the specimen and result in a higher load-carrying capacity.
- The addition of two layers of FRP increased the capacity by 47% and 82% increased from two to four layers. Thus, adding more layers of FRP wrapping results in a significant increase in the strength and stiffness of the corroded column.

REFERENCES

[1] Shan Gao, Yulin Wang, Youchun Xu, and Jun Iyama, "Axial behavior of circular steel tube with localized penetrating corrosion simulated by an artificial notch," Thin-Walled Structures, vol. 172, 2022.

[2] Wang, Kaixin, et al., "Finite element simulation of load bearing capacity of circular CFST long columns with localized corrosion under eccentric load," Structures, vol. 43, 2022.

[3] İpek, Süleyman, Ayşegül Erdoğan, and Esra Mete Güneyisi, "Compressive behavior of concrete-filled double skin steel tubular short columns with the elliptical hollow section," Journal of Building Engineering, vol. 38, 2021.

[4] Albero, Vicente, et al., "Behaviour of slender concrete-filled dual steel tubular columns subjected to eccentric loads," Journal of Constructional Steel Research, vol. 176, 2021.

[5] Wang, Renhua, Haichao Guo, and R. Ajit Shenoi, "Experimental and numerical study of localized pitting effect on compressive behavior of tubular members," Marine Structures, vol. 72, 2020.

[6] Guo, Lanhui, Haijia Huang, Chen Jia, and Kirill Romanov, "Axial behavior of square CFST with local corrosion simulated by artificial notch." Journal of Constructional Steel Research, vol. 174, 2020.

[7] Al-Mekhlafi, Galal M., Mohammed A. Al-Osta, and Alfarabi M. Sharif, "Experimental and numerical investigations of stainless-steel tubular columns strengthened by CFRP composites," Thin-Walled Structures, vol. 157, 107080, 2020.

[8] Lin, Weiwei, Nozomu Taniguchi, and Teruhiko Yoda, "A preventive strengthening method for steel columns: Experimental study and numerical analyses," Journal of Constructional Steel Research, vol. 138, pp. 357-368, 2017.