Modelling the thermal behaviour of GFRP reinforced concrete beams subjected to elevated temperature by standard fire exposure

Mervin Ealiyas Mathews*, Yellapragada Sai Manas, Tattukolla Kiran and N Anand
Department of Civil Engineering, Karunya Institute of Technology and Sciences, Coimbatore
Email Id - *mervi.567@gmail.com

Abstract: The effective implementation of a quality fire safety model of Reinforced Concrete (RC) structures rely on the reliable numerical simulation tools of RC exposed to elevated temperature. To assess the thermal behaviour, models were created for Glass Fibre Reinforced Polymer (GFRP) RC beams exposed to fire loads following ISO 834 standard fire curve. Three-dimensional (3D) Finite Element (FE) models were developed. Appropriate material data is used to model the thermal and structural behaviour of GFRP reinforced beams. Different cover to concrete and diameters of bars were used as variables in the model. Temperature-dependent material properties were used for modelling the flexural behaviour of the reference and the temperature exposed GFRP beams. The developed model with the appropriate material properties simulated the flexural behaviour of beam with GFRP and steel bar.

Keywords: Elevated temperature, GFRP, Load-carrying capacity, Concrete cover

1. INTRODUCTION

Fire is one of the most significant hazards that affect the durability of a Reinforced Concrete (RC) structure. The fire resistance of the RC member has to be taken into account in the design RC building. The fire resistance period of an RC member is generally defined by a prescriptive approach that specifies certain requirements such as minimum member size, minimum concrete cover for steel and duration of heating. In recent years, a gradual shift from a performance-based approach in the design of RC members to more economical, flexible and rational approach to achieve the required fire safety.

Exposure of the RC beam to high temperatures during a fire results in significant loss of strength and stiffness of the member, and also a reduction in the bond between the concrete and steel. Higher temperature exposure on RC beams affects the performance of the Fibre Reinforced Polymer (FRP) bar. Although FRP bars are not burning due to the lack of oxygen, epoxy may smooth out if embedded in concrete. The temperature at which this takes place is called the glass transition temperature, (Tg). Beyond Tg, a polymer elastic modulus is dramatically reduced by the change in its molecular structure (Hawileh, 2011). In the RC members that are under heat exposure and explosive loading, significantly affect the load-carrying capacity of FRP beams. The FRP composites are increasingly necessary and suitable for concrete technology and are being used in a growing number of applications of FRP composites (Uomoto et al., 2002). The 3-D FE model presents a detailed analysis of the local nature of fire exposed beams of the RC beams, both stresses in concrete and steel...
and their complex deformation interaction (Dai et al., 2011). FE predictions for both the temperature field and the structural response are in reasonably close agreement with the test data (Sakashita et al., 1997). The modelling process using FE software is accurate and using FRP in strengthening reinforced concrete beams is an effective method (Ahmed et al., 2014). At about 400°C, the calcium hydroxide starts to dehydrate in the cement above the moisture level and creates more water vapour, which also greatly decreases the material's physical strength. At high temperatures, more aggregate changes will occur. Depending on the concrete mixing pattern, including the amount of moisture or related environmental factors such as level of temperature and duration of heating, the physical characteristics of cement are significantly deteriorated (Fletcher et al., 2007). High levels of stress (over 60 percent of the ultimate tensile strength) lead to fibre cracking, leading to higher water consumption at saturation and a decrease in the density of GFRP concerning the higher void content. Furthermore, moisture absorption and high temperatures did not seem to influence the interaction between the resin and the fibres (Mathieu and Benmokrane, 2010). While the amorphous polymer material increases stiffness at lower temperatures, mechanical properties such as tensile, shear and flexural strength and flexural elastic modulus of the GFRP bars grow as the temperature decreases (Fletcher et al., 2007). The energy for interface fractures is almost constant initially but begins to deteriorate with the temperature exceeding the Glass Transition Temperature (GTT). The index of interfacial brittleness also shows a decreasing rate, but before hitting the GTT the decrease is nearly over (Lin et al., 1988).

This study aims to explore the flexural behaviour of fire exposed RC beam following ISO 834 transient fire curve, also to study the performance of beam with GFRP bar as internal reinforcement, thereby providing an alternative to steel.

The following are the objectives of the study

1. To model the thermal and structural behaviour of beams with GFRP and steel reinforcement.
2. To analyse the flexural behaviour of GFRP beams exposed elevated temperature as per standard fire.

2. THERMAL MODELLING OF BEAM SPECIMEN

Thermal and structural modelling of the RC beam carried out with the program ANSYS. Steel-reinforced concrete beam and concrete beams with GFRP bars were modelled. The model consists of different diameters of GFRP bars to carry to the coupled analysis (both thermal and structural). The actual fire load shall be simulated by coupled thermal structural analysis. The models were developed with fixed end conditions and uniform loading was applied in the top surface.

An important fact to be considered in the design of RC building is the fire resistance of RC members. It is, therefore, the critical factor that RC member undergoing heat reduces its efficiency. The previous findings related to RC member performance under fire loads are investigated by a suitable literature survey. The GFRP bar, concrete interface, and the steel-concrete interface were then modelled for the problem by selecting the appropriate element type in ANSYS. The structure is eventually subdivided into finite elements called discretization. The model was then assigned by appropriate boundary conditions (Fixed). The developed model is subject to temperature loads as per the ISO834 fire curve. Figure 1 shows the methodology adopted for the investigation.

FEM has been used to solve a number of physical problems, where experimental works are time-consuming and costly. In general, this approach minimizes the running time and reduce the solution error.

In the proposed modelling, behaviour of GFRP, concrete and steel interface was simulated. Temperature loads were applied in the models to simulate the effect of flame. The temperature versus
time values of the ISO-834 standard fire curve and defined material properties can be used to simulate the heat transfer on an RC beam. SOLID65, LINK180 and their thermal components (SOLID70, LINK33) are the elements used for modelling the beam.

Figure 1. Methodology

3. MODELLING

ANSYS tool provides an extensive range of engineering simulation sets to build and simulate a prototype finite element that provides access to virtually all the area of engineering simulation that is needed for the design process.

3.1. Development of Finite Element Model
ANSYS has been used to build and simulate the FE beam model. An analytical procedure to be derived to simulate the complex behaviour of the model. Different material properties are obtained from literature and the related constitutional laws. In the process of this development, coupled thermal structural analysis was used to simulate the behaviour of concrete, the steel bar and GFRP bar reinforcement elements exposed to standard fire as a beam section. Appropriate meshing was done and thermal loads were applied on the surface of the beam model.

3.2. Modelling of Control Beam & GFRP Reinforced Beam
Models are developed for a control beam of size 250 x 400mm, with an effective span of 3.6m using steel of Fe500 and M30 concrete and beam with GFRP reinforced bar of size 250x400mm with an effective span of 3.6m for the same grade of steel and concrete. An isometric view of reference and GFRP reinforced beam developed in ANSYS is depicted in Figure 2 (a) to Figure 2 (d). The details of specimens are given in Table 1.
Figure 2. (a) View of Control RC beam (b) Reinforcement details of control RC beam (c) View of beam reinforced with GFRP (d) Reinforcement details of beam reinforced with GFRP

Table 1. Details of Specimen

| Nominal Cover | Name   | GFRP specification |
|---------------|--------|--------------------|
| 30mm          | 30GFB8 | 8 mm diameter      |
|               | 30GFB12| 12 mm diameter     |
|               | 30GFB16| 16 mm diameter     |
|               | CB*    | -                  |
| 40mm          | 40GFB8 | 8 mm diameter      |
|               | 40GFB12| 12 mm diameter     |
|               | 40GFB16| 16 mm diameter     |
| 50mm          | 50GFB8 | 8 mm diameter      |
|               | 50GFB12| 12 mm diameter     |
|               | 50GFB16| 16 mm diameter     |
|               | 50GB12 | 12 mm diameter alone |

*Note: CB-Control RC Beam
30GFB8- 30mm nominal cover with GFRP bar of 8mm diameter
50GFB16- 50mm nominal cover with GFRP bar of 16mm diameter

3.3. Details of Reinforcement
A beam of size 250 x 400mm with an effective span of 3.6 m was applied with a factored moment of 36.186 kNm, shown in Figure 3, which was considered from the analysis for the study. The reinforcement details of the beam are shown in Figure 4.
3.4. Properties of Constituent Materials

The thermal and structural properties are required as input to simulate the nonlinear behaviour FE model. The model is subjected to fire load based on the transient fire curve given in ISO 834 along with the structural loading as a two-point load. Table 2 depicts the thermal and structural material properties of the materials at ambient temperature.

| Material | \( K_0 \) (W/mm.K) | \( C_s \) (J/kg.K) | \( \rho \) (N/mm\(^3\)) | \( E_s \) (N/mm\(^2\)) | \( \mu \) | \( \alpha \) (mm/mm.K) |
|----------|-------------------|-------------------|-----------------|-----------------|--------|-----------------|
| Concrete | 2.7\times10^{-3}  | 722.8             | 2.4\times10^{-5} | 2.7\times10^{4} | 0.2    | 14.5\times10^{-6} |
| GFRP     | 4.0\times10^{-5}  | 1310              | 1.6\times10^{-5} | 7.5\times10^{4} | 0.22   | 5.53\times10^{-6}  |
| Steel    | 43\times10^{-3}   | 510.8             | 7.8\times10^{-5} | 2.1\times10^{5} | 0.3    | 12\times10^{-6}   |

Note: \( K_0 \) - Thermal conductivity, \( C_s \) - Specific heat capacity, \( \rho \) - Density, \( E_s \) - Modulus of elasticity, \( \mu \) - Poisson’s ratio, \( \alpha \) - Coefficient of thermal expansion

Thermal conductivity and specific heat values of concrete and reinforcing steel are taken based on the relationship given in EN 1992.

\[
\lambda_s = \begin{cases} 
27.3 & 0^\circ C \leq T_s < 20^\circ C \\
470 + 2T_s^2 & 20^\circ C \leq T_s \leq 800^\circ C \\
T_s & 800^\circ C < T_s \leq 1200^\circ C \\
0.001241T_s + 1.7162 & T_s > 1200^\circ C
\end{cases}
\]

\[
\lambda_c = \begin{cases} 
1.355 & 0^\circ C \leq T_c < 293^\circ C \\
0.001241T_c + 1.7162 & T_c > 293^\circ C
\end{cases}
\]
\[ C_C = -4\left(\frac{T}{120}\right)^2 + \frac{2T_C}{3} + 900 \quad 20^\circ C \leq T_C \leq 1200^\circ C \]

Figure 5 shows the time temperature graph based on ISO 834/IS 3809, the similar rate of heating is used for heating the specimens.

4. VALIDATION OF MODEL

The analysis results obtained from ANSYS post-processing were validated with the theoretical approach. Moment carrying capacity of the section at both ends for the provided reinforcement is 42.47kNm.

The failure load at which the support section fails, obtained from ANSYS was 171.96kN and the corresponding value calculated theoretically was 141kN. The variation of stress in the control beam, obtained from ANSYS is shown in Figure 6.

Temperature loads following the standard fire curve were applied at the surface of the specimen and the applied values were compared with the temperature obtained from empirical relation given as per
ISO 834. Figure 7 shows the temperature values measured at the surface of the section.

![Figure 7. Temperature values measured at the surface of section](image)

5. RESULTS & DISCUSSIONS

Failure criteria are checked in this research was based on the deflection of the steel/GFRP beams due to the yielding of steel or crushing of concrete whichever first occurs. Details of the load-carrying capacity of the beam section exposed to elevated temperature and loaded with UDL of 24 kN/m is given in Table 3. A comparison graph showing the load-carrying capacity of the RC beam with different cover and reinforcement is shown in Figure 8.

| Cover (mm) | Type of Specimen | Load at which the beam start to deflect (kN) |
|-----------|------------------|---------------------------------------------|
| 30        | 30GFB8           | 7                                           |
|           | 30GFB12          | 12                                          |
|           | 30GFB16          | 13                                          |
|           | CB               | 12                                          |
| 40        | 40GFB8           | 17                                          |
|           | 40GFB12          | 20                                          |
|           | 40GFB16          | 24                                          |
|           | 50GFB8           | 18                                          |
|           | 50GFB12          | 22                                          |
| 50        | 50GFB16          | 29                                          |
|           | 50GB12           | 12                                          |
Temperature profile of the control beam is shown in Figure 9. Eleven models were analysed including control beam and their load carrying capacity is presented in Table 3.
Figure 10 and Figure 11 shows the nodal displacement of 40GFB8 specimen exposed to 150 minutes duration and variation in stress of reinforcement of 40GFB12 respectively. The GFRP strengthened beam failed at higher loads and lower displacement even at mid-span at higher temperature levels (Garcez et al., 2008). Also, the required flexural capacity is achieved. The development of thermal stresses is mainly due to temperature-induced thermal gradients. Because of this, internal stresses are built up inside the core concrete with the pore pressure, resulting in the concrete spalling and reduction in moment of resistance of beam (Parandaman P & Jayaraman M, 2014). Due to the development of internal stresses in concrete and when it reaches the total permissible tensile stress the thermal crack and concrete spalling occurs. When the temperatures elevated from 500°C and 700°C the strengthening effects of GFRP systems were reduced significantly. Thermal decomposition and resin volatilization are responsible for this reduction (Kiang Hwee Tan and Yuqian Zhou, 2011).

6. CONCLUSION

The conventional FEM is considered and the developed model is analysed by using ANSYS. Coupled thermal structural analysis was carried out for the RCC beam with boundary conditions as fixed. The analysis results are validated by theoretical calculations. The following are the conclusions derived based on the analysis results are given below:

- Thermal gradient development in the beam section is due to the thermal stress variation across the cross-section.
- As the diameter of the GFRP bar increased from 8mm to 16mm, the load-carrying capacity is increased from 60% to 108%. Similarly, the increase in cover of concrete from 30mm to 50mm also increased load carrying capacity (8mm, 12mm and 16mm GFRP bars) of 160%, 190%, and 250% respectively.
- It was observed from the investigation that, with the increase of cover to the reinforcement in the RC beam, the load-carrying capacity of the RC beam under thermal exposure improved. An increase in the diameter of GFRP bars also gives the same result. Variation in the diameter of the bar does not affect load-carrying capacity.
- GFRP can be used as an alternative material for steel bars provided with a clear cover of 50 mm or more, to avoid the failure of concrete due to spalling.

REFERENCES

[1]. Dai J G, Gao W Y & Teng J G “Finite Element Modelling of Insulated FRP-strengthened RC Beams Exposed to Fire” Advances in FRP Composites in Civil Engineering, 2011 428
[2]. Fletcher I, Welch S, Torero J, Carvel R & Usmani A “Behaviour of concrete structures in fire” Thermal Science, 2007 11 37
[3]. Ahmed A, Elshafey M, Mostafa M, Shamib E & Kamel S K “Strengthening of Concrete Beams Using FRP Composites” Concrete Research Letters, 2014 5 37
[4]. Mathieu R & Bemokrane B “Behaviour of GFRP Reinforcing Bars Subjected to Extreme Temperatures” Journal of Composites for Construction, 2010 14 353

[5]. Garcez M, Meneghetti L & Filho S D B “Structural Performance of RC Beams Post strengthened with Carbon, Aramid, and Glass FRP Systems” Journal of Composites for Construction, 2008 12 522

[6]. Tan H K & Zhou Y “Performance of FRP-Strengthened Beams Subjected to Elevated Temperatures” Journal of Composites for Construction, 2011 15 304

[7]. Sakashita M, Masuda Y, Nakamura K, Tanano H, Nishida I & Hashimoto T “Deflections of continuous fibre reinforced concrete beams under high temperatures loading Non-metallic (FRP) Reinforcement for Concrete Structures” Proceedings of the Third International Symposium, 1997 02 51

[8]. Lin T D, Ellingwood B, & Piet O U.S. Department of Commerce, National Bureau of Standards Centre of Fire Research Gaithersburg, 1988

[9]. Uomoto T, Mutsuyosh H, Katsuki F & Misra S “Use of fibre Reinforced Polymer Composites as Reinforcing Material for Concrete” Journal of Materials in Civil Engineering, 2002 14 191

[10]. Hawileh R A “Heat transfer analysis of reinforced concrete beams reinforced with GFRP bars” American University of Sharjah, 2011

[11]. Parandaman P & Jayaraman M “Finite Element Analysis of Reinforced Concrete Beam Retrofitted with Different fibre Composites” Middle-East Journal of Scientific Research, 2014 22 948

[12]. ISO: 834 1975 Fire resistance tests, Elements of building construction, International Standards Organisation, Geneva