Determination of structural reliability of a reinforced concrete slab under fire Load

Nizamani Zafarullah[1*], *Ameir* Eltigani[1], *Akihiko* Nakayama[1], and *Haider Syed* Muhammad Bilal[1]

[1]Environmental Engineering Department, Faculty of Engineering & Green Technology, Universiti Tunku Abdul Rahman, Kampar P.C. 31900, Perak, Malaysia.

Abstract. Four reinforced concrete rooms are used in this study, with varying floor areas, openings, and fuel loads. These rooms are office, Classroom, computer, and chemical laboratories of institutional buildings. The time versus Eurocode (EC) parametric fire relationship is determined and compared with ISO 834 and ASTM 119. The performance of the slab is evaluated based on the EC target reliability index of 3.8 for 50 years design period using the First Order Reliability Method (FORM). The probability of failure and structural reliability of each fire compartment at different fire duration is determined. Variables used were concrete compressive strength, a reduction factor of concrete compressive strength, steel yield strength, concrete cover, slab depth, unit width, and area of steel reinforcement provided. The reliability is determined at each 30 minutes fire duration for all fire compartments. The starting point is ambient temperature, then after every thirty minutes until the time when the maximum gas temperature is reached. The fire compartments were able to show fire resistance for two hours and then started to drop over time. Yield strength reduction factor, concrete cover, and area of reinforcement respectively were the most significant variables to determine the reliability index. The structure was able to withhold fire until two hours with a reliability of more than 3.8after that, the slab reliability was less than the target reliability and will need a repair.

1 Introduction

Annually, structural fire causes fatalities and loss of properties. During a fire situation, the worst thing that can happen to the structure is to become endangered, to the extent of becoming unserviceable. This building member condition will undermine the safety of the occupants and firefighters. They will be at extreme risk, especially in high-rise structures and hence the proper selection of material. Consideration of fire load and design is significant to avoid any untoward incident.

Concrete is a good choice of building material due to its structural resistance and economy. Still under fire concrete cover can spall based on the duration of exposure and the

* Corresponding author: zafarullah@utar.edu.my

fire temperature. In reinforced concrete, the cover provides a defence to the reinforcement, until either fire load is no more, or the cover has spalled. Furthermore, concrete structures are typically resilient, allowing them to tolerate localized damage without compromising the ultimate structural strength. However, the literature with actual fires indicates that a detailed comprehension of concrete behaviour and structural mechanics is still required to be studied to enhance fire resistance [1].

Fire has four stages starting from the fire initiation phase, the growth phase, the completely developed fire phase, and finally the decay phase. There are several factors that determine the fire spread over the combustible materials such as environmental factors include oxygen concentration, humidity, air velocity, imposed radiant heat flux, and temperature [2]. The material factors are divided into chemical factors such as the presence of retardants and composition of the fuel, and physical factors such as the surface orientation, initial temperature, thickness, thermal conductivity, the direction of propagation, geometry, and continuity [2].

For the fire to ignite three elements should exist and react together, i.e., fuel, heat or ignition supply, and oxygen where the amount of oxygen and fuel supply determine the duration and nature, or severity of the fire as shown in Fig.1. If anyone element is not present, then the fire will not start. The kinds of fuel sources include combustible materials, for example, paper, clothing, wood, trash, flammable liquids, and gas. Fires can happen even with far less oxygen that is required for human respiration, with the kind of fuel present [2].

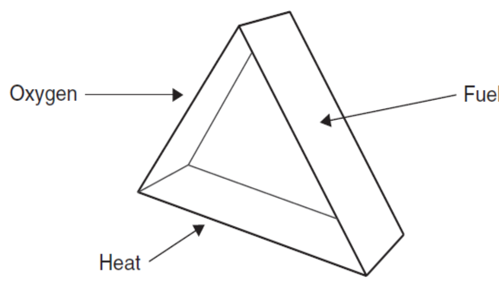

Fig. 1. Fire triangle with three main ingredients of fire [2].

The classical fire triangle does not truly exhibit the chemical reactions involved and it is too simple, so another factor needed to be considered and this factor is the reaction chain wherein the fire growth phase burning continues and accelerates as well, this is called the tetrahedron concept of fire shown in Fig. 2. The reaction chain is there due to the breakdown and recombination of the combustible material molecules such as cellulosic molecules with the atmospheric oxygen. When these combustible molecules get in contact with a heat source they start to vibrate with an increasing level of vibration. Then instantaneously starts to break apart in a series of chemical reactions producing hydrogen and carbon that will eventually combine with the atmospheric oxygen. As a result, more energy will be produced, and more cellulosic materials will break down until no fuel remains to support this chain reaction anymore.

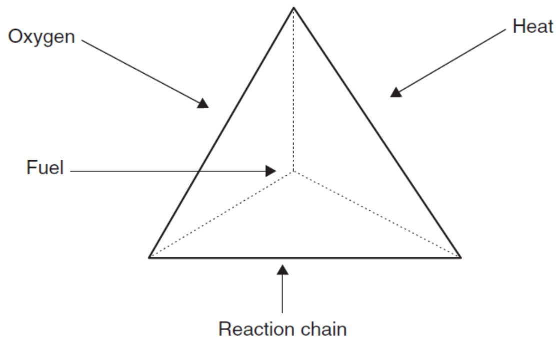

Fig. 2. The tetrahedron concept of fire ignition and materials required to start a fire [2].

Prescriptive based design codes produce inconsistent levels of structures of fire safety. They fail to represent the performance of a structure subjected to a fire scenario because it only assumes that input equals output without considering any uncertainties. This can lead to an output different from the input and hence the incorrect reliability of the structure can be assumed.

Prescriptive design codes only exhibit the building procedure description without providing any information regarding the fire safety of the structure especially if the structure is densely occupied such as an institutional building or a hospital. Here fire safety information that shows how long the structure can withstand fire before collapsing is very important. This makes this study necessary to carry out a reliability assessment and be able to provide information on the structural fire performance in the real-life fire scenario. Therefore, structural fire performance needs to be considered and prioritized [3].

The First Order Reliability Method (FORM) is used here for determining the reliability of the structure. This study is conducted with the aim of finding the critical time when reinforced concrete slab will not be able to take the design load. The study also highlights the variation of reliability with respect to the time under fire.

2 Building thermal analysis

Fire engineering is an application of engineering and scientific principles, rules, codes [4-9], and judgement. According to fire engineering structural fire design, six different classes of fire can be classified as shown in Table 1.

Table 1. Fire Classification.

Fire class	**Description**
Class A	Fire due to solid materials (paper, textiles, and wood)
Class B	Fire due to flammable liquids (diesel, oils, and petrol)
Class C	Fire due to gases
Class D	Fire due to metals
Class E	Fire due to live electrical apparatus
Class F	Fire due to cooking oils

When a building or its components are under a sustained fire load, the resistance is measured to determine the ability of the building components to resist fire. It is the resistance of the building component or assembly to endure exposure to fire without reduction in load-bearing capacity. The determination of fire resistance involves the time for which the element is required to meet certain criteria during fire exposure. The standard criteria are:

i. Stability: resist structural failure.
ii. Integrity: resist flame dispersion.
iii. Insulation: resist high temperature on the unexposed side.

EC 1-2 has recommended Eq (1) to determine the fire compartment opening factor and the thermal absorptivity (*b*) is defined by Eq. (2). These parameters have a significant role to determine the time-temperature curves [6].

$$O = \frac{A_v\sqrt{H_v}}{A_t} \tag{1}$$

$$b = \sqrt{\lambda \rho \, cp} \tag{2}$$

Where ρ is density, λ is thermal conductivity, *cp* is heat capacity. The variables used in Eq. 1 are defined in Table 2, which shows the fire compartment thermal absorption, opening factor, and average height of openings.

Table 2. Building's boundaries thermal properties [9].

Normal Weight Concrete Thermal Properties	Values
Thermal conductivity, λ (W/mK)	2
Density, ρ (kg/m^3)	2300
Heat Capacity, c_p (J/kg^{0}K)	900
Thermal Inertia, b (J/m^{2}s$^{1/2}$K)	2034.7

Table 3 shows the dimensions of four fire compartments and the thermal absorptivity which is the same because all rooms are built from concrete.

Table 3. Fire compartments dimensions and the corresponding thermal absorptivity.

Fire compartment	Total enclosure area A_t (m^2)	Average height of vertical openings, H_v (m)	Total area vertical openings A_v (m^2)	Compartment opening factor (m$^{1/2}$)	Thermal absorptivity of the total enclosure (*b*) [J/ m^2/ s^1/2/k]
Classroom	670.5	2.0	32.2	0.07	2034.7
Office	190.9	2.1	7.2	0.06	2034.7
Chemical lab	737.9	1.9	37.9	0.07	2034.7
Computer lab	340.5	1.9	23.5	0.1	2034.7

3 Time Temperature curve

Uncertain parameters i.e., the reinforcement yield stress (f_{yk}) and the corresponding reduction factor, concrete compressive strength (f_{ck}), depth of the slab, the slab concrete cover (c), and the area of tensile steel (A_{st}). All these variables directly affect the result of the probability of failure evaluation. Eq. 3 shows the ISO ideal time-temperature curve this can be compared with actual compartment time-temperature curves [10].

$$T = 345\, log_{10}(8t + 1) + 20 \quad (3)$$

Fig. 3 shows the time-temperature curve for the four different compartments and using the ISO 834 and ASTM E119 [11]. In the initial phase within the first six minutes, the temperature increases rapidly and reaches up to 600 degrees. After few minutes the behaviour shows that both curves become nonlinear after the initial phase. ASTM shows an increase after five hours whereas the ISO curve shows less increase with time after the first 30 minutes.

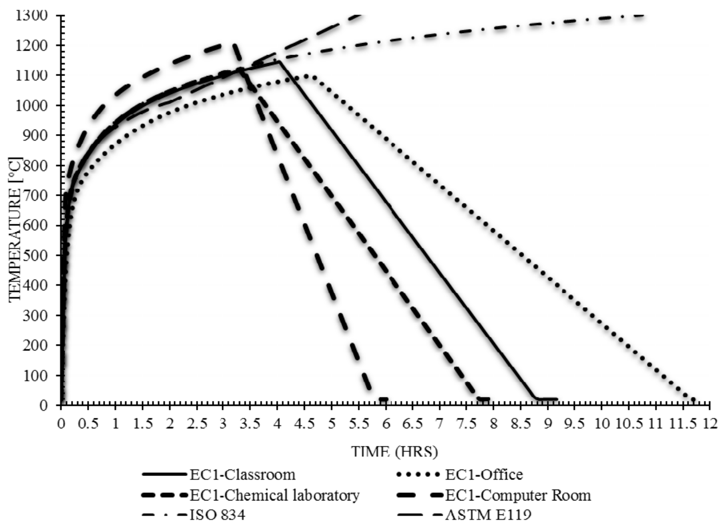

Fig. 3. The time temperature curve for four different rooms, ISO 834 and ASTM E119

4 Structural reliability of fire compartments

The reliability index is evaluated for the reinforced concrete slabs using the First Order Reliability Method. The load and resistance uncertainty variables used in this study were fire, imposed, and permanent loads. Corresponding design moment and resisting moment were determined accordingly.

4.1 Load uncertainty

Effect of load on construction highly differs in space and time during its life service. There are two categories of action that act on a structure which are thermal action and mechanical action. While for mechanical action, there are imposed load (Q), dead load (G), wind load (W). Fire load is an example of thermal action on the structure, and it is evaluated using temperature analysis. Fire load (Q) is the collective amount of heat emitted by the combustion of contents present in the building compartment. Fire load varies throughout the building's design life because of the fire stochasticity event as well as the response of active firefighting measures throughout the real event.

According to EC 1-2, the fire load density, q_f Eq. (4) is the summation of the material mass, combustion factor, fire load factor, and the net calorific value of the material over the floor area (A_f).

$$q_f = \frac{1}{A_f} \sum_i (\Psi_i \, m_i \, H_{ui} \, M_i) \tag{4}$$

Where, Ψ_i= material fire load factor, m_i= material combustion Factor, H_{ui}= net calorific value, Mi= material mass

4.2 Concrete compressive strength (f_{ck})

Concrete compressive strength has a significant role to play in the structural resistance during the fire. For the new structure, the strength should be analysed to determine whether the concrete mix meets the requirement of specified strength or not. As the temperature increases, the exposed concrete compressive strength reduces, and EC2-1 has recommended a reduction factor shown by Eq. (5) [8]. The k factor is used to find the reduced strength of concrete from ambient temperature i.e., 20 to 1200 degrees Celsius.

$$k_{fc,T} = \frac{f_{ck,T}}{f_{ck,20^0C}} \tag{5}$$

The concrete cover is the minimum distance between a surface of fixed reinforcement and the outer surface of the concrete. Commonly, failure of an inappropriate amount of concrete cover can cause cracks and spalls.

4.3 Yield strength of the reinforcement (f_{yk})

EC 1-2 provides guidelines for the reinforcement yield strength at ambient temperature such as yield and tensile strength and elastic modulus. As the temperature increase, the reinforcement yield strength reduces by a factor shown in Eq. (6) [6].

$$k_{fy,T} = \frac{f_{yk,T}}{f_{yk,20^0C}} \tag{6}$$

4.4 Moment of resistance

For the safety of the structure, the limit state equation for the moment is given by Eurocode 2, the resisting moment should be greater than the design moment to maintain integrity as shown in Eq. (7). The combinations of the M_G and M_Q will give the maximum bending moment at the structure.

$$M_{Ed} < M_{Rd} \tag{7}$$

The load ratio, χ in Eq.(8) is the load effect induced by the variable load Q_k with respect to permanent and variable load combination [3].

$$\chi = \frac{Q_k}{Q_k + G_k} \tag{8}$$

4.5 Ultimate limit state

An ultimate limit state is a state that concerns the safety of both the residents and the structure. Structural collapse due to mechanical or thermal action on the reinforced Concrete Slab occurs when this external load exceeds the allowable resistance of the structure and as a result, several types of structural failures may arise, such as failure due to excessive deformation, loss of stability, loss of equilibrium, and failure caused by time-dependent effects. In this research, the ultimate limit state of the slab strength Eq. (9) is used to obtain the slab reliability index.

When the external load causes a bending moment that is greater than the bending moment capacity or resistance of the slab a possible failure might occur. The slab design moment generated by design loads can be computed using Eq. (7) of concrete slabs subjected to self-weight and imposed load [3].

$$M_R = \mathrm{A_{sb}}\ \mathrm{k_{fy,res}}\ \mathrm{f_{y,20}}(\mathrm{h} - \ \mathrm{a_b} - \frac{\mathrm{A_{sb}}\ \mathrm{k_{fy,res}}\ \mathrm{f_{y,20}}}{2\ \mathrm{f_{c,20}}\ \mathrm{b}} \tag{9}$$

4.6 Limit state equation

Many researchers have worked on the fire impacts on the reinforced concreted members specially the slabs [12-15]. The primary purpose of using the limit state equation is that it inhibits the effect of load (L) from exceeding the effect of resistance (R) that can lead to structural failure. The random variables L and R are dependent on variable X and the failure occurs when G <0. Thus, when the load is more than the resistance of the system. To determine the reliability, the limit state equation can be computed using Eq. (10) [2 &7].

$$\mathrm{G(X)} = \mathrm{R(X)} - \mathrm{L(X)} \tag{10}$$

The ultimate limit state for the slab strength that is undergoing bending will have a slab limit state equation, Z as shown in Eq (11).

.

$$Z = M_{R,span} - M_{E,span} \tag{11}$$

Where, $M_{R,fi,tE}$ = Bending moment capacity during the fire, M_E = Bending moment due to load effect and represented by L and R, respectively. Table 4 shows the design of the classroom fire compartment RC slab and the main parameters shown in the Table 4 were physically measured at UTAR, Kampar.

Table 4. Design properties of the Classroom RC Slab.

Long Span Length, *Ly*	= 8941 mm	**Imposed** load	= 3 $\frac{KN}{m^2}$
Short Span Length, *Lx*	= 3000 mm	Slab Thickness, t.	= 175 mm
Factor for structural system, *K*	= 1.3	Slab effective depth, d	= 135mm
Basic span effective depth ratio	= 26	Concrete compressive strength, f_{ck}	= 30 MPa
Minimum thickness for REI 90	= 120mm	Reinforcement yield stress, f_{yk}	= 500 MPa
Concrete cover, *c*	= 35 mm	Ultimate design load, n	= 11.13 $\frac{KN}{m^2}$
Unit weight concrete	= 23 KN/m^3	For 1 m run	= 32.45 $\frac{KN}{m}$
Reinforcement steel bar diameter	= 10mm	Slab Type, Ly/Lx.	= 2.98, One-way slab
Permanent load	= 4.9 $\frac{KN}{m^2}$	Design Moment, Md = 0.075nlx	0.63(11.1285) (3) =2.4KN.m

Fig. 4 shows the reliability index for the chemical laboratory used here as a fire compartment the straight blue line shows the target reliability as indicated by the Eurocode i.e., 3.8, and the yellow line indicates the reliability was 10 at the ambient temperature but it decreased with the increase of temperature. This shows that the reliability is more than the target reliability and the structure is safe. The RC slab was safe just before 2 hours of fire but after, that the reliability decreased below the target reliability, and it failed at 3.5 hours of the fire. This indicates that the structure could only sustain a fire for up to about two hours of the fire. This should be considered in the safety of the structure and further firefighting measures should be provided to enhance the structural integrity such as the sprinkler system. Yield strength reduction factor, concrete cover, and area of reinforcement respectively were the most significant variables have direct effect on the change of the reliability index.

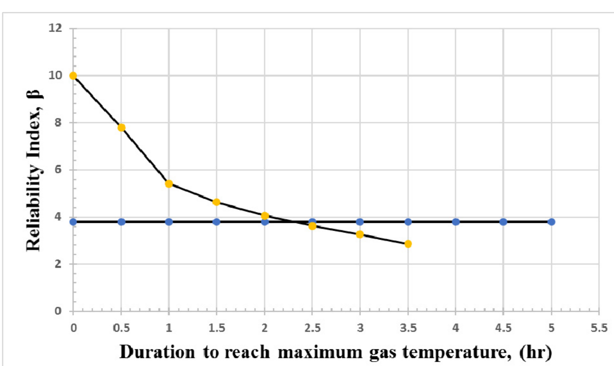

Fig. 4. Chemical laboratory end slab reliability index versus the duration to reach maximum gas temperature**.**

5 Conclusion

The classroom reached a maximum gas temperature of 1145.3 °C after four hours of fire duration. The office reached a maximum gas temperature of approximately 1100.6 °C after four hours and a half, the chemical laboratory reached a maximum gas temperature of 1119.1 °C after three hours of fire duration, and lastly, the computer room made a maximum gas temperature of 1198.1 °C after three hours fire duration.

All the four fire compartments end slabs made two hours of fire resistance, the office showed a reliability index value of 3.9 at three hours and a half and then the structural performance started to drop. The reinforced concrete slab failed to match the target reliability index for a design period of fifty years for institutional buildings as suggested by the Eurocode, thus the structural element is considered unsafe below the recommended target reliability index. After one hour of fire duration the computer room reliability index decreased below the target reliability index, β at ambient temperature, the fire rooms reinforced concrete one-way slab reliability index, β varies between 8.2 and 10.0. The variables that showed the most significant effect on the moment of resistance are the reduction factor of steel yield strength, the slab cover and last is the area of reinforcement.

References

1. L. Taerwe, Fib Bulletins: *Fire design of concrete structures—Structural behavior and assessment*. International Federation for Structural Concrete (fib) (2008)
2. A. Hasofer, V. R. Beck, I. D. Bennetts, *Risk Analysis in Building Fire Safety Engineering*, Routledge (2006)
3. T. Molkens, R. Van Coile, T. Gernay, *Assessment of damage and residual load bearing capacity of a concrete slab after fire: Applied reliability-based methodology*. Engineering Structures, **150**, 969–985 (2017)
4. Eurocode, *Basis of structural design*. European Committee for Standardization; Brussels, Belgium (2002)
5. Eurocode, *Actions on structures–Part 1-1: General actions–Densities, self-weight, imposed loads for buildings*, European Committee for Standardization; Brussels, Belgium (2002)
6. Eurocode, *Actions on structures – Part 1-2: General actions – Actions on structures exposed to fire*. European Committee for Standardization; Brussels, Belgium (2002)
7. Eurocode, *Design of concrete structures – Part 1-1: General rules and rules for buildings*. European Committee for Standardization; Brussels, Belgium (2004)
8. Eurocode, *Design of concrete structures—part 1–2: General rules—Structural fire design*. European Committee for Standardization; Brussels, Belgium (2004)
9. Ulf Wickström, *Temperature Calculation in Fire Safety Engineering*, Springer International Publishing Switzerland (2016)
10. International Organization of Standardization, *ISO 834* (2014)
11. ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials* (2021)
12. C. Lisa, R. Selvarajah, Z. Chao, C. Charles, *Behavior of Composite Floor Assemblies Subject to Fire: Influence of Slab Reinforcement*. The 9th Eurosteel Conference, University of Sheffield, 1-3 September 2021 (2021)

13. W. Yong, J. Yaqiang, H. Zhaohui, L. Lingzhi, H. Yuner, Z. Yajun, Z. Gengyuan, Z. Xiaoyue, D. Yakun, *Post-fire behaviour of continuous reinforced concrete slabs under different fire conditions*. Engineering Structures, **226** (2021)
14. J. Balša, L. Andrea, R. Coile, M. Bart, C. Robby, R. Edwin, L. Geert, *Effects of the fire decay phase on the bending capacity of a fire-exposed reinforced concrete slab.* ASFE'21, Proceedings. In Applications of Structural Fire Engineering pp. 336-341 (2021)
15. R. Suwondo, L. Cunningham, M. Gillie, M. Suangga, I. Hidayat, *Model Parameter Sensitivity for Structural Analysis of Composite Slab Structures in Fire*. International Journal of Technology. **12**, 2, pp. 339-348 (2021)
16. F. Mariam, M. Ghazy, A. Elaty, M. Z. Nagat, *Prediction of temperature distribution and fire resistance of RC slab using artificial neural networks*. International Journal of Structural Engineering, **11**, 1 (2020)