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RELIABILITY ANALYSIS OF REINFORCED CONCRETE BEAM EXPOSED TO FIRE BASED ON EUROCODE 2

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ABSTRACT

Structures are expected to have satisfactory performance in their expected lifetime, making the design of structures a challenging task for civil and structural engineers. Safety of the structures and economy are the main issues in the design but the earlier (that is, safety) must be given higher priority. As failure of the structure or any of the structural element such as beam either at normal condition or when prone to accident, might results into loss of lives and property. Thus, the need for reliability analysis of the structures and structural elements. Reliability simply put, is the ability of a structural element to

Introduction

In the last several decades, there has been limited research on the probabilistic analysis of structures exposed to fire, though diverse types of analyses have been considered. Theseinclude Beck (1985), who studied the reliability of structural steel members exposed to fires; Shetty et al. (1998) who applied reliability analysis to assess the fire safety of offshore structures;Teixeira and Soares (2006) who estimated the reliability of load bearing steel plates subjected tolocalized heat loads; and Vaidogas and Juocevicius (2008), who considered the reliabilityanalysis of a timber structure exposed to fire. Based on an analysis of load frequency,Ellingwood (2005) summarized practical design load combinations that need to be considered forfire design (Eamon and Jensen, 2013).For the Development of performance based design on a proper scientific basis the use of the concept of reliability analysis is inevitable. Reliability is defined as the probability of 'success', or the complement of the probability of failure.

In this research, the reliability analysis of reinforced concrete beam exposed to fire is evaluated and compare with the reliability indices provided by the Joint Committee on Structural Safety reports JCSS (2001). Other parameters that affect the reliability indices are also studied.

The Global Fire Engineering Concept

This new approach to fire safety moves away from the prescriptive approach of the past where elements of the structure were rated as having a certain fire resistance time. Emphasis is placed on human safety and active fire resistance

perform its required functions under stated conditions for a specified period of time. Reliability analysis was carried out on a simply supported reinforced concrete beam exposed to fire based on Eurocode 2 (2004) using First Order Reliability Method (FORM) approach to evaluate the reliability index. Sensitivity analysis was also carried out on the design parameters, such as span of section, depth of the section, Breadth of the section, characteristics strength of concrete and characteristics strength of steel of the reinforced concrete beam. Reliability design methods are very attractive as they allow a systematic treatment of uncertainties and set performance requirements in terms of explicit safety targets.

measures. According to Schleich et al, 2005, when the safety of the people is being addressed in an optimal way the structure itself will also benefit.The global fire engineering concept is based on statistical data and probabilistic procedures. By using fundamental principles combined with newly developed methods, structural safety can be achieved in a performance based manner.

Fundamental Stages of a Fire

There are 4 fundamental stages in a natural fire. These stages are schematically illustrated in Figure 1. The first stage is the incipient ignition phase, wherein heating of the potential fuel source(s) takes place. The second stage is the growth stage, which involves ignition with visible flaming combustion. The "flashover" condition, which generally marks the beginning of the third stage called the burning period. Eventually, the fuel for the fire in the given compartment becomes exhausted, and the fire will start to die out during the fourth stage called the decay period. The decay phase generally begins when about 70 percent of the combustible materials in the compartment have burned.

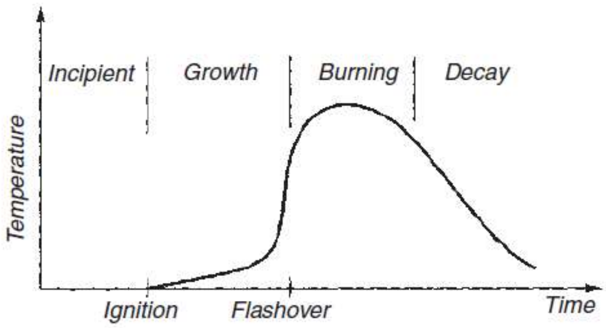

Figure1: Stages of Fire Development (Buchanan, 2001)

Performance Based Objective

The target failure probability not to be exceeded in normal conditions is given by7.23×10^{-5} for the building life of ≈55 years (EN 1990). Hence the objective for the fire situation should also be:

$P_{f,55}$ (probabilty of failure) ≤ $P_{t,55}$ (target failure probability) = 7.23×10^{-5}

The first method of safety quantification is given by a full probabilistic approach(LEVEL 2), which requires to establish the limit state function and hence the mathematical expresssion of the probability of the physically relevant failure in the fire situation. This limit state function shall be given by a continous algebraic function and the corresponding probability of failure determined by a software able to deal with a set of variable given by different statistical distribution (Schneider, 1997).

Safety Index Concept

The reliability analysis is based on First Order Reliability Method FORM (Ranganathan, 1999). Performance function is a function of random variables X_i which is given as:

$$g(x) = g(X_i) = R - S \quad (1)$$

R and S are the resistance and load effect respectively.

Where X_i represent basic variables. The performance function can be expressed as

$g(x) = 0$ Represents limit state surface, (2)

$g(x) > 0$Represents state of safety,

Whereas,

$g(x) < 0$ Represent an unsafe domain.

The solution of performance function gives the required ReliabilityIndex, β. While the degree of violation of state function is expressed by the probability of failure as:

$$P_f = P_r(g(X) < 0) \quad (3)$$

The probability of failure in an equation is a function of reliability index given as:

$$P_f \approx \emptyset(-\beta) \quad (4)$$

Where $\emptyset(.)$is the standard normal integral andβ is the reliability index.

Reliability R is

$$R = 1 - P_f \quad (5)$$

Reliability Analysis

In the reliability analysis, a structure is said to be unsafe if the load effect is greater than the resistance and vice versa. In the analysis of reinforced concrete beam exposed to fire, limit state functions are developed for the R.C Beam at normal state and while exposed to fire as given in equation 2.1- for different failure modes. And all basic variables are described by a type of probability distribution and parameters. The variables are presented in table 1.

The limit state equation for the performance function for bending is given by:

$$g(x) = 0.167 \times f_{ck} \times b \times d^2 - 0.1875 \times Q_k \times (0.9\alpha + 1) \times l^2 (6)$$

The limit state equation for the performance function for shear is given by;

$$g(x) = ((0.17 - 0.00068 \times f_{ck}) \times b_w \times d) - 0.75 \times Q_k \times (0.9\alpha + 1) \times l \quad (7)$$

The limit state equation for the performance function for deflection is given by:

$$g(x) = \left(\frac{10^4}{f_{yk}}\right)\beta - \frac{l}{d} \quad (8)$$

The limit state equation for the performance function for bending exposed to fire is given by:

$$g(x) = Q_k l^2 \left[0.216\theta(0.9\alpha + 1)\left(\frac{A_{s,prov}}{A_{s,req}}\right) - 0.1875(0.9\alpha + 1)\right] \quad (9)$$

The limit state equation for the performance function for shear exposed to fire is given by:

$$g(x) = ((0.25 - 0.001 \times f_{ck}) \times b_w \times d) - 0.75 \times Q_k \times (0.9\alpha + 1) \times l \quad (10)$$

The limit state equation for the performance function for deflection exposed to fire is given by:

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$$g(x) = \left(\left(\frac{10^3}{f_{yk}}\right)\beta + l\right) - \frac{l}{d} \qquad (11)$$

Where;

f_{ck} is the characteristics strength of concrete.

f_{yk} is the characteristics strength of steel.

$\alpha = \frac{G_k}{Q_k}$ dead-live load ratio

Q_k is live load

Table 1. Probabilistic models of basic variables

S/No.	Physical meaning	Type	No. code	Mean	COV	Std dev.
1	Steel strength, f_y	Log-normal	3	500N/mm²	0.10	50.0N/mm²
2	Depth of section, d	Log-normal	3	450mm	0.09	40.5mm
3	Breadth of section, b	Log-Normal	3	230mm	0.06	13.8mm
4	Span, L	Normal	2	3230mm	0.02	64.6mm
5	Imposed load, Q_k	Gumbel	7	2.5N/mm²	0.12	0.3N/mm²
6	Temperature	Gumbel	7	115°C	0.12	13.8 °C
7	Concrete strength, f_{cu}	Log-normal	3	25N/mm²	0.10	2.5N/mm²

Method of analysis

FORM5 a structural engineering package that was written on the principle of First Order Reliability Method (FORM) is used to compute the reliability index.

ANALYSIS OF RESULTS

The reliability analysis of the reinforced concrete beam is carried out for different load ratio and reinforcement ratio. The probabilistic distribution of the random variables and the deterministic values given in Table 1 are used.

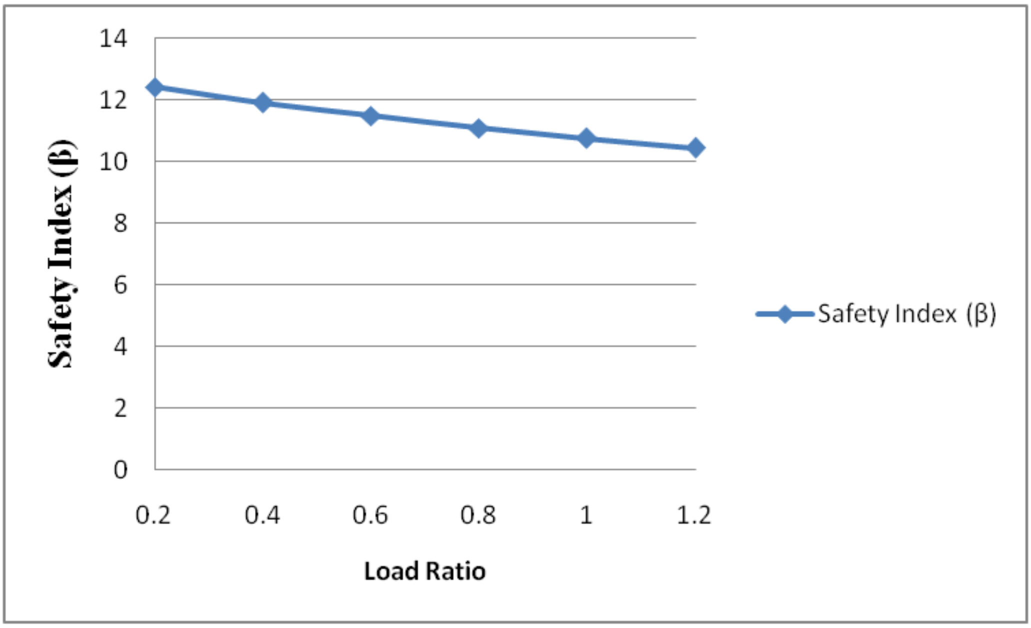

Figure 2: Safety index (β) against Load ratio for reinforced concrete beam in bending.

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The implied safety indices for bending at normal condition in accordance to the provision of Eurocode 2 ranges from 12.402 to 10.422 with corresponding dead-live load ratio of 0.2 to 1.2 as depicted in figure 2 above. This result shows that the simply supported reinforced concrete beam is safe in bending as compared for the range of 3.1 to 4.2 for structures with minor consequences of failure for ultimate limit state as recommended by the JCSS, 2001

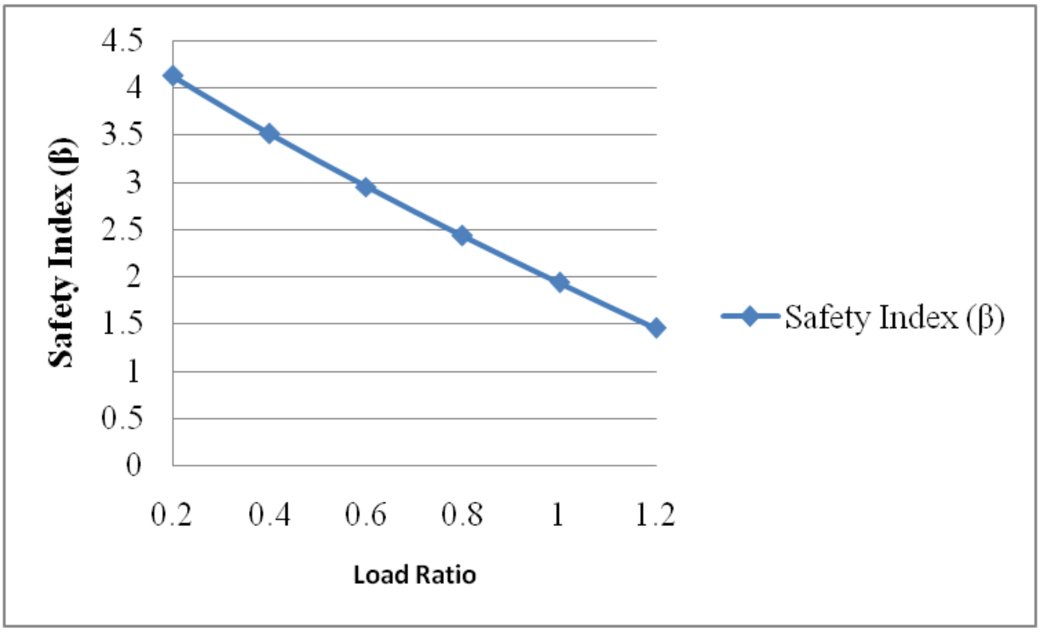

Figure 3: Safety index (β) against Load ratio for reinforced concrete beam in shear.

The implied safety indices for shear at normal condition in accordance to the provision of Eurocode 2 ranges from 4.126 to 1.450 with corresponding dead-live load ratio of 0.2 to 1.2 as depicted in figure 3 above. This result shows that the simply supported reinforced concrete beam is safe in shear for load ratio not greater than 0.3 as compared for the range of 3.1 to 4.2 for structures with minor consequences of failure for ultimate limit state as recommended by the JCSS, 2001

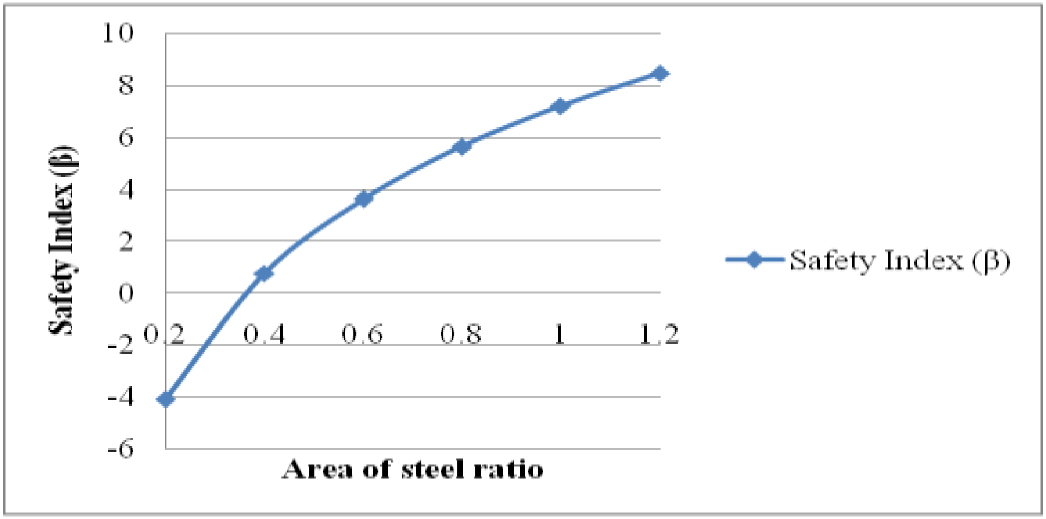

Figure 4: Safety index (β) against Area of steel ratio for reinforced concrete beam in deflection.

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The implied safety indices for deflection at normal condition in accordance to the provision of Eurocode 2 ranges from -4.103 to 8.474 with corresponding dead-live Area of steel ratio of 0.2 to 1.2 as depicted in figure 4 above. This result shows that the simply supported reinforced concrete beam is safe in deflection as compared for the range of 3.1 to 4.2 for structures with minor consequences of failure for ultimate limit state as recommended by the JCSS, 2001

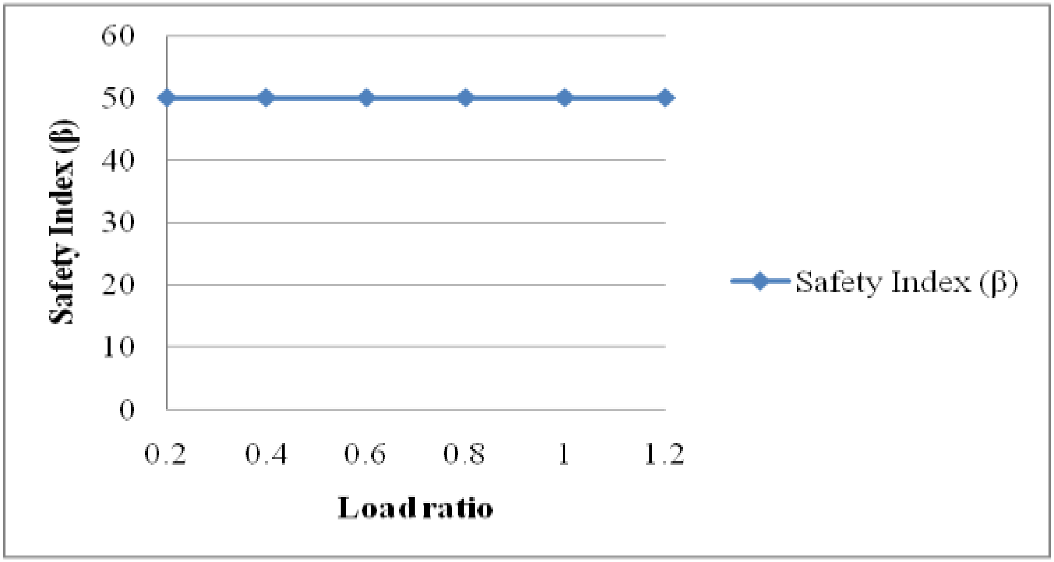

Figure 5: Safety index (β) against Load ratio for reinforced concrete beam exposed to fire in bending.

The implied safety indices for bending when exposed to fire in accordance to the provision of Eurocode 2 remain constant at 49.997 with corresponding dead-live load ratio of 0.2 to 1.2 as depicted in figure 5 above. This result shows that the simply supported reinforced concrete beam is obviously safe in bending as compared for the range of 3.1 to 4.2 for structures with minor consequences of failure for ultimate limit state as recommended by the JCSS, 2001

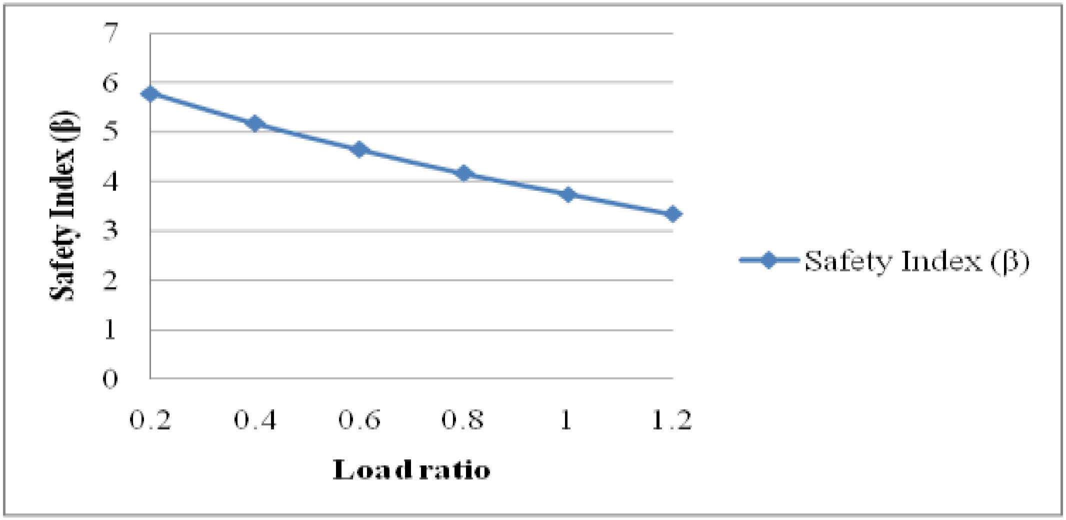

Figure 6: Safety index (β) against Load ratio for reinforced concrete beam exposed to fire in shear.

The implied safety indices for shear when exposed to fire in accordance to the provision of Eurocode 2 ranges from 5.774 to 3.333 with corresponding dead-live load ratio of 0.2 to 1.2 as depicted in figure 6 above. This result shows that the simply supported reinforced concrete beam is safe in shear as compared for the range of 3.1 to 4.2 for structures with minor consequences of failure for ultimate limit state as recommended by the JCSS, 2001

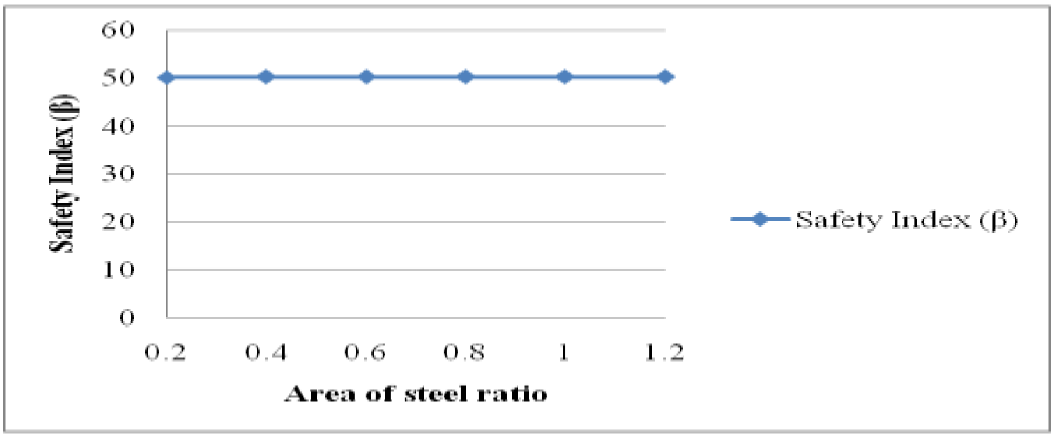

Figure 7: Safety index (β) against Area of Steel ratio for reinforced concrete beam exposed to fire in deflection.

The implied safety indices for deflection when exposed to fire in accordance to the provision of Eurocode 2 ranges from 50.162 to 50.192 with corresponding dead-live Area of steel ratio of 0.2 to 1.2 as depicted in figure 7 above. This result shows that the simply supported reinforced concrete beam is safe in deflection as compared for the range of 3.1 to 4.2 for structures with minor consequences of failure for ultimate limit state as recommended by the JCSS, 2001

Sensitivity of the reliability index

The sensitivity of the reliability index of reinforced concrete beam based on Eurocode 2 for the following parameters is studied.

1. Characteristics strength of concrete, f_{ck}
2. Characteristics strength of steel, f_{yk}
3. Breadth of the cross-section, b
4. Depth of the cross-section, d
5. Span of the section, L

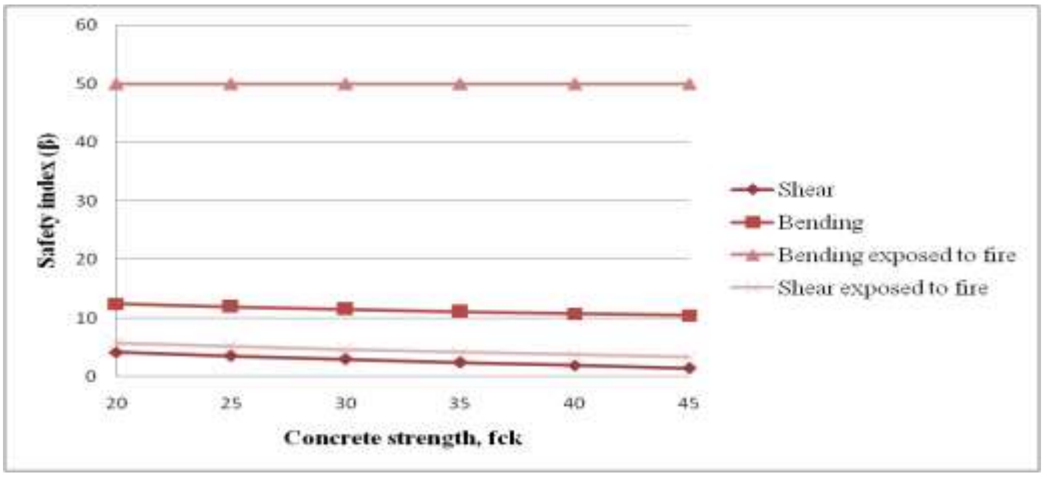

Figure 8: Safety index (β) against Concrete strength, f_{ck}

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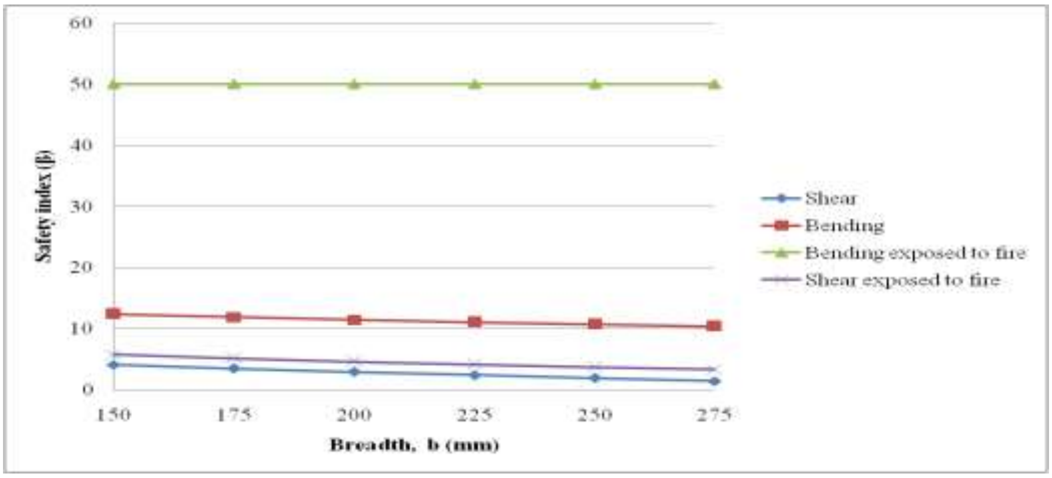

Figure 9: Safety index (β) against Breadth, b (mm)

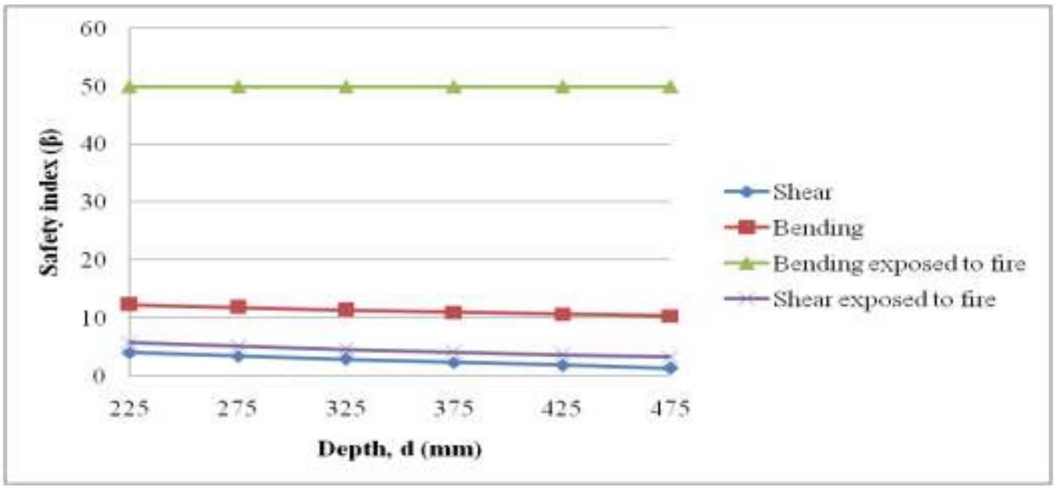

Figure 10: Safety index (β) against Depth, d (mm)

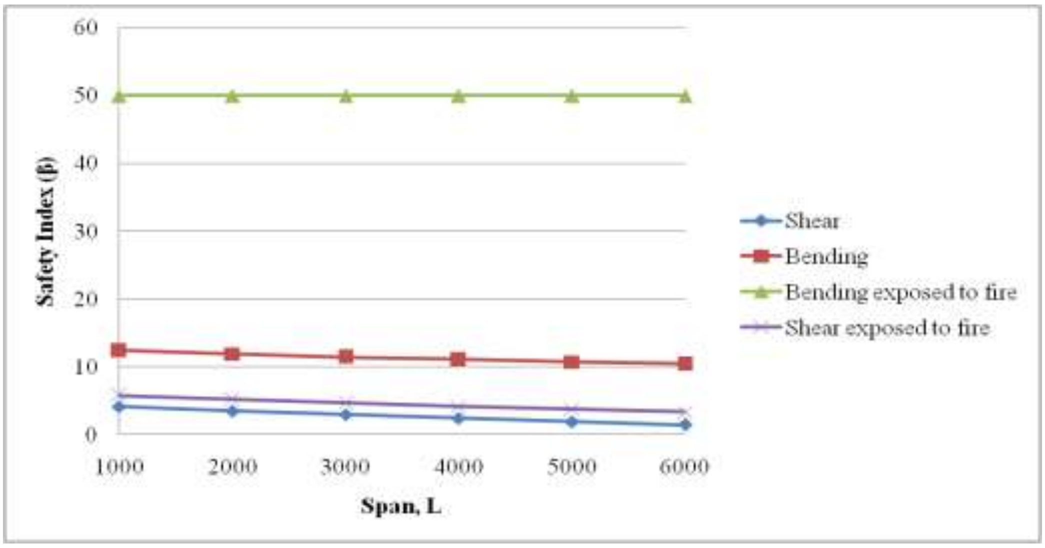

Figure 11: Safety index (β) against Span, L (mm)

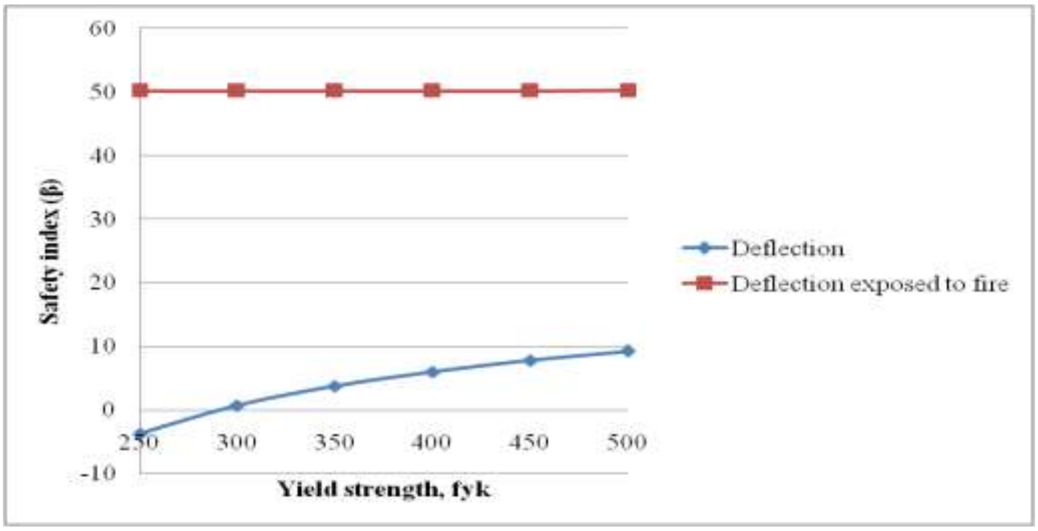

Figure 12: Safety index (β) against Yield Strength, f_{yk}

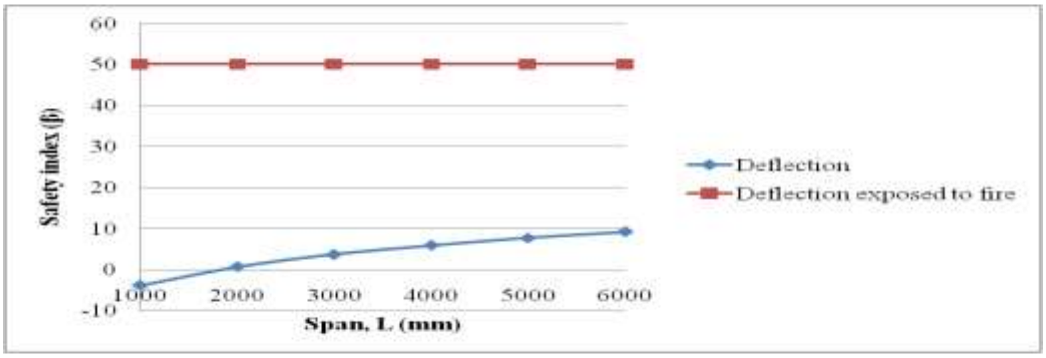

Figure 13: Safety index (β) against Span, L (mm)

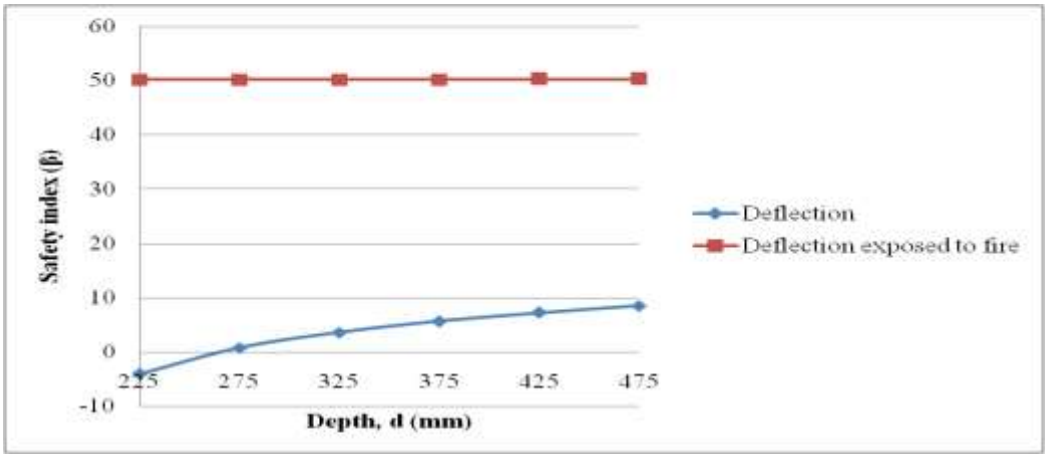

Figure 14: Safety index (β) against Depth, d (mm)

The sensitivity analysis of the parameters considered shows that the safety indices remains constant for different variation of the parameters as depicted in the above figures. Thus, this shows that the reliability analysis carried out is valid for reinforced concrete beam at normal condition and when exposed to fire for different variation of parameters considered.

Conclusion

Reliability analysis of reinforced concrete beam exposed to fire based on Eurocode 2 (2004) considering both ultimate and serviceability limit states were investigated using FORM. The following conclusions are drawn from the observations:

1. The Reinforced concrete beam is designed using deterministic criteria for both ultimate and serviceability limit state.
2. The results of the investigation show how modeling of fire using Eurocode 2 (2004) design procedure of the Reinforced concrete beams are consistent to checks carried out for the reliability analysis of the Reinforced concrete beam when exposed to fire.
3. Generally, it can be deduced from the reliability analysis result that, if all design criteria and considerations as provided in Eurocode 2 (2004) are strictly adhered to, the Reinforced concrete beam would resist failure for the time considered (that is R120). Thus, the structural element is safe.
4. The sensitivity analysis results also show that the Reinforced concrete beam is safe and reliable due to the nature of the graph.
5. The comparison used, is in reference with the recommendation of safety indices that range from 3.1 to 4.7 for minor to large consequences of failure for ultimate limit state given by JCSS, 2001. Thus, due to high value of reliability indices obtained compare to the targeted value, it signifies that the structural element has a low probability to fail.

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