IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 17, Issue 1 Ser. V (Jan - Feb 2020), PP 30-35
www.iosrjournals.org

Structural Safety Reliability Of Carbon Fibre Reinforced Polymer(CFRP) Reinforced Concrete In Fire.

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***Abstract**: This paper presents the structural behaviour of Carbon Fibre Reinforced polymer strengthened concrete beams under fire loading. The resistance of fire for concrete members reinforced with carbon fibre reinforced polymer (CFRP) needs to be investigated as the material has been widely accepted as a construction material and the global implementation of CFRP composite material in buildings is on the way.The investigation is undertaken considering the ISO834 standard fire conditions given in ACI 216.1(2007)and Eurocode 2(2002). A program was developed using FORTRAN that implemented the probabilistic assessment based on the First Order Reliability Method (FORM). The safety of the CFRP reinforced beam increases withan increment in the thickness of the concrete cover.*

(Keywords: Fire Resistance, Concrete, First Order Reliability Method, CFRP.)

Date of Submission: 19-02-2020 Date of Acceptance: 03-03-2020

I. Introduction

There is an increasing level of an unacceptable level of deterioration in concrete structures, particularly in a fire, and has attracted attention in of the area of concrete structural engineering development. The development of advanced techniquesin the construction of high-performing construction materials andhigh strength concrete introduction into the industry are two vital ways by which the civil engineering construction industry have experienced a revolution(Karbhari, 1999). Composites made from carbon fibre reinforced polymer (CFRP) are listed as one of these high-performing materials, gaining approvalfrom engineers and researchers.Some merits of CFRP as compared with some other materials used for construction like steel include the ratio of strength andweight, moldability, and resistance to environmental conditions which results in potential low maintenance cost. Marine structures like bridges, docks, off-shore platforms, dams and other water structures are among the fields in civil engineering benefiting from the introduction of CFRP composites (Rubino et al, 2020). This work thus evaluates the structural safety in fire of CFRP in reinforced concrete off-shore platforms, bridge, residential buildings and other structures.

Concrete undergoes series of significant changes in physical nature and concrete chemical composition when exposed to high temperatures (Poon et al,2001).The deformability and mechanical Strength of the reinforced concrete structure are not the only deterioration that is caused by firebut alsoreduced durability and seismicstability of the structure. The chemical decomposition of concrete during fire results in the production of CaO and H_20 from $Ca(OH)_2$. Morsy et al (2009) stated that the decomposition of $Ca(OH)_2$ starts when the temperature reaches 400^oC and the decomposition is completed when the temperature reaches 500^oC. This decomposition of chemicals within the concrete mass results in a sharp lose in mechanical strength and durability. For high strength concrete, the mechanical strength loss is lower than than the durability loss as explained by Poon et al (2001). Spalling of concrete cover, surface cracks, and further disintegration renders the concrete structure unserviceable.A report by Yu et al (2011) stated that the steel reinforcements begin to corrode when there is continued carbonation of the uncarbonated zone until the remaining protecting layer of concrete becomes completely carbonated.

Turkowski et al (2017) presented the outcome and findings of CFRP strengthened beams subjected to fire. They carried out ten (10) test of fire resistance on CFRP strengthened reinforced concrete beams with levels of loads varying from 100% to 163%. They concluded that theresistance of fire for CFRP-strengthened reinforced concrete members has three models depending on the fire protection thickness needed, and the reduction of load level.Hu et al (2007) In their paper strengthened reinforced concrete (RC) beams with carbon fibre-reinforced polymer (CFRP) and which was attached with a thick-painted fire-resistant coating were tested for fire resistance. The results revealed that 50mm thickness of CFRP can withstand fire for about 2.5hours and when a steel wire mesh is imbedded, it can prevent the concrete from cracking and further eroding under fire.

II. Experimental Program

Computation of Reliability Index

First Order Reliability Method (FORM)assumes the performance function G(X) to be linear as expressed by Tailor expansion.

$G(X) = G(X_1^*, X_2^*, X_3^* \dots, X_n^*) + \sum_{i=1}^{n} \left[\frac{\partial z}{\partial xi}\right]_{(x_i = x_i^*)} (x_i - x_i^*) = 0$ 1

Where G(X) = linearized in $(X_1, X_2, X_3 \dots, X_n)$

N= No. of stochastic variable in the reliability function.

$[\frac{\partial z}{\partial_{x_i}}]_{(x_i - x_i^*)}$ = Partial derivative of G with respect to X_i evaluated in $X_i = X_i^*$

The mean value, $\mu_{G(x)} = Z(X_1^*, X_2^*, X_3^* \dots, X_n^*) + \sum_{i=1}^{n} \left[\frac{\partial z}{\partial xi}\right]_{(x_i = x_i^*)} (\mu_{xi} - x_i^*) = 0$

2

While standard deviation,$\sigma_{G(x)} = \sqrt{\sum_{i=1}^{n} \left[\frac{\partial z}{\partial x_i}\right]^2_{x_i = x_i^*} + \sigma_{x_i}^2}$

3

The mean value of the probability of failure is obtained whenthe mean value $X_i^* = \mu_{xi}, \dots \dots \dots \dots, X_{xn} = \mu_{xn}$ are substituted.

The design point is given by, $X_i^* = \mu_{xi} - \alpha_i \beta \sigma_{xi}$

4

Where:

μ_{xi} = basic variables of the mean value.

σ_{xi} = basic random variables of the standard deviation.

The initial value of the design point can be taken as the mean value of the basic random variables. That is

$\mu_x = X_i^*$ 5

$\alpha_i = \frac{\sigma(x_i)}{\sigma(Gx_i)} . \frac{\delta G}{\delta x}$

6

α =factor of influence of variable I

$\beta = \frac{\mu(Gx)}{\sigma(Gx)}$

7

Flexural Failure

Member sections in flexure should be ductile and the failure should occur with a gradual yielding of the reinforcing materials at the ultimate limit state, and not by a sudden catastrophic compression failure of the concrete.

Condition of flexure failure of a beam is given as:

For limit state: R – S≤ 0 8

Hence, the limit state function is given as;

G(X) = R – S

9

Where:

Moment of resistance $(R) = 0.167 K_c(\Theta) f_{ck} b d^2$, d = effective depth = $h - C_c - \frac{\emptyset}{2}$ 10

Applied moment $(S) = \frac{W_u l^2}{8} = (1.4 G_k + 1.7 Q_k) \frac{l^2}{8}$(ACI 318 -10) 11

But $(S) = \frac{W_u l^2}{8} = (1.35 G_k + 1.5 Q_k) \frac{l^2}{8}$(EC2, 2008) 12

Divide through byQ_k to factor it out of the bracket

But $\frac{G_k}{Q_k} = \alpha = l$oad ratio

$S = [0.125 Q_k (1.35\alpha + 1.5) L^2]$ 13

$G(X) = 0.167 K_c(\Theta) f_{ck} b_w \left(h - C_c - \frac{\emptyset}{2}\right)^2 - 0.125 Q_k (1.35\alpha + 1.5) L^2$ 14

Where θ = temperature

K_c = Reduction Factor of the characteristic strength of concrete as a function of temperature, f_{ck} = Design compressive strength of Concrete, b_w = Rib of web in a beam, h = overall depth of beam, C_c = concrete cover, $\emptyset$ = diameter of reinforcement, Q_k = Imposed load, L = span of the beam.

The reduction factor of the characteristic strength of concrete as a function of the temperature is allowed by the coefficient $K_c(\theta)$ namely $f_{ck}(\theta) = K_c(\theta) f_{ck}(20^oC)$. The following are used according to Petru (2008)

$K_c(\theta) = \frac{1600 - \theta}{1500}$, for $100^oC \leq \theta < 400^oC$ 15a

$K_c(\theta) = 1,\ 20^{o} \leq \theta < 100^{o}C$ 15b
$K_c(\theta) = 900 - \theta/625$ for $400^{o}C \leq \theta < 900^{o}C$ 15c
$K_c(\theta) = 0$ for $900^{o}C \leq \theta \leq 1200^{o}C$ 15d
All the above conditions holds for tension reinforcements in slabs and beams.

Shear Failure
The shear forces in a concrete section are the difference between the shear capacity ($v_{Rd,c)}$ and the ultimate shear force($v_{E,d}$).
The failure condition of the reinforced beam is given by;

$$v_{E,d} - v_{Rd,c} \leq 0 \qquad 16$$

Thus, the limit state function is as follows;

$$G(X) = v_{E,d} - v_{Rd,c} \qquad 17$$

$$v_{Rd,c} = \frac{Fl}{2} = 0.5Q_k l(1.35\alpha + 1.5) \qquad 18$$

$$v_{E,d} = 0.36b_w d\mathrm{Kc}(\theta)\ f_{ck}\,(1 - 0.004\mathrm{Kc}(\theta)\ f_{ck}) \qquad 19$$

$$\mathrm{G(x)} = 0.36b_w(h - C_c - \frac{\phi}{2})\mathrm{Kc}(\theta)\ f_{ck}\,(1 - 0.004\mathrm{Kc}(\theta)\ f_{ck}) - 0.5Q_k l(1.35\alpha + 1.5) \qquad 20$$

III. Results And Discussion

An algorithm developed in FORTRAN module was designed for flexural and shear failure modes with varyings span of beam, imposed load, concrete cover, design compressive strength of concrete and reduction factor.

Relationship betweenSafety Indicesand Concrete Cover

The relationship between safety indicesβ, and the coefficient of concrete cover is shown in figure 4 to 4. All designs are based at a predefined target safety index of 3.0 as per the recommendation of JCSS (2001). The designed imposed load is 1.5 N/mm^2, the diameter is 16mm, while the span, L varies from 3m to 6m. It is observed that, increasing the concrete cover of the beam results to increase in structural safety from 6.45 to 6.51 in figure 1 for temperature between 100°C to 600°C. Thus, the durability of the CFRP reinforcement is greatly enhanced by the thickness of the concrete cover. When the moment capacity of the beam is reduced to the magnitude of the moment caused by the applied load, (at a temperature of 1000°c, which corresponds to a reduction factor K_c (θ) near zero) flexural collapse occurred.

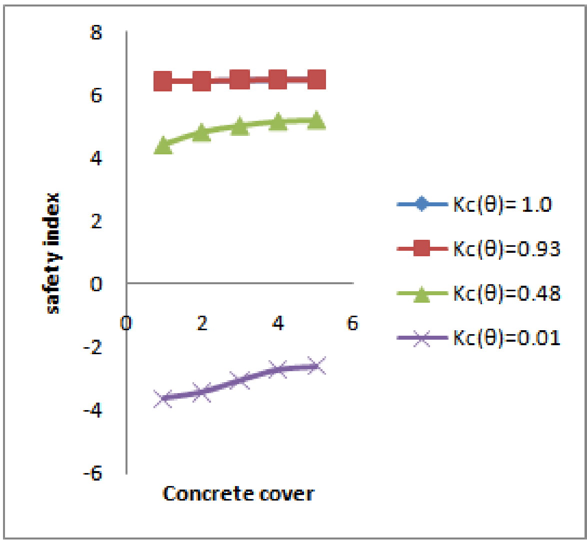

***Figure 1:** Relationship of safety index to concrete cover at L = 3m*

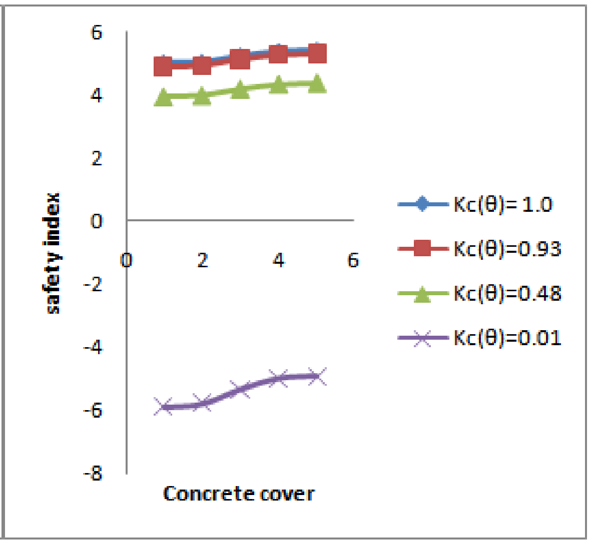

***Figure 2:** Relationship of Safety index to concrete cover (L = 4m)*

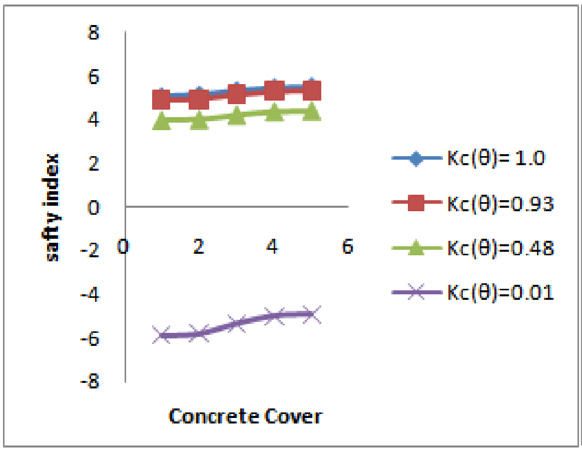

Figure 3:*Relationship of Safety index to concrete cover (L = 5m)*

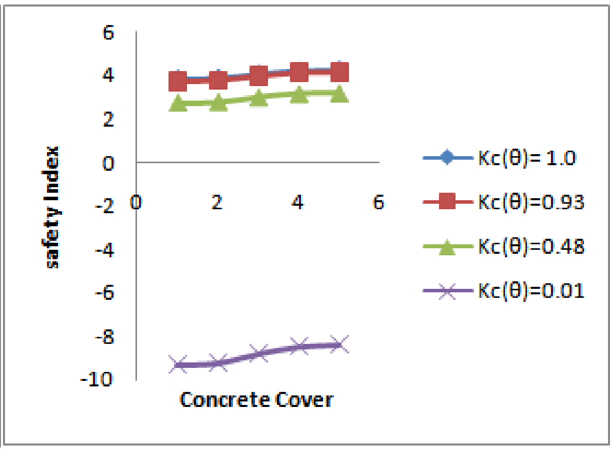

Figure 4:*Relationship of Safety index to concrete cover (L = 6m)*

figures 5 and figure 6 show the relationship between the safety indices and the coefficient of concrete cover at constant temperatures of 100°C, 200°C, 600°C and 1000°C (K_c=0.01). From the figures, increasing the concrete cover increased the load-carrying capacity of the CFRP reinforced beam from 4.44 at a temperature of 100°C (K_c=1.0) and span of 3000mm to 8.09 in figure 5 and 4.65 to 3.62 at an increased span of 6000mm, the temperature of 100°c (K_c=1.0). Irrespective of the thickness of the concrete cover, as the temperature increases, the safety index decreases and shear failure becomes imminent.

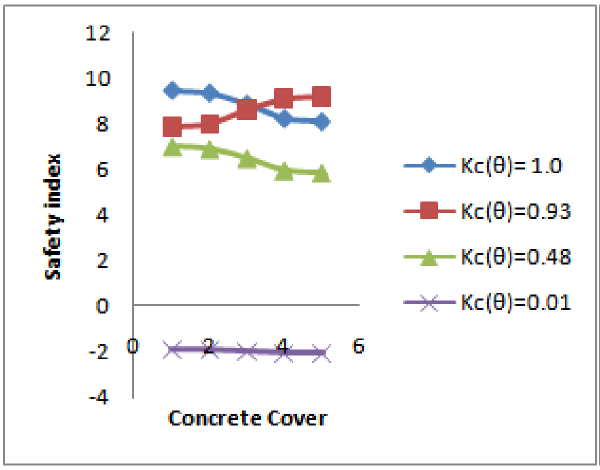

Figure 5: *Relationship of Safety Index to Concrete cover at 3m*

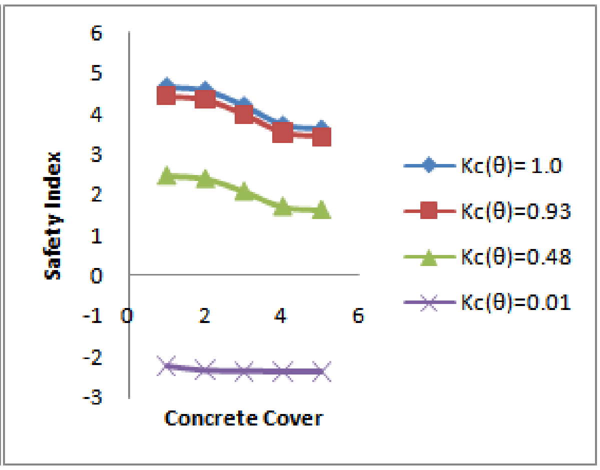

Figure 6*: Relationship of Safety Index to Concrete cover at 6m*

Relationship BetweenSafety Indices and Load Ratio

The relationship between the safety index and the Load ratio is shown in figure 7 – figure 10 for four different spans of 3, 4, 5 and 6m at an imposed load of 1.5N/mm^2 and diameter of CFRP reinforcements of 16 mm. The safety of using CFRP was observed to decrease from 3.55 to 1.31 as the span of the beam increases from 3000 to 6000mm for all the load ratio considered. The safety and consequent durability of the beam decrease from 6.59 to 3.55 for L= 3000mm as the load ratio increases. With increases in the overall depth from 250mm to 650mm, the safety of the beam increases from 3.01 to 6.57 for a span of 3m and 0.5 to 4.47 for a span of 6m. This implied that high concrete depth reduces susceptibility to cracks and increases resistance to flexural failure under fire loading.

Figure 9 shows the relationship between safety indices and the coefficient of design compressive strength of the concrete component of the beam. From the plot, the safety indices of the beam increase from 5.77 to 8.34 with increasing design compressive strength of concrete from 25 N/mm^2 to 50 N/mm^2. Thus, high strength concrete has a higher resistance to shear failure than low strength concrete under fire loading.

Similarly, figure 10 shows the relationship between safety indices and coefficient of concrete cover. With constant concrete strength, an increase in the concrete cover resultsinto decreases in the safety indices. This implies that the concrete cover to the CFRP reinforcement should be used with care.

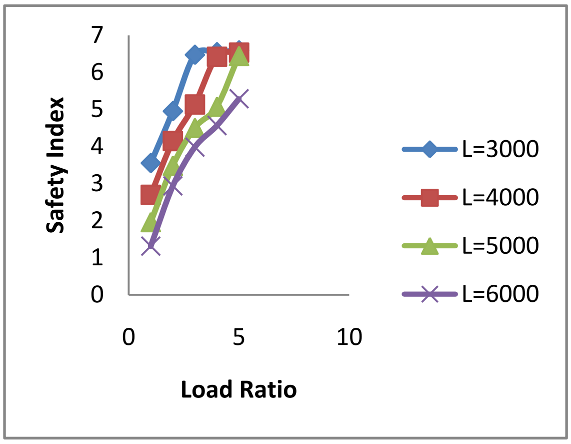

Figure 7: *Relationship of safety index to load ratio at varying lengths*

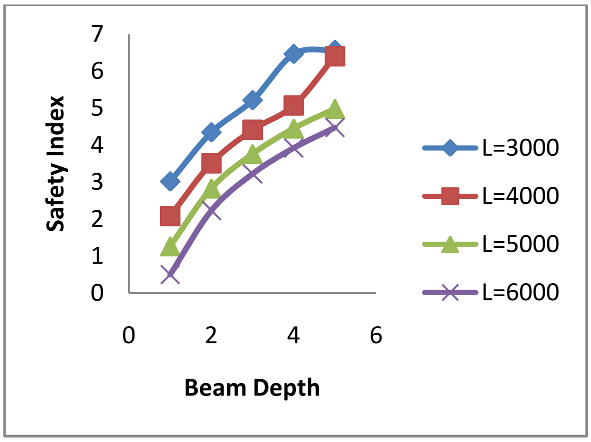

Figure 8: *Relationship of safety index to beam depth at varying lengths*

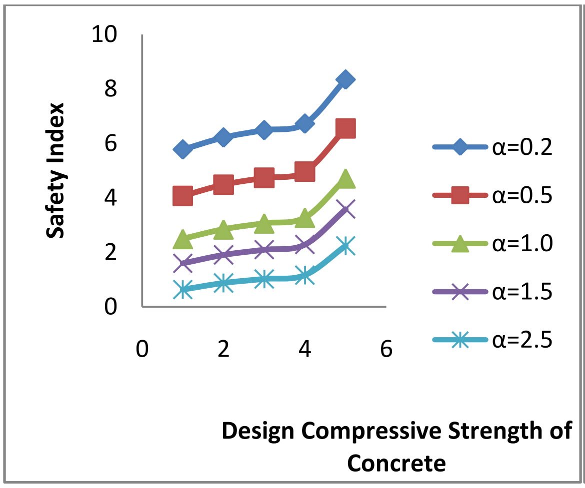

Figure 9: *Relationship of Safety Index to Design Compressive Strength of Concrete*

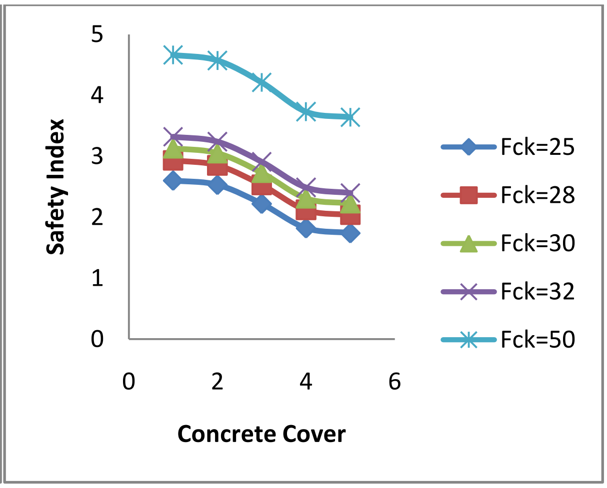

Figure 10: *Relationship of Safety Index to Design Compressive Strength of Concrete*

IV. Conclusion

From the results, the structural safety reliability of CFRP reinforced concrete beams increases with increases in the thickness of the concrete cover, the web of the beam, design compressive strength and the overall depth of the beam.

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Dugguh Ngutor Leonard. "Structural Safety Reliability Of Carbon Fibre Reinforced Polymer(CFRP) Reinforced Concrete In Fire.". *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, 17(1), 2020, pp. 30-35.