© INNOVATIVE RESEARCH THOUGHTS
Refereed | Peer Reviewed | Indexed
ISSN : 2454 – 308X | Volume : 09 , Issue : 01 | January - March 2023

PERFORMANCE ANALYSIS OF I CROSS SECTION STEEL BEAM WITH A LAYER OF CFRP COATING

Prabhat Kumar[1], **Rachana Bajaj**[2]
[1]*Research Scholar, Department of Civil Engineering, Rabindranath Tagore University, Bhopal*
[2]*Assistant Professor, Department of Civil Engineering, Rabindranath Tagore University, Bhopal*

ABSTRACT

The need to reinforce structural components is universal in the modern era. Therefore, Fiber Reinforced Polymer (FRP) reinforcement seems to be a useful option for such retrofitting. While there are a number of case studies available for using FRP to reinforce concrete buildings, its application to steel presents certain challenges. Researchers have found a promising new use for the Carbon Fiber Reinforced Polymer (CFRP) in the fortification of steel structures, in particular steel beams. With advantages including high tension strength, low weight, and high strength to weight ratio, CFRP laminates are being used more often in recent years for the rehabilitation of steel I-beams. Because of its malleability and ability to take on a variety of forms, it can be easily retrofitted to a variety of constructions. A steel beam with I cross section has been considered for analysis with a dimensions of 1000 mm x 149 mm x 74 mm and a flange thickness of 6.3mm with 5.2mm thick web. The corroded steel beam has been partially coated with a layer of CFRP coating of 0.43mm thickness. 3 more different cases with a full CFRP coating of 0.43mm, 0.75 mm and 1mm thickness has been considered. It has been concluded that a 1mm full CFRP coating is the best option for reducing the risk of failure of the corroded steel beams.

Keywords: Carbon Fiber Reinforced Polymer (CFRP), steel beams, I cross section, high tension strength, low weight, and high strength to weight ratio

INTRODUCTION

When steel is mixed with concrete, it often takes on a passive role and does not corrode. Steel-reinforced concrete, on the other hand, is commonly employed in severe settings where saltwater or deicing salts are present. Steel's passive layer of protection against chlorides in concrete is broken, allowing the metal to corrode and become deformed. Steel corrosion is exacerbated by carbonation of concrete. Corrosion occurs rapidly in these environments, as well as the steel does not stay passive. Corrosion caused by carbonated concrete coating is less rapid than that caused by the chlorides. Sometimes, the steel bar may dissolve due to the absence of oxygen, resulting in a liquid with a low pH.

Corrosion of the uncoated steel is an intricate process. The rusting and pitting that happens to steel over time may be thought of as a multi-step electrochemical process. In the first stage of corrosion, ferrous ions dissolve at the surface's anodic regions. The anode gives out electrons, which travel through the metal to the cathodic sites on the surface, where they react with oxygen and water to generate hydroxyl ions. Corrosion rates and patterns are affected by a number of variables, including the steel's composition/structure, the presence of impurities owing to the increased prevalence of recycled steel, the distribution of internal stress, as well as the presence of non-uniform surroundings. For those working in manufacturing, corrosion is among the top worries. Surfaces made of steel or concrete are susceptible to corrosion when subjected to aggressive chemicals, acids, solvents, etc. Worldwide, corrosion-related metal loss amounts to over US$ 5,000 per year. The next sections describe the various forms of steel corrosion and the corresponding structural repercussions.

Steel has been utilised in construction ever since the Industrial Revolution, attesting to its reliability and efficacy. It's durable, long-lasting, sustainable, and affordable. Of course, steel corrodes when exposed to the air just like any other metal. It is crucial to think about corrosion prevention measures while building with exposed steel. A variety of corrosion prevention methods are available, including as:

- Duplex Systems

- Hot-Dip Galvanizing
- Sacrificial Anodes
- EPDM – a synthetic polymer derived from oil
- Special Steels
- Zinc Coatings
- Protective Coatings

To prevent the concrete from cracking during freezing and thawing, further precautions must be taken. Permeability is enhanced by water exudation and is decreased by air. Damage to embedded reinforcing bars from corrosion may be hastened by peeling the concrete's surface.

Fibre reinforced polymer (FRP) is finding growing usage in steel construction. Glass Fiber Reinforced Polymer (GFRP), often known as fibreglass rebar, is a fantastic option for eliminating the risk of corrosion in building constructions. This is a substitute for steel in the building trade. GFRP has a wide variety of desirable properties, including resistance to corrosion, low weight, a long service life, and strength greater than that of steel.

To repair concrete, other FRPs are also being utilised. Carbon fibre reinforced plastic (CFRP) is a composite material made of carbon carbon fibres and a polymer matrix. The carbon fibres contribute to the material's stiffness, strength, and load bearing ability. The primary characteristics of a CFRP composite are determined by the resin material, the proportion of carbon fibre, the curing conditions, and the carbon fibre orientation (transverse or longitudinal). Therefore, several CFRPs exist, each with its own set of characteristics.

LITERATURE REVIEW

[1] One of the most common composite elements nowadays is the "concrete-encased steel beam" (CESB). The purpose of this study is to compare the results of strengthening CESB with or without the presence of apertures. Under static loading with a four-point loading system, eleven completely supported CESB beams with as well as without web opening were examined. Examining the impact of a web opening in the shear zone, and then adding three distinct strengthening materials to either the flexure or shear zone of the beams, were the two primary phases taken into account while analysing the CESB's performance. Materials such as glass fiber-reinforced polymer wraps, carbon fiber-reinforced polymer wraps, as well as steel plates were employed as the externally bonded reinforcement strengthening materials. The mechanism of failure, fracture pattern, load-strain curves at various sites, midspan load-deflection curve, first crack load, serviceability load, ultimate load, energy absorption, as well as ductility ratio were all determined experimentally. Finite-Element Analysis (FEA) simulations are run on a set of eleven test specimens using the ANSYS version 19.0 software. The effects of the web opening were measured, and the results revealed that the ultimate load as well as its corresponding deflection were reduced by around 58.28% & 80.17%, respectively, throughout the course of the tests. Also, the shear strengthening of CESB with a web opening in the shear zone is more successful than the flexural strengthening with any of the three strengthening materials. Steel plates improve the performance of the tested beams more than carbon fibre wraps or glass fibre wraps. Results from FE & experiments are shown to be very consistent with one another thanks to the FEA.

[2] Marine assets, like ships, offshore wind farms, and subsea oil & gas platforms, rely heavily on maintenance to ensure their continued operational safety and reliability. Multiple material degradation processes (including corrosion, fatigue cracking, & pitting) as well as environmental pressures that vary with geography and climate significantly impact the service life of maritime assets. One of the most important elements impacting the deterioration of marine assets is the composition of saltwater components (such as temperature content, salinity, dissolved oxygen, etc.). The operational availability as well as dependability of maritime assets may be significantly impacted by better maintenance management systems. Over the last several decades, many studies have been done to foresee how maritime constructions may degrade in a variety of contexts. Integral to the creation of a trustworthy, risk-free, as well as cost-effective maintenance plan is the use of structural deterioration data, especially on maritime corrosion. In this work, we survey current practises and emerging trends in the asset maintenance management systems for protecting steel structures from corrosion in harsh maritime environments. Experts in the field of corrosion prediction and maritime steel structure maintenance conduct an in-depth analysis of the current state of the art in both fields. Moreover, several uses of cutting-edge technology like CMMS (computerised maintenance management system), AI,

& BN (Bayesian network) are highlighted. Researchers found that corrosion behaviour of maritime steel structures as well as industrial maintenance techniques differ significantly depending on environmental factors. Variation in the seawater composition/characteristics as well as their intricate interrelationships have been linked to this phenomenon.

[3] The behaviour of steel I-beams that have been reinforced with steel plate as well as steel angle section has been studied, specifically their susceptibility to lateral buckling as well as Lateral Torsional Buckling. The research team collected five samples. Each specimen is 1800mm in length and has an ISMB150 section. Steel plate sections and steel angle sections are positioned in a variety of orientations relative to a steel I-beam to create the various strengthening patterns. In order to create the finite element model, we use ANSYS 19.2. The beam under consideration is a laterally unsupported beam. It was ANSYS 19.2 that was used to do the finite analysis. The analytical findings demonstrated that the lateral buckling as well as lateral torsional buckling of steel beams may be reduced by reinforcing the steel I-beam at its compression flange with steel plate section & steel angle section. When compared to a control beam, Specimen No. 4's lateral deflection is reduced by as much as 50 percent thanks to the steel angle section added to the Compression Flange over its entire length. Costs have gone up because of the Mweight rise in steel beams. When intermediate points are reinforced with steel plates, Specimen No. 2's lateral deflection drops to 42.85% and the cost is reduced. Ultimately, one can say that the addition of a steel plate to the compression flange of a steel beam is a novel method for lowering lateral deflection.

[4] The widespread usage of Polyurethane (PU) coated steel samples in the chemical industries has led to the development of a rusting issue that has to be addressed and prevented. Composite materials are being considered as potential solutions to this problem. Because acids are not affected by the chemicals used in industry, this presents a dilemma for the use of these composites. Nevertheless, the production of composites is difficult and expensive. The composite glass-fiber plates, sized and trimmed to perfection. Then, they were adhesively bonded at the Web Flange Joint (WFJ) to simplify and cheapen production. The outcomes of using Huntsman Araldite as an adhesive at WFJ have been found to be superior. Finite element analysis (FEA) using the ANSYS software verifies this. The WFJ region has a much higher "Hundsman Araldite failure strength". Further, cleats of 4 mm and 12 mm are employed to expand the WFJ area and boost the composite I-load Beam's bearing capability. After being submerged in an acidic bath solution for a certain amount of time, the glass fibre shows no discernible response, as proven by the studies. Consequently, it has significantly increased its resistance to acidic assault and has not rusted. Composite Beam performed better than expected in the acidic environment, as shown by a strong connection between the experimental and analytical data. As an alternative to steel I-beams, composite I-beams are preferred in acidic conditions due to their superior resistance to corrosion and extended lifespan.

[5] The purpose of this research is to determine whether "carbon fiber-reinforced polymer" (CFRP) laminates can be successfully used to reinforce the compression flange of a structural I-beam, thereby preventing local failure of compression flange and allowing the beam to withstand loads up to its ultimate capacity. For this, we use the usage of light weight beam (LB) 100, with a density of 5.1 kg/m, and LB 115, with a density of 8.1 kg/m. In order to prevent debonding during testing, the compression flange of a beam is carefully treated to provide a rust-free surface. Adhesive-bonded sheets of carbon fibre reinforced plastic (CFRP) are used to reinforce the beam's flange. The CFRP beam is cured in air for 48 hours before being put through its paces. The experiments are carried out on a 100 T loading frame. Compared to the control beam (non-strengthened), the strengthened beam's load bearing capacity rose by 25-30 percent, and local failure of the compression flange owing to the applied load was completely avoided. In addition to having a greater yield point, the stronger beam exhibits better elastic behaviour than the non-strengthened beam.

[6] Bonded carbon fibre reinforced plastic (CFRP) plates have recently been utilised as an alternative to welding or bolting plates onto steel bridges for reinforcement or repair. The primary purpose of this research is to evaluate the flexural behaviour of the steel beams reinforced with CFRP plates and compare the results to those of unreinforced steel beams. Passive adhesive-bonded plates as well as active adhesive-bonded plates were compared in the study. In all of these instances, the ductility as well as the yield/ultimate carrying capacity of the steel beams and the efficacy of strengthening have been verified. Depending on strengthening system (passive or active) as well as various system characteristics like the CFRP modulus of elasticity, the end plate anchoring, as well as plate prestressing level, the failure modes of the reinforced beams included either plate debonding or plate rupture. They have also spoken about how these variables affect how efficient the strengthening is.

[7] Plating steel is susceptible to the pitting corrosion when used in high-stress corrosion situations. This study presents the results of numerical research into the effects of random pitting damage on the structural behaviour as well as the ultimate strength of the plated steel structures. Due to the unpredictable nature of the pitting corrosion, stochastic simulations have been utilised to represent its variable pitting form, depth, as well as distribution. To investigate the processes of structural failure owing to random pitting damage, a number of nonlinear calculations have been run on both un-stiffened plates as well as stiffened panels. From the numerical data, empirical equations were constructed using regression analysis to forecast the decreases in the ultimate strength of both unstiffened plates as well as stiffened panels. Corrosion from random pitting causes a change in ultimate strength and may cause a failure mode changeover. In the failure of pitted structures subjected to the uniaxial compression, plasticity begins towards the unloaded edge of structure and spreads to connect the pits that have experienced the most stress. Pitted region with intensely stress-concentrated pits undergoes a locally amplified deformation which defines the failure mechanism, resulting to the structural collapse.

[8] Unbonded retrofit systems save time and money since they don't need any surface preparation before bond application. Different variations of the retrofit systems may be designed to facilitate field deployment since the carbon fibre reinforced polymer (CFRP) plate in the un-bonded (tendon) systems is not attached to a metallic substrate. Four distinct types of prestressed un-bonded retrofit (PUR) systems are discussed in this paper: triangular PUR (TriPUR), trapezoidal PUR (TPUR), flat PUR (FPUR), as well as contact PUR (CPUR). To foretell how metal beams would react after being outfitted with PUR systems, we offer analytical methods based on flexibility approach. To represent the functioning of the modified beams, a finite element (FE) model is developed. The analytical answers are tested against the FE model's findings. Experimental findings on PUR-reinforced steel and aluminium beams have been compared with those from analytical and computational models. Several parametric tests are conducted to learn how factors like PUR system type and CFRP pre-stress level affect the performance of the upgraded beams. The findings reveal that, for a given degree of CFRP pre-stress, the stress reduction in steel beam bottom flanges is almost the same for all four PUR systems. As a result, any one of the 4 pre-stressing methods may be used, as long as it meets the needs of the building.

MATERIALS AND METHOD

1. Design and Material

A steel beam with I cross section has been considered for analysis with a dimensions of 1000 mm x 149 mm x 74 mm and a flange thickness of 6.3mm with 5.2mm thick web. The corroded steel beam has been partially coated with a layer of CFRP coating of 0.43mm thickness. 3 more different cases with a full CFRP coating of 0.43mm, 0.75 mm and 1mm thickness has been considered.

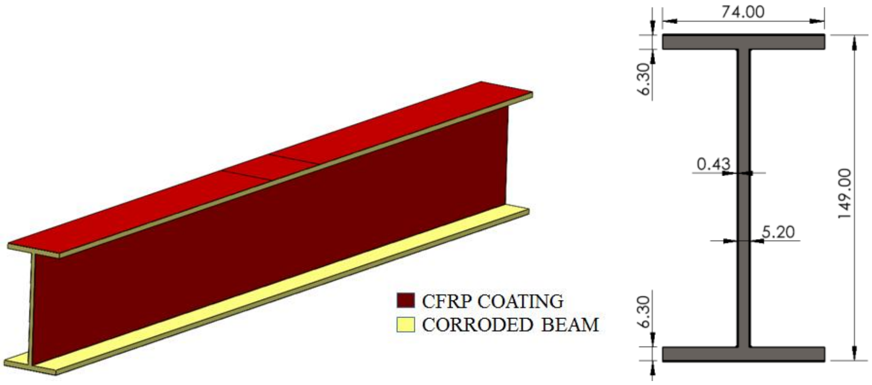


Figure 1 Design of the Steel Beam

Table 1 Properties of CFRP

CFRP material properties	
Density (Kg/m3)	1800
Young's modulus (MPa)	240000
Poisson's Ratio	0.3

2. Methodology

A corroded steel beam with I cross-section with a coating of Carbon Fibre Reinforced Polymer (CFRP) has been designed with help of SOLIDWORKS. Further converting file into .stp format. Importing the file in ANSYS design modular for performing the simulation in ANSYS. Meshing is performed on the imported design. For the structural analysis fluid inlet and outlet is given at name selection. Material properties are applied to the steel beam and the CFRP coating. Boundary conditions are applied on steel structure. Structural results are evaluated with the help of ANSYS workbench in which the modal used for this study is fluid fluent.

3. Mesh Generation

Meshing is a method for precisely describing the physical shape of an object by breaking down the continuous geometric space into a thousands or more discrete forms. The more dense the mesh, the more accurate the 3D CAD model will be and the more accurate the simulations will be. Mesh is a term used to describe the process of dividing a complex shape into distinct parts. Two or three-dimensional meshes may be generated via mesh generation. Since meshing often consumes a significant portion of the time it takes to get simulation results, more efficient and more accurate ways of meshing may be available. Below is the meshing of the corroded steel beam with the CFRP coating comprising of 363676 nodes and 54769 elements.

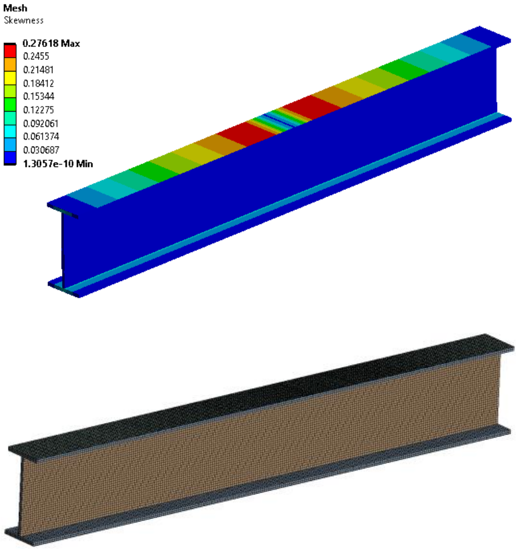
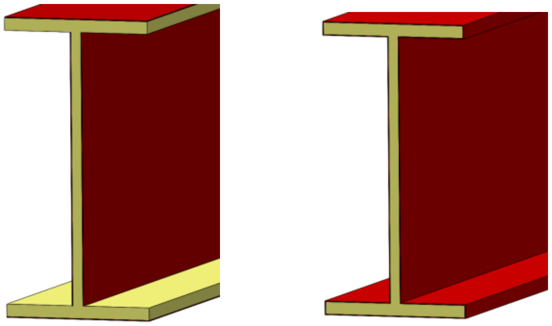


Figure 2 Meshing of the Steel Structure

4. Modification In Design

The Figure 3 below shows the modification that has been carried out in the new design. The previous design was partially coated while the new design has been now fully coated with CFRP laminate.



(a) (b)

Figure 3 (a) Previous design - Partial coated (b) New design – Fully coated

Table 2 Number Of Cases

CASES	TYPE
CASE-1	Partially coated with 0.43 mm CFRP thickness
CASE-2	Fully coated with 0.43 mm CFRP thickness
CASE-3	Fully coated with 0.75 mm CFRP thickness
CASE-4	Fully coated with 1 mm CFRP thickness

5. Boundary Conditions

- Steel is selected as Corroded I-beam material
- CFRP material is selected as coating material
- 200KN of force is implemented at center of beam.
- Roller support is provided at one end of I-Beam
- Fixed Support is Provided at other end of the I-beam

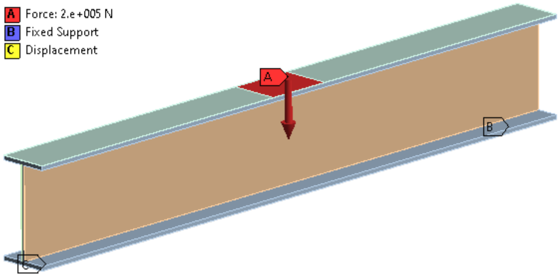
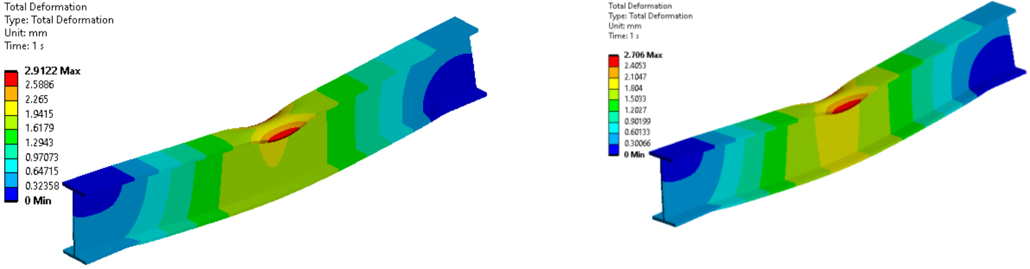


Figure 4 Boundary Conditions Applied

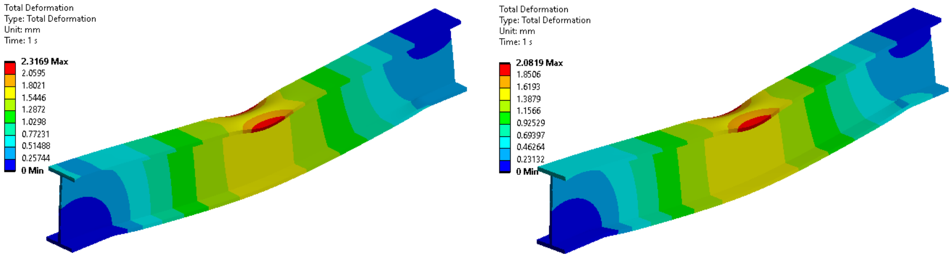
RESULTS AND DISCUSSIONS

1. Variation In Total Deformation

The total deflection for all the 4 cases have been shown in the figure 5 below:



(a) CASE-1 (b) CASE-2



(c) CASE-3 (d) CASE-4

Figure 5 Total Deflection for (a) Case 1: Partially coated with 0.43 mm CFRP thickness (b) Case 2: Fully coated with 0.43 mm CFRP thickness (c) Case 3: Fully coated with 0.75 mm CFRP thickness (d) Case 4: Fully coated with 1 mm CFRP thickness

Table 3 Total deformation in all the cases

Total Deformation (mm)	
Case-1	2.9122
Case-2	2.706
Case-3	2.3169
Case-4	2.0819

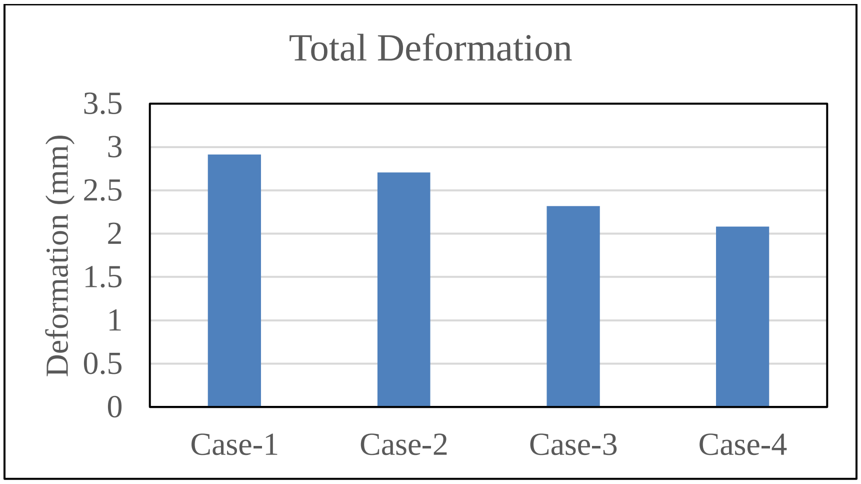
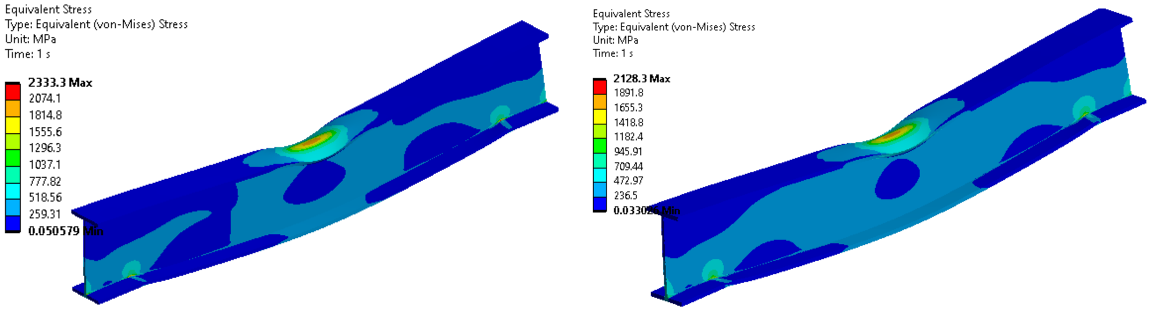


Figure 6 Comparison of deformations in all the 4 cases

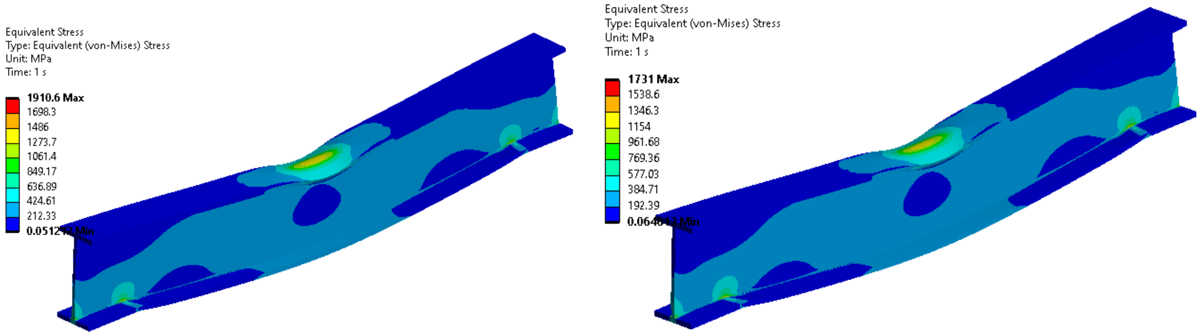
As can be observed in the figure 6, the deformation is minimum in case 4 with full 1mm thick CFRP coating, i.e. 2.0819mm, while the maximum deformation is the case 1 with partial coating 0.43 mm CFRP. It can be inferred that increasing the thickness of the CFRP coating reduces the risk of failure due to deformation of the steel beam.

2. Variation In Equivalent Stress

The variation in Equivalent Stresses for all the 4 cases has been seen in the figure 4-4 below:



(a) CASE-1 (b) CASE-2



(c) CASE-3 (d) CASE-4

Figure 7 Total Equivalent Stress for (a) Case 1: Partially coated with 0.43 mm CFRP thickness (b) Case 2: Fully coated with 0.43 mm CFRP thickness (c) Case 3: Fully coated with 0.75 mm CFRP thickness (d) Case 4: Fully coated with 1 mm CFRP thickness

Table 4 Total Equivalent Stress in all the cases

Equivalent Stress (MPa)	
Case-1	2333.3
Case-2	2128.2
Case-3	1910.6
Case-4	1731

As can be observed in the figure 7, the equivalent stress is minimum in case 4 with full 1mm thick CFRP coating, i.e. 1730 MPa, while the maximum equivalent stress is the case 1 with partial coating 0.43 mm CFRP, ie. 2333.3 MPa. It can be inferred that increasing the thickness of the CFRP coating reduces the risk of failure due to equivalent stress of the steel beam.

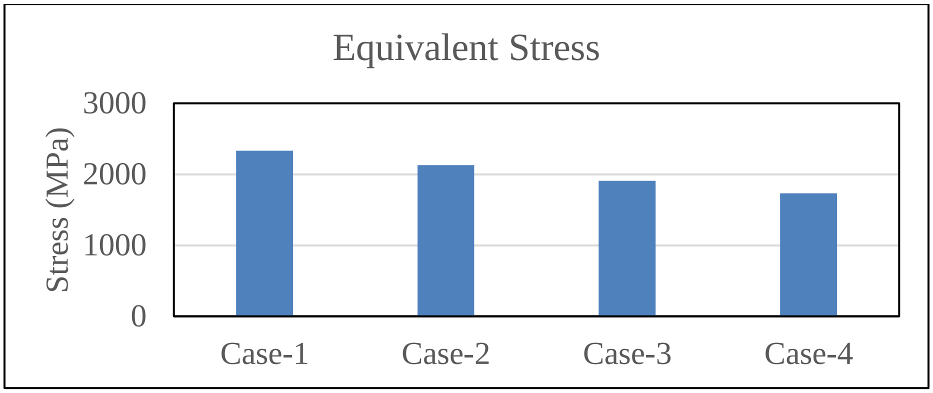
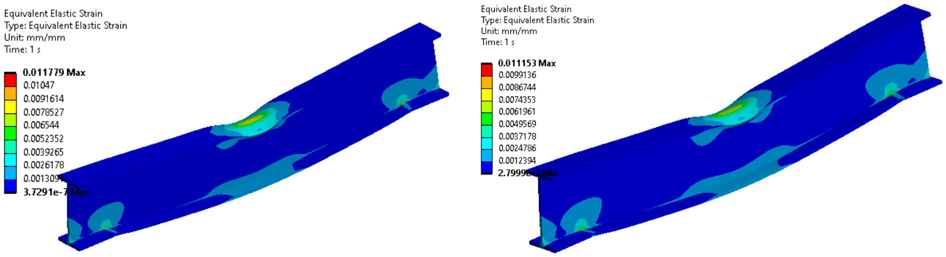


Figure 8 Comparison of Equivalent Stress in all the 4 cases

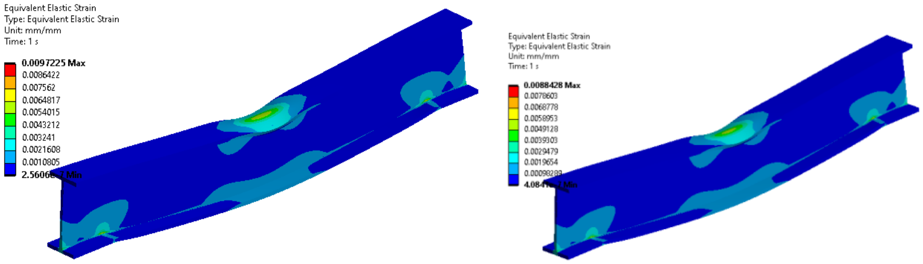
3. Variation In Equivalent Elastic Strain

The variation in Equivalent Elastic Stress for all the 4 cases has been seen in the figure 4-6 below:



(a) CASE-1

(b) CASE-2



(c) CASE-3

(d) CASE-4

Figure 9 Total Equivalent Elastic Stress for (a) Case 1: Partially coated with 0.43 mm CFRP thickness (b) Case 2: Fully coated with 0.43 mm CFRP thickness (c) Case 3: Fully coated with 0.75 mm CFRP thickness (d) Case 4: Fully coated with 1 mm CFRP thickness

Table 5 Total Equivalent Elastic Stress in all the cases

Equivalent Elastic Strain (mm/mm)	
Case-1	0.011779
Case-2	0.011153
Case-3	0.009723
Case-4	0.008843

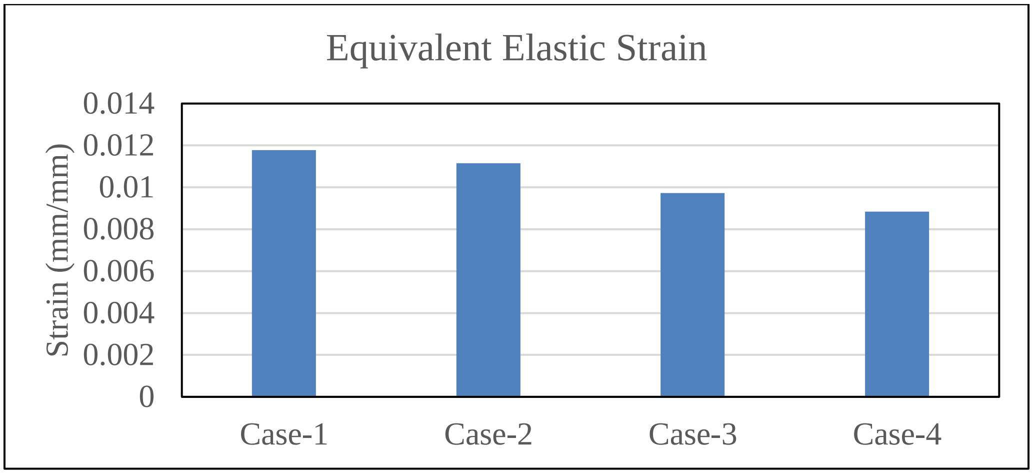
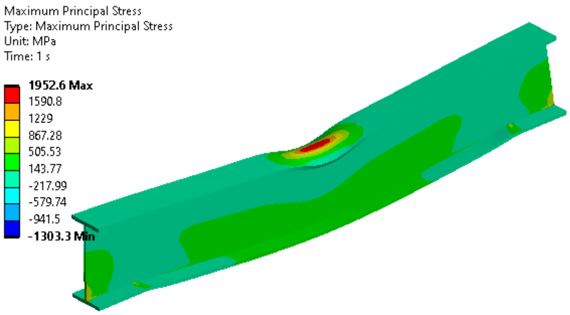


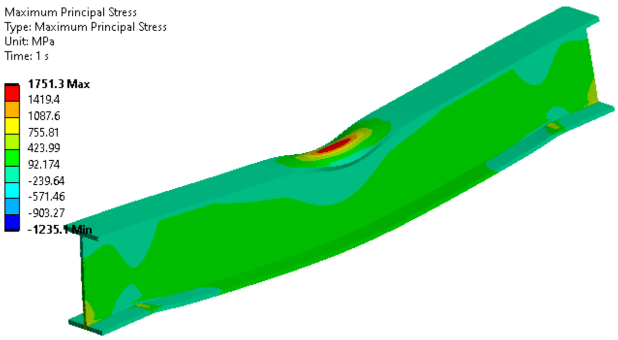
Figure 10 Comparison of Equivalent Elastic Stress in all the 4 cases

As can be observed in the figure 10, the equivalent elastic stress is minimum in case 4 with full 1mm thick CFRP coating, i.e. 0.008843, while the maximum equivalent elastic stress is the case 1 with partial coating 0.43 mm CFRP, ie. 0.011779. It can be inferred that increasing the thickness of the CFRP coating reduces the risk of failure due to equivalent elastic stress of the steel beam.

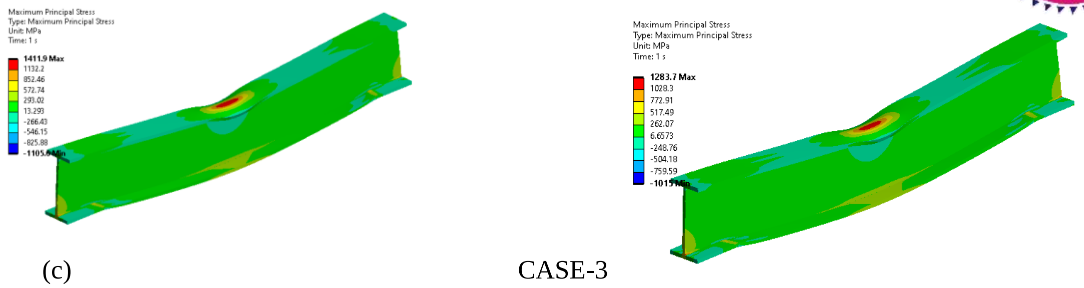
4. Variation In Maximum Principal Stress



(a) CASE-1



(b) CASE-2



(c) CASE-3 (d) CASE-4

Figure 11 Total Maximum Principal Stress for (a) Case 1: Partially coated with 0.43 mm CFRP thickness (b) Case 2: Fully coated with 0.43 mm CFRP thickness (c) Case 3: Fully coated with 0.75 mm CFRP thickness (d) Case 4: Fully coated with 1 mm CFRP thickness

Table 6 Maximum Principal Stress in all the cases

Maximum Principal Stress (MPa)	
Case-1	1952.6
Case-2	1751.3
Case-3	1411.9
Case-4	1283.7

As can be observed in the figure 12, the Maximum Principal Stress is minimum in case 4 with full 1mm thick CFRP coating, i.e. 1283.7 MPa, while the Maximum Principal Stress is the case 1 with partial coating 0.43 mm CFRP, ie. 1952.6 MPa. It can be inferred that increasing the thickness of the CFRP coating reduces the risk of failure due to Maximum Principal Stress of the steel beam.

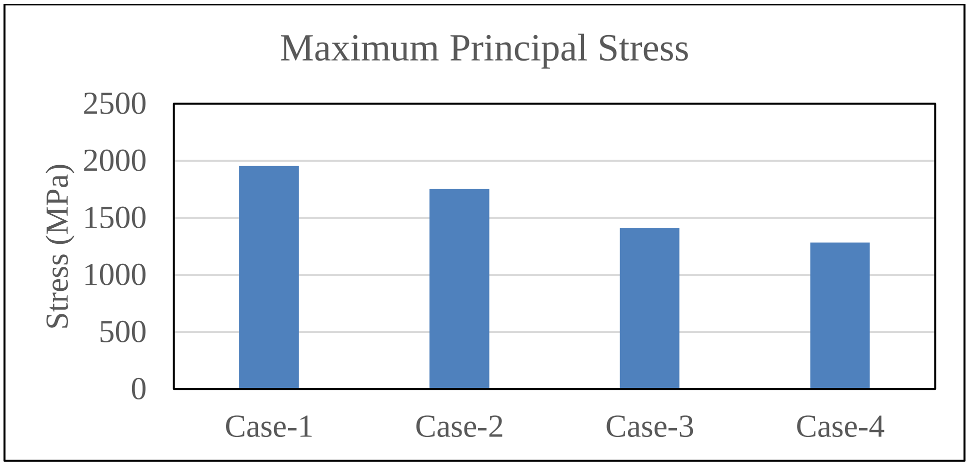


Figure 12 Comparison of Maximum Principal Stress in all the 4 cases

a. Variation In Weight

Table 7 Weight in all the cases

Weight (Kg)	
Case-1	13.2129
Case-2	13.34004
Case-3	13.67891
Case-4	13.9447

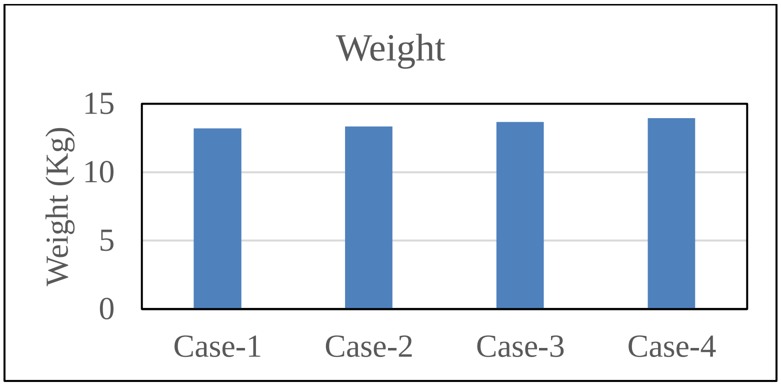


Figure 13 Comparison of Weight in all the 4 cases

Comparing all the cases, its obvious that case 4 with full 1mm CFRP coating has the maximum weight of 13.9447 Kg due greater thickness of the coating, while case 1 with 0.43 mm partial coating has a minimum weight of 13.2129 Kg. It can be observed that there isn't much difference in the weights in the different cases, so it can be a negligible factor in the final conclusion

CONCLUSION

A steel beam with I cross section has been considered for analysis with a dimensions of 1000 mm x 149 mm x 74 mm and a flange thickness of 6.3mm with 5.2mm thick web. The corroded steel beam has been partially coated with a layer of CFRP coating of 0.43mm thickness. 3 more different cases with a full CFRP coating of 0.43mm, 0.75 mm and 1mm thickness has been considered. The following conclusions have been made:

- The equivalent stress is minimum in case 4 with full 1mm thick CFRP coating, i.e. 1730 MPa, while the maximum equivalent stress is the case 1 with partial coating 0.43 mm CFRP, ie. 2333.3 MPa.
- The deformation is minimum in case 4 with full 1mm thick CFRP coating, i.e. 2.0819mm, while the maximum deformation is the case 1 with partial coating 0.43 mm CFRP.
- The equivalent elastic stress is minimum in case 4 with full 1mm thick CFRP coating, i.e. 0.008843, while the maximum equivalent elastic stress is the case 1 with partial coating 0.43 mm CFRP, ie. 0.011779.
- The Maximum Principal Stress is minimum in case 4 with full 1mm thick CFRP coating, i.e. 1283.7 MPa, while the Maximum Principal Stress is the case 1 with partial coating 0.43 mm CFRP, ie. 1952.6 MPa.
- Comparing all the cases, its obvious that case 4 with full 1mm CFRP coating has the maximum weight of 13.9447 Kg due greater thickness of the coating, while case 1 with 0.43 mm partial coating has a minimum weight of 13.2129 Kg.

Hence, it can be concluded that a 1mm full CFRP coating is the best option for reducing the risk of failure of the corroded steel beams.

REFERENCES

[1] B. El-Taly, M. Hamdy, K. Kandil, and A. Bashandy, "Structural Behavior of Strengthened Concrete-Encased Steel Beams with Web Openings," *Int. J. Civ. Eng.*, vol. 19, no. 3, pp. 245–263, 2021, doi:

10.1007/s40999-020-00552-1.

[2] M. Abbas and M. Shafiee, “An overview of maintenance management strategies for corroded steel structures in extreme marine environments,” *Mar. Struct.*, vol. 71, no. December 2019, p. 102718, 2020, doi: 10.1016/j.marstruc.2020.102718.

[3] S. Gharabude and V. I. Hosur, “Strengthening of Steel Beams against Lateral Buckling and Lateral Torsional Buckling,” no. June, pp. 2522–2528, 2020.

[4] J. K. Shaikh, A. Jain, and F. B. Sayyad, “Improving Axial Load Carrying Capacity of Composite I-Beam Section,” vol. 06, no. 01, pp. 569–584, 2019.

[5] P. R. Jagtap and S. M. Pore, “Effectiveness of CFRP composites on compression flange of structural I-beam,” *J. Eng. Des. Technol.*, vol. 17, no. 4, pp. 782–792, 2019, doi: 10.1108/JEDT-09-2018-0155.

[6] T. W. Siwowski and P. Siwowska, “Experimental study on CFRP-strengthened steel beams,” *Compos. Part B Eng.*, vol. 149, pp. 12–21, 2018, doi: 10.1016/j.compositesb.2018.04.060.

[7] R. Wang, R. Ajit Shenoi, and A. Sobey, “Ultimate strength assessment of plated steel structures with random pitting corrosion damage,” *J. Constr. Steel Res.*, vol. 143, pp. 331–342, 2018, doi: 10.1016/j.jcsr.2018.01.014.

[8] F. Kianmofrad, E. Ghafoori, M. M. Elyasi, M. Motavalli, and M. Rahimian, “Strengthening of metallic beams with different types of pre-stressed un-bonded retrofit systems,” *Compos. Struct.*, vol. 159, pp. 81–95, 2017, doi: 10.1016/j.compstruct.2016.09.020.