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A Finite Element Method Investigation of Mechanical and Thermal Behavior of Composite Coatings on Steel Bar.

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ABSTRACT

Damage to steel structures can be catastrophic in fire incidents due to the 'softening' effect of high temperatures on metals. Various coating materials have been developed to protect steel components from dangerously high fire-related temperatures and increase the overall fire ratings of steel-column high-rise buildings. Intumescent coating is one such spray-painted polymer material that expands at high temperatures and creates a thermal barrier to protect the steel components. In this research, we investigate a new type of intumescent coating material consisting of carbon fiber reinforced polymer composites. As carbon fiber is an excellent thermal conductor, it is expected that the surface heat will be conducted away longitudinally while keeping the inner core of steel material protected. In addition, carbon fiber composites have higher strength-to-weight ratios, meaning these coatings are supposed to increase the component strength and stiffness. The thermomechanical analysis is performed on a Finite Element Analysis (FEA) software. Simulations are carried out for various thicknesses of the composite coating layer. The results show increase in stiffness of the hybrid coated plate with a 8/10 mm thickness of the composite layer. Thermal resistance is also increased with the epoxy composite layer. These results suggest that Carbon/Glass fiber-based epoxy composite coatings have the potential to significantly improve the performance and fire ratings of steel structure.

Keywords**:** Composite materials, Intumescent Coating, Thermal barrier, Carbon/glass fiber, Resin epoxy.

1. Introduction

When two or more elements are united at a macroscopic level and are not soluble in one another, the result is a structural substance known as a composite. The reinforcing phase of one component is referred to as fiber, while the matrix refers to the component in which it is embedded [1]. Since of their exceptional qualities, composites are well-liked because no single constituent element can produce them. Composite coating improves surface characteristics including corrosion resistance and thermal behavior. The main drawbacks of steel buildings are corrosion, wear, and thermal failure [2]. Especially thermal failure makes the structure vulnerable at high temperatures. At higher temperature both the tensile strength and yield strength of steel decreases. The modulus of elasticity does also deteriorate with the rise of temperature. Generally, around 50% of steel's strength and stiffness are retained at an ambient temperature of 593 °C [3]. Steel retains 20% strength and stiffness at 704 °C. So, fire intumescent coating is widely used for the fire safety of steel structures [4]. The composite coating helps to improve the property, protection from corrosion and environment, and thermal protection. So, the composite coating can be a new alternative in the field of fire protection of steel structures, which can simultaneously enhance the mechanical property. Carbon fiber with modified epoxy resin can be used as a fire retardant. incorporation of magnesium hydroxide filler in epoxy blend improves compressive properties [5]. For further improvement Carbon nanofiber (CNF), MWCNT show 60% better results than carbon fiber composite. These two types not only reduce the fire they also significantly reduce the smoke production after fire hazards [6]. Coating thickness has affected mechanical properties. Another most effective composite coating is glass-fiber-based epoxy composite. Glass fiber reinforced polymer can be used on high-strength concrete bars. It significantly increases the compressive strength with the increase of the thick layer of the composite [7]. This fiber is recently used for fire retardance for its low thermal conductivity. Silica aerogel with glass fiber composite can be used for fire shield of steel. An experimental procedure shows that with the optimum aging of glass fiber composite it shows much better resistance against fire and shows that with the increase of thickness less shrinkage of the coating [8]. Recently glass fiber reinforcement is used in the automobile industry for

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better cyclic loading for lightweight and better thermal insulating from excess heat transfer [9].

Later experiments conducted on glass fiber composite under different temperature of 200℃,400℃,600℃ and SEM shows that it can withstand its property till 600℃ and basalt, and carbon fiber was also tested under those conditions [10]. For the matrix material, different types of substances can be used. Epoxy resin, Polystyrene, and Polyester show better adhesion properties with reinforced fiber. Epoxy resin alone doesn't show very high thermal resistance. But it can be modified for higher thermal resistance using an aliphatic amine agent [11]. Resin modification with carbone shows great potential as fire-resistant matrix material. By increasing the percentage of carbon thermal resistant increases significantly. The thermogravimetric curve shows that around 40% addition of these additives reduces the weight loss under high temperatures [12].

In this paper, we investigated the thermal and mechanical properties of carbon and glass fiber reinforced with modified epoxy resin. The volume fraction of fiber is another important parameter for mechanical properties. Using the Rule of mixture composite UD lamina properties can be estimated. In the case of glass fiber adhesion strength drastically increases with the increase of volume fraction. Glass fiber fire resistance is dependent on the volume fraction of fiber and a simulation shows that the volume fraction (1-1.5%) shows a better thermal resistance as a coating of concrete material for building [13]. Recently, graphene shown considerable promise as a carbon fiber alternator that can maintain its properties at extremely high temperatures.

2. Materials and Methodology

2.1 Materials used:

T- bar Structural Steel Beam, Carbon Fiber, Glass Fiber, Resin epoxy

2.2 Mechanical Modeling:

The simulation made use of T-bars made of structural steel of the S235 type [14]. As reinforcements, glass fiber (S glass fiber [15]) and carbon fiber (290GPa) were selected, with resin epoxy serving as the composite's matrix material. All the components were modeled in SolidWorks, and numerous studies were used to define the material properties. In ANSYS Workbench, ANSYS Material Designer was used to create the composite material, and ANSYS Static Structural Analysis was used to create the appropriate finite element network. Following the specification of the boundary conditions, system analysis was used to arrive at the ANSYS analytical solution. In this study, the analytical solution of the tensile, compressive, and three-point bending tests on a steel T-bar beam with composite coating was achieved using the ANSYS Workbench software. Using finite element analysis (FEA), the efficiency of the coating material is examined to determine whether it can prevent the properties change of the base material. The properties of the composite materials, which were modeled in ANSYS Material Designer using a 0.5 volume fraction of fiber, are shown in the Composites Properties Table. In Fig:1 the steel was represented by gray portions and the composite coating (8mm/10mm) by green areas. There was bonded contact between the T-bar and the indenter treated as no sliding or separation between faces or edges was allowed.

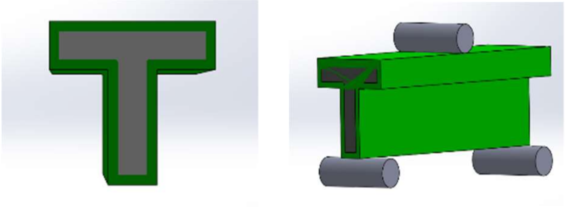

Fig.1 Composite coated T bar Steel element setup.

Dimension of model:

Steel T bar: 500 mm extruded, Height: 150mm, Width: 150 mm, Thickness:30 mm.

The mechanical properties of Composites were obtained from ANSYS material designer library. To get different results about different types of composite and different composite layer thicknesses, the Steel T-bar was coated with 8 mm and 10 mm Carbon Fiber-Resin epoxy or Glass Fiber-Resin epoxy composite material. Fixed support and Force were employed as boundary conditions for tensile and compression tests in ANSYS Static Structural analysis. And a "3-point bending test" was conducted for the bending test.

2.3 Thermal Modeling:

For Thermal property of that structure, COMSOL MULTIPHYSICS was used which uses the finite element method to solve it. COMSOL provide defined function and provide flexibility to modify according to the requirement. The temperature profile of the composite construction was tracked using the finite element approach. Fine, tetrahedron-sized, with 24 degree of freedom finite element mesh (67,868 elements) was used for much more accurate data.

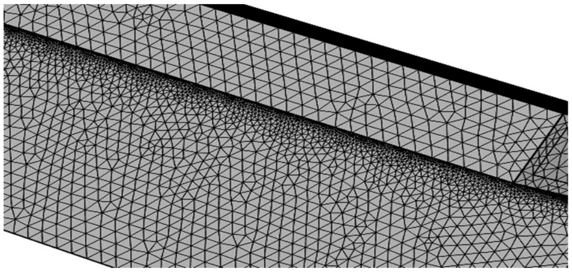

Fig.2 Fine mesh on the structure

After defining the structure, this geometry was exported to the COMSOL software. Here for the coating, we have used UD lamina [16]. It shows the best result for thermal resistivity. Carbon fiber epoxy composite consists of a volume fraction of 50% fiber. Glass fiber- resin epoxy composite consists of a volume fraction of 50% fiber. Additionally, the top of the T-shaped surface received a steady heat flux. The structural steel was coated with carbon-epoxy and glass-fiber-epoxy. For our observation, we have created a 3D cut line throughout the T bar's thickest point.

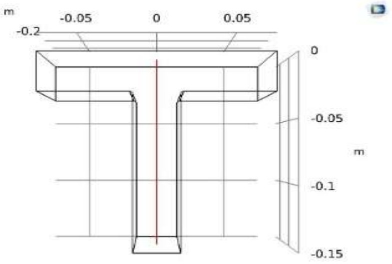

Fig.3 3D cut line through the Bar

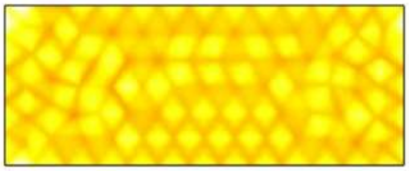

Fig.4 Constant heat flux on the flat surface

In **Fig. 3,4** a 3D cut line was traced across the thickness of the T-shaped bar for simulation purposes. Combining this cut line with a data point All of these points added after the heat source will reveal the temperature through the thickness.

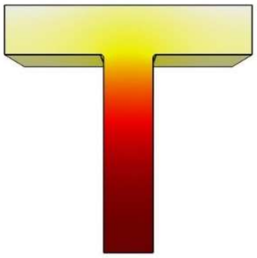

Fig.5 Heat Propagation through T-bar without Coating

Fig.6 Heat Propagation through T-bar with Coating

The images in **Fig. 5,6** were captured using the simulation program. This depicts the state of the bar's top after applying heat flux. All the sides except the top layer was assumed to be insulating layer. Here, the crimson area represents the lower temperature in this structure, while the yellowish area represents the high temperature zone.

2.4 Equations:

$$\sigma = \frac{F}{A} \tag{1}$$

$$E = E_f V_f + E_m V_m \tag{2}$$

$$\sigma = \frac{Mc}{I} \tag{3}$$

$$q = k\frac{dT}{dx} \tag{4}$$

$$\Delta L = \frac{F \times L}{E \times A} \tag{5}$$

$$Q = mc_p \Delta\theta \tag{6}$$

3. Results and Discussion

3.1 Mechanical

Table 1 Modulus of elasticity of Composite: (in MPa)

Composite	Theoretical	Simulation
Carbon Fiber-Resin epoxy	1.1689×10^5	1.4694×10^5
Glass Fiber-Resin epoxy	0.46890×10^5	0.46916×10^5

From Table 1, The theoretical and simulated Modulus of elasticity were observed quite similar with a slight variation.

(i) Tensile test:

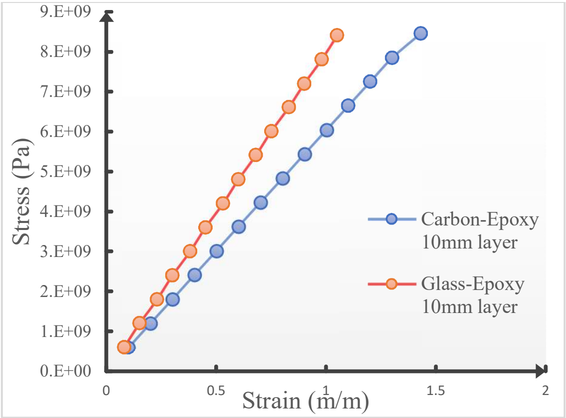

Fig 7: Comparison of Stress-Strain Curve of Composite coated Steel T-bar for tensile test.

From Fig 7 The Stiffness was observed higher in Glass fiber- Resin Epoxy composite than Carbon fiber- Resin Epoxy composite coated Steel T bar for tensile test.

(ii) Compression test:

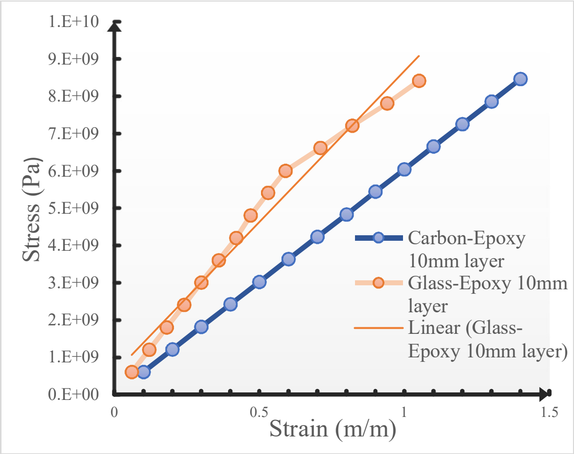

Fig 8: Comparison of Stress-Strain Curve of Composite coated Steel T-bar for compression test

From Fig 8 The stiffness was observed higher in Glass Fiber-Resin Epoxy composite than Carbon Fiber-Resin Epoxy composite coated Steel T bar for compression test.

(iii) Bending test:

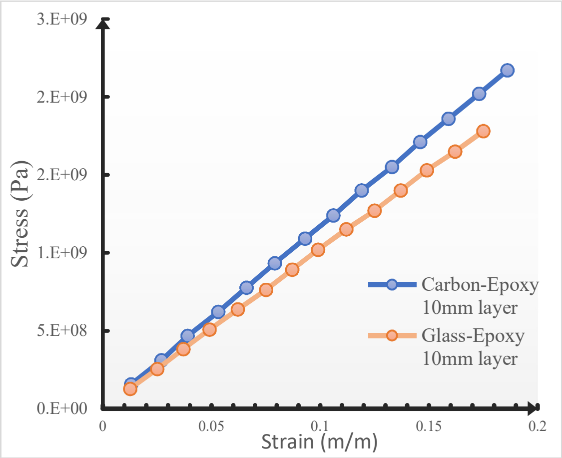

Fig 9: Comparison of Stress-Strain Curve of Composite coated Steel T-bar for compression test

From Fig 9 The Flexural stiffness was observed higher in Carbon Fiber-Resin Epoxy than Glass Fiber-Resin Epoxy composite coated in Steel T-bar for bending test.

Effect of variable thickness: In tensile, compressive, and bending tests, stiffness varied slightly depending on the thickness. Despite a small increase in stiffness with increasing coating thickness. (Fig 10)

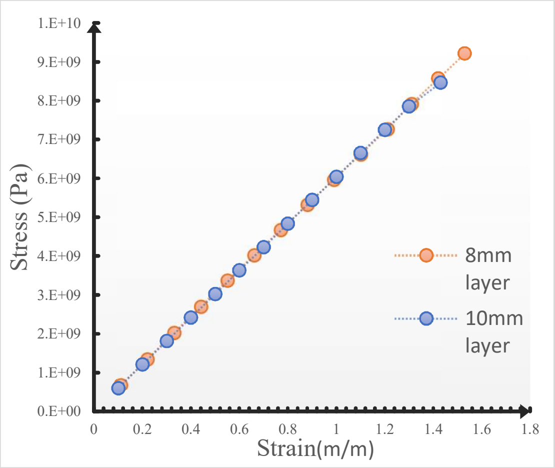

Fig 10: Comparison of Stress-Strain Curve for different thickness of composite layer.

3.2 Comparison of Carbon fiber and Glass fiber reinforced Resin Epoxy composite:

The figures 7, 8, and 9 showed the stress-strain behavior. The best performance under the same load in tension and compression tests was demonstrated by steel T bar with Glass-Epoxy composite. However, bending tests on the Carbon-Epoxy composite show that its flexural stiffness was higher. As the composite layer got thicker, the rigidity likewise got stiffer.

3.3 Thermal

The different colors were drawn to show different temperature gradient with respect to time.

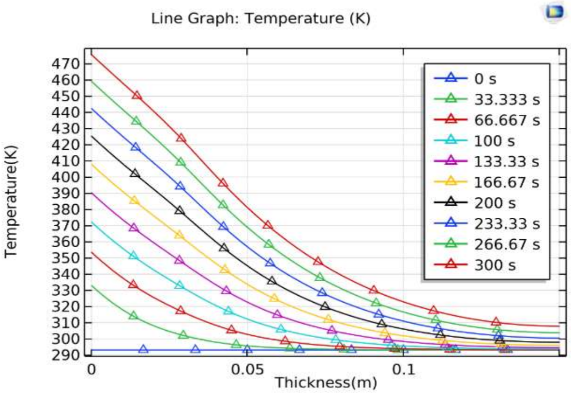

Fig.11 Temperature distribution through the T bar without Composite Coating

Here at **Fig.11** the flat portion's top has had a heat flux applied to it. After five minutes It was observed that the top of the temperature profile, close to the heat flux, had the highest temperature. There was a greater temperature difference across the thickness. Due to the ease with which heat could pass through the bar, the steel structure maybe got exposed.

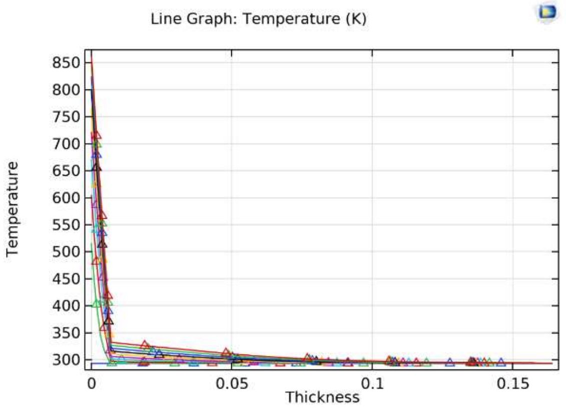

Fig.12 Temperature distribution through the T bar with 8mm Carbon-epoxy Coating

In that instance (**Fig.12)**, the top surface of the steel structure was coated with 8mm thick carbon fiber epoxy composite. As this composite has a significantly lower transverse heat conductivity. Steel was shielded from high temperatures and the rate of heat transfer rapidly decreases.

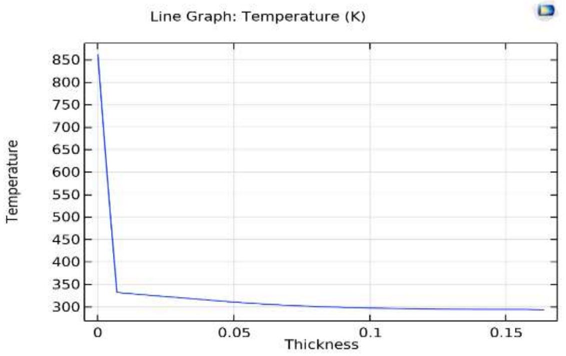

Fig.13 Temperature distribution through the T bar with 10mm Carbon-epoxy Coating

In that instance (**Fig.13**), the top surface of the steel structure was coated with a 10 mm thick carbon fiber epoxy composite. Because of the much lower transverse heat conductivity of this composite. Steel was protected from extreme heat, and the heat transfer rate rapidly reduces.

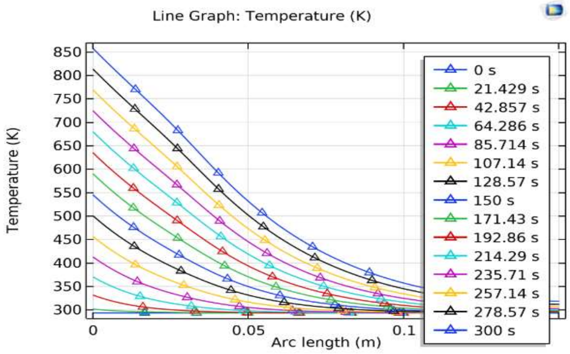

Fig.14 Temperature distribution through the T bar with 8mm Glass-fiber-epoxy Coating

In a different scenario (**Fig. 14**), the T bar's covering was an 8 mm Glass Fiber-Epoxy composite. The temperature profile from the simulation was examined after Heat Flux was again applied to the bar's flat part. Here, the effects of the heat flux were observed five minutes later.

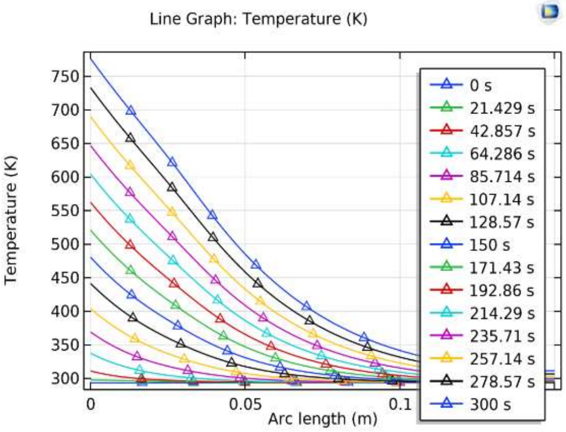

Fig.15 Temperature distribution through the T bar with 10mm Glass fiber-epoxy Coating

Once more, temperature did not drop quickly in the case of the 10 mm glass fiber-epoxy composite in (Fig. 15), failing to shield steel from higher temperatures. From those findings, carbon fiber-epoxy can be a good substitute for chemical coatings that resist fire.

Table 2 Thermal Conductivity (W/ m K)

Steel	45	
Composite	Theoretical	Simulation
Carbon Fiber +epoxy	0.833	0.658
Glass Fiber +epoxy	0.46875	0.36

From Table 2, The theoretical and simulated Thermal conductivities were observed. Some variations were observed due to the simulation method.

4. Conclusion

In this study, the mechanical and thermal characteristics of steel structures with various composite coatings were examined. Based on the findings, the following conclusion can be drawn:

- The mechanical characteristics of the material decrease as temperature rises. Except for flexural stress, we found that the stiffness of glass fiber-resin-epoxy composite was higher than that of carbon fiber-resin-epoxy composite coated in steel T bar.
- When there is a composite coating made of epoxy reinforced with carbon fiber or glass fiber, the heat flow is reduced. To lessen heat flux and propagation inside the steel core,

however, carbon fiber- resin epoxy performs better.
- Steel gets protected from excessive heat for a certain time.
- Carbon Fiber-Epoxy is selected even if Glass Fiber exhibits greater mechanical qualities since it is enriched with good mechanical properties and significant thermal resistivity.

From simulation, It was found that Steel T bar coated with carbon fiber-resin epoxy works better for the intended use.

5. References

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NOMENCLATURE

σ =Tensile/Compressive stress

$\frac{\mathrm{dT}}{\mathrm{dx}}$ = Temperature Gradient [$\mathrm{K.m^{-1}}$

E = Modulus of elasticity of Composite

Q = Total Heat [J]

E_f / E_m = Modulus of elasticity of Fiber / matrix

C_p = heat Capacity [$\mathrm{J.Kg^{-1}.\,K^{-1}}$]

V_f / V_m = Volume fraction of fiber / matrix

M = Moment about the neutral axis

q = Heat Flux Density at the surface [$\mathrm{W.m^{-2}}$]

C = distance to the neutral axis

k = Thermal Conductivity [$\mathrm{W \cdot m^{-1}k^{-1}}$]