SAFETY OF PREMATURE LOADING ON REINFORCED CONCRETE SLABS

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ABSTRACT
The provision of safe structural systems has always been the object of any structural design formulation and practice. This paper investigates the safety of premature loading on reinforced concrete slabs in a more rational manner. The slab was designed to BS8110 (1985; 1997) provisions. The moment of resistance of a prematurely loaded slab was simulated and safety indices corresponding to the probability of failure of the slab were determined. From results obtained, it was observed that a reinforced concrete slab may be safely loaded prematurely if it has attained at least two-thirds of its characteristic strength. The reliability indices of a prematurely loaded reinforced concrete slab in flexure are directly proportional to the characteristic strength of concrete. Therefore in practice, due consideration must be given to early-age strength development in reinforced concrete slabs before loading.

Key words: reinforced concrete slabs, flexure and safety.

1.0 INTRODUCTION

Concrete, when subjected to loading is good in compression, but poor in tension; while steel is good in tension under the same condition and poor in compression [1]. The concept of putting them together is referred to as reinforced concrete design, and the resulting structure is called reinforced concrete.

A reinforced concrete slab is a flat-plate like element which carries load by flexure. One vital feature of a slab is that its width is very much greater than its depth [2]. Slabs are usually designed by using the theory of bending and shear [3]. A slab may be loaded prematurely when it has not being allowed to develop its full characteristic strength at the normal 28 days period after casting and with adequate curing procedure following proper mixing and placing of the concrete. When loading is made on a slab prematurely, it will result in misbehavior in service [4] hence, it is necessary to investigate the effect of premature loading on reinforced concrete slabs in order to avoid such failures as wide cracks, de-bonding, other defects and consequently failure.

Premature loading of reinforced concrete members may not be deliberate as we find in the construction industry and site procedures [5]. It occurs most of the time in order to meet project time targets as individual structural elements is not allowed to fully develop their characteristic strength before being loaded. For example, a slab may be used to support the formwork for another floor or other structural elements, or it may be loaded with masonry blocks for walls before being laid.

This paper presents a mathematical modeling of the safety of premature loading of reinforced concrete slabs, or the value of the prediction of failure when a reinforced concrete slab is loaded before it is matured enough to sustain its design loads. Although there could be so many reasons for the failure of reinforced concrete slabs, the consideration herein is limited only to failures due to the flexural resistance of a concrete slab under applied loads of a maximum of its designed value in service. An example is given to illustrate this position.

2.0 REINFORCED CONCRETE SLABS UNDER LOADS

The basis for the analysis of reinforced concrete structures has been the theory of elasticity in many countries. It was developed and formed on the basis of Hooke's law [6]. This method with respect to the perfection it reaches is known as classical method. The classical method assumes that the material of which the structure is made, that is, the concrete and the reinforcing bar both obey Hooke's law, although the application of Hooke's law has limitations when considering concrete structures [7, 8, 9, 10]. The deviations from Hooke's law are undoubtedly apparent at high stresses as can be seen in the stress-strain relationships of reinforced concrete [1]. It cannot be said that this law is applicable to concrete since the stress-strain curve of concrete does not have similarity to the classical theory [11, 12].

This also applies to reinforcement. The steel stress-strain curve certainly satisfies the demands of ideally elastic material but up to the yield zone it satisfies the demand of an ideally plastic material [13, 14].

2.1 Stress-strain Relationship

The behavior of concrete as depicted in its stress-strain relationship is given in many manuals and textbooks, for example, BS8110 [8, 9] and EC2 [10]. It has a parabolic relationship where at a certain point, ε, on the strain axis, the strain increases while the stress remains constant. The strain, ε, is specified as a function of the characteristic strength of concrete f_{cu}. The ultimate design stress is given by BS8110 [8, 9] for example, as:

$$\frac{0.67 f_{cu}}{\gamma_m} = 0.45 f_{cu}$$

where γ_m = 1.5, that is, the partial safety factor for the strength of concrete when the designing members are cast-in-situ. The ultimate strain of 0.0035 is typical for all grades of concrete. The behavior of steel is the same in tension and compression, that is, it is linear in elastic range up to the design yield stress (f_y/γ_m); where f_y is the design yield stress, γ_m is a partial safety factor equal to 1.15 within the classical range [8, 9, 10].

2.2 Effect of Loading

Reinforced concrete slabs are usually subjected to vertical loading and as such are liable to bending [15]. Under loading conditions, the concrete takes care of the compressive forces at the top of the slab while the steel resist the tensile forces at the bottom [8, 9, 10].

Cracking occurs when there is tension, but it does not affect the safety of the slab provided that there is good reinforcement bond and the crack-width does not permit the exposure of the embedded steel to corrosion [16]. Sometimes when the compressive forces exceed the strength of the concrete, compression reinforcement is required to support the load carrying capacity of the concrete [13, 14, 17].

2.3 Effect of Premature Loading on Reinforced Concrete Slabs

When a reinforced concrete slab is loaded before it is mature enough to sustain loads, it may not reach its designed lifespan [5, 18]. Also, Mirza, et al [19] has noted that these slabs may consequently deteriorate and later on fail. However, there are different ways in which a concrete slab can fail; these may include: excessive deflection, development of tensile cracks, bond failure, and shear failure [5, 20, 21]. When a slab is loaded before it hardens enough to sustain loads, the concrete compressive strain at the column edge due to bending moment in the slab reaches critical values that are lower than the generally acceptable ultimate compressive strain of 0.0035 for slabs loaded in bending [18]. This type of failure is brittle and occurs without warning. Cracking and increased deflection occur. Punching at one column may lead to punching at adjacent columns and may also lead to total collapse of the structure. After punching, the slab loses its shear and bending capacity and consequently leads to total collapse. This could be as a result of de-bonding of the reinforcing bars from the concrete [18].

Also, when the slab is loaded prematurely, there could be improper bond between the cement, aggregates and the reinforcing steel since the reinforced concrete section has not been fully developed [20]. May and Lodi [22] have observed that improper or incomplete curing may have a detrimental effect on the overall strength of the concrete; and according to them, this is due to the fact that the reinforcing bars may not have fully bonded with the concrete. Bars subjected to forces induced by flexure must be anchored to develop their design stresses. The anchorage depends upon the bond between the bar and the concrete and area of contact [13, 14].

Hardening of concrete makes it reduce in volume. Such reduction is referred to as shrinkage. Shrinkage is liable to cause cracking. It is as a result of absorption and adsorption of water by the concrete and the aggregate [13, 14, 20]. Cracking occurs when the tensile stresses caused by shrinkage or thermal movement exceed the strength of the concrete [13, 14, 17]. Therefore, if the concrete is not hardened enough to sustain loads or is loaded prematurely, it will eventually crack [1, 5, 16].

Steel reinforcement is provided close to the concrete surface as specified by the codes of practices [8, 9, 10]. In order to control the crack-widths in the concrete the stress of the reinforcement and distance to the nearest bar should be reduced [8, 9, 10, 23].

2.4 Construction Load Distribution

The simplified method of calculating construction load distribution carried by slabs has been given by Pericles [24].

However, the rate of strength gain of concrete is connected to the curing of concrete. The flexural, tensile, shear and bond strength of early age slab is proportional to the concrete compressive strength at that age [20, 24]. Cracking and deflections are dependent on the early-age concrete tensile strength and modulus of elasticity, respectively. The load capacity of an early age slab is also determined by the total service load for which the slab has been designed [24]. Pericles [24] also noted that at an early age, the concrete should be susceptible to tensile cracking prematurely due to flexure. A concrete failure due to deficiency in tensile strength and low shear resistance is the most serious slab failure type, since it occurs without any warning [25]. It has been observed [24] that tensile cracks caused by excessive construction loading of an early age concrete can cause non-recoverable deflections.

Pericles [24] has opined that premature loading at an early age in combination with normal shrinkage and many other factors can cause higher creep deflections and more extensive cracking than anticipated and affect the long term serviceability of the structure. He continued that premature non-recoverable deflections and cracking are due to initial low concrete strength. Premature loading of concrete members having low modulus of elasticity and stiffness will cause larger non-recoverable deflections. Deflections are caused by low modulus of elasticity while cracking is caused by low modulus of rupture [24].

Creep deflections are as a result of premature loading before strengthening of slab [5, 18, 24, 26]. The extent of initial premature slab cracking depends on the magnitude of early age shrinkage, the magnitude of construction load and the age of concrete when the loads are applied and these may affect the shoring and re-shoring schedule [24]. These creep effects on the concrete depend on the magnitude of the stress resulting from the applied loads relative to the concrete strength [22]. Most of the early-age deflections are not recoverable [20]. For example, deflections due to creep and premature cracking caused by premature loading on the slab can be several times the normal elastic, creep and shrinkage deflections [20]. This is due to the incomplete development of the internal resisting capacities of the reinforced concrete member [8, 9, 10, 27].

It is in this regard that the effect of premature loading of concrete slabs in a probabilistic environment is investigated herein using the ultimate criteria so as to ascertain their behavior under a reliability environment and their practical safety criterion in bending when loaded during the construction process.

3.0 METHODOLOGY

Assume that R and S are random variables whose statistical distributions are known very precisely as a result of a very long series of measurements. *R* is a variable representing the variations in strength between nominally identical structures, whereas S represents the maximum load effects in successive T-yr periods.

Then, the probability that the structure will collapse during any reference period of duration T years is given by:

$$P_f = P(R - S \leq 0) = \int_{-\infty}^{\infty} F_R(x) f_s(x)\, dx$$

where, F_R is the probability distribution function of R and f_s the probability density function of S. Note that R and S are statistically independent and must necessarily have the same dimensions.

The reliability of the structure is the probability that it will survive when the load is applied, given by:

$$R = 1 - P_f = 1 - \int_{-\infty}^{\infty} F_R(x) f_s(x)\, dx$$

3.1 First Order Reliability Method

The First Order Reliability Method (FORM) has been designed to provide approximate solutions of probability integrals occurring in many fields especially structural reliability. These approximate computations are very useful since closed-form solutions do not exist for the integral in equation (2). One of the first problems to solve is to decide which variables (quantities of parameters) are of relevance to the given structure. This variable called 'basic variables' include geometric quantities, material strengths and external loads. They are designated:

$$X = X_1, \ldots, X_n \qquad (3)$$

and have a joint distribution function given as;

$$F_X(X) = P\left(\bigcap_{i=1}^{n} \{X_i \le x_i\}\right)$$

The state of the system is defined by the state function which is denoted by $g(x)$. {This is synonymous with (R - S) in equation (2). Thus, the following condition can be defined: $g(x) > 0$ corresponds to safe states; $g(x) = 0$ corresponds to limit state; $g(x) < 0$ corresponds to failure. Then the probability of failure is approximated to:

$$P_f = P(x \in F = P(g(x) \le 0) = \int_{g(x)\le 0} dF_x(x) \qquad (5)$$

where F is the failure domain.

3.1.1 Determination of the Reliability Index

For the estimation of the probability of failure, Level 2 methods are employed in this case, which involve approximate iterative calculation procedures. In this method, two important measures are used:

(a) Expectations: $\mu_i = E[X_i]$, i, (3) ..., n (6)

(b) Covariances:

$C_{ij} = COV[X_i, X_j]$, $i, j = 1, 2, \ldots, n$ (7)

The safety margin is the random variable $M = g(x)$ (also called the state function). Non-normal variables are transformed into independent standard normal variables, by locating the most likely failure point, β-point (called the reliability index), through an optimization procedure. This is also done by linearizing the limit state function in that point and by estimating the failure probability using the standard normal integral.

The reliability index, β, is then defined by

$$\beta = \frac{\mu_m}{\sigma_m} \qquad (8)$$

where μ_m = mean of moment, M and σ_m = standard deviation of moment, M. If R and S are uncorrelated (4) and with $M=R–S$, then,

$$\mu_m = \mu_R - \mu_S \qquad (9)$$

and

$$\sigma_m^2 = \sigma_R^2 + \sigma_S^2 \qquad (10)$$

Therefore,

$$\beta = \frac{\mu_R - \mu_S}{\left(\sigma_R^2 + \sigma_S^2\right)^{1/2}} \qquad (1$$

4.0 DESIGN AND ESTIMATES

The behavior of a prematurely loaded reinforced concrete slab can be modeled by applying the full loads on it while reducing the characteristic strength of the concrete, since the reinforced concrete section could not have attained the full strength at the time of application of the full design loads. However, when the slab is not fully loaded, for example, when it is subjected to dead loads only or its own weight (which may be during shoring, re-shoring or removal of formwork), the safety of the slab in flexure is much higher as the applied bending moment may just be resisted by the instantaneous moment of resistance at the time of loading. An example is given below to illustrate the practical design procedure of a slab and the intrinsic safety achieved thereby, using the First Order Reliability Method (FORM) as packaged in FORM5 by Gollwitzer, et al [28]. The characteristic strength of the concrete is then subsequently reduced at intervals of 5N/mm² in order to obtain the implied safety and probability of failure. Results obtained are as shown in Figure 1. The implied safety of the formulations for the design of singly reinforced concrete slabs in BS8110 [8,9] and EC2 [10] is also indicated in Figure 1. Thus, Figure 1 gives a comparison of the compatibility of the safety of prematurely loaded slabs (an example is modeled herein) and the formulations in the codes [8,9,10]. It is clear from this figure that procedures for strength gain of concrete and its associated quality control in its production and placement in forms implied according to the formulations in EC2 [10] needs to be achieved on site so that concrete slabs can attain the predicted implications of their formulations in flexure. EC2 [10] predicts that the moment of resistance of a singly reinforced concrete slab is; $M_u = 0.167bd^2 f_{ck}$; where M_u and f_{ck} are the moment of resistance and the characteristic strength of the concrete respectively; which is higher than that formulated in BS8110 [8, 9]. The example is illustrated below.

A simply supported slab of 4.5m span is to be designed to carry a live load of 3.0 kN/m² plus floor finishes and ceiling loads of 1.0kN/m². If loadings were made prematurely, the characteristic material strengths are; for concrete, f_{cu} = 30N/mm² and steel, f_y = 460N/mm². Check the safety of the slab section in flexure.

Now, the basic span effective depth ratio = 20, since the beam is simply supported.

Therefore minimum effective depth,

$$d = \frac{\text{span}}{20 \times \text{modification factor}}$$

$$= \frac{4500}{20 \times \text{m.f}} = \frac{225}{\text{m.f}}$$

Estimate the modification factor to be of the order of 1.3 for a lightly reinforced slab. Try effective depth, d = 170mm. For a mild exposure, the concrete cover = 25mm. Allowing, say, 5mm, half the diameter of the reinforcing bar, then, the loadings on the slab can be estimated as follows:

overall depth of slab, h = 170 + 25 + 5
= 200 mm.

self-weight of slab = 200 × 24 × 10^{-3}
= 4.8 kN/m²

total dead load = 1.0 + 4.8
= 5.8 kN/m²

For a 1m width of slab

Ultimate load = $(1.4g_k + 1.6q_k)\, L$
= (1.4×5.8+1.6×3.0)4.5
= 58.14kN
Ultimate moment, M = 58.1 × 4.5/8
= 32.7 kNm.

The actual span – effective depth ratio can be obtained as shown in the procedure below.

$$\frac{M}{bd^2} = \frac{32.7 \times 10^6}{1000 \times 170^2} = 1.13$$

From the BS8110 design code, service stress f_s = 288 N/mm², hence, the span-effective depth modification factor = 1.4. Therefore, the limiting

$$\frac{span}{effective\ depth} = 20 \times 1.34 = 26.8$$

and actual $\frac{span}{effective\ depth} = \frac{4500}{170} = 26.5.$

Thus effective depth, d = 170mm is adequate, since 26.5 < 26.8.

Bending Reinforcement

The bending reinforcement is calculated as follows:;

$$\frac{M}{bd^2 f_{cu}} = \frac{32.7 \times 10^6}{1000 \times 30 \times 170^2} = 0.038$$

Also, from BS8110 design code, lever arm curve, l_a = 0.95. Therefore, lever arm, $z = l_a.d = 0.95 \times 170 = 161$mm. Thus, the area of reinforcement, A_s, is given as:

$$A_s = \frac{M}{0.87 f_y z} = \frac{32.7 \times 10^6}{0.87 \times 460 \times 161}$$

$$= 508 mm^2/m$$

Provide T10 bars at 150 mm centres, A_s = 523 mm² / m

Shear

At the face of the support

$$\text{Shear} \quad V = \frac{58.1}{2}\left[\frac{2.25 - 0.5 \times 0.23}{2.25}\right]$$

$$= 27.5\, kN$$

Shear stress,

$$v = \frac{V}{bd} = \frac{27.6 \times 10^3}{1000 \times 170}$$

$$= 0.16 N/mm^2 < 0.8\sqrt{f_{cu}}$$

$$\frac{100 A_s}{bd} = \frac{100 \times 523}{1000 \times 170} = 0.31$$

From BS8110 design code, v_c=0.55N/mm² and since at a distance, d from support, $v < v_c$ no further shear checks is required.

4.1 Limit State Equations

Applied loading on a reinforced concrete slab will cause a response which depends on the strength of the concrete slab. This response will determine the safety of the slab with respect to its limits in terms of deformation and collapse. When it is loaded prematurely, then a limit state violation occurs.

The probability of failure, P_f, was noted by Melchers [29] and Gollwitzer, et al [28] as;

$$P_f = P(R \leq S) \qquad (12)$$

and safety index, β as;

$$\beta = \varphi^{-1} P_f \qquad (13)$$

Hence the probability of failure is identical to the probability of a limit state violation. The probability of violating a limit state can thus be expressed as:

For Flexure

$$P_f = P(R - S \leq 0) = \int_{-\infty}^{\infty} F_R(x) F_s(x)\, ds \quad (14)$$

The limit state function $g(x)$ is given as

$$\frac{1}{\gamma_m} \times 0.79 \left(\frac{f_{cu}}{25} \right)^{1/3} \left[\frac{100\rho h}{d} \right]^{1/3} \left[\frac{400}{d} \right]^{1/4}$$

$$= Q_k (1.4\alpha + 1.6) \quad (13)$$

Where α is the ratio of dead to imposed load and Q_k the imposed load.

The parameters for the stochastic model are given in Table 1; while the result of the reliability test or modeling of a loaded slab designed to BS8110 [8, 9] is shown in Table 2 and is plotted for the safety of the slab with respect to the corresponding characteristic strength of concrete as modeled in Figure 1.

4.2 Discussions of Results

It may be observed from Figure 1 that the safety indices for a slab under loading conditions in flexure decreases as the concrete characteristic strength decreases. At a characteristic strength, f_{cu}, of 30N/mm² for instance, for the modeled slab, the reliability index, β, is 3.883, while at a very small, f_{cu} value of 5N/mm² the safety index is -0.952 which is not within the acceptable safety limit of not less than the prediction in CP110 [30] and BS8110 [8, 9] of 2.011 as noted by Abejide [31]. It can be clearly seen that the safety index of 2.011 corresponds to about two-thirds of the intrinsic safety of the modeled fully developed reinforced concrete slab in Figure 1. Also, the result indicates that at small values of f_{cu} and with the slab loaded prematurely (that is, before adequate strength is developed), the slab is not safe against flexure, and will consequently fail. Thus, care needs be taken to ensure that reinforced concrete slabs are not loaded when they have not developed sufficient strength during construction. The safety indices of the modeled slab is a true representation of the formulations in BS8110 [8, 9] as the plots indicates, but varied significantly from that of the EC2 [10] although, it follows the same pattern with it.

5.0 CONCLUSIONS

A mathematical modeling was conducted to investigate the actual safety of premature loading on a reinforced concrete slab design based on CP110 [30] and BS8110 [8, 9]. The First Order Reliability Method (FORM) was used to estimate the reliability levels and the practically safe limits for application of loads during construction. On the basis of the result obtained, for the condition of flexure when the slab is loaded prematurely, the slab can be safely loaded when it has developed at least two-thirds of its characteristic strength otherwise the slab is likely to fail as indicated by the safety indices below this point. Also, the prediction of the moment of resistance for EC2 [10] is higher than that in BS8110 [8, 9] and CP110 [30], thereby necessitating that the stringent procedures for strength gain of concrete and its associated quality control in its production and placement in forms implied according to the formulations in EC2 [10] needs to be achieved on site so that concrete slabs, when the is used, can attain the predicted implications of their formulations in flexure.

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TABLE 1: BASIC VARIABLES FOR A PREMATURELY LOADED SLAB

S/No	Variable	Definition	Distribution	$E(X_i)$	$COV(X_i)$	$S(X_i)$
1	f_{cu}	characteristic strength	Log-normal	30kN/mm²	0.15	4.5N/mm²
2	Q_k	Imposed load	Gumbel	3kN/mm²	0.3	0.9kN/mm
3	D	Effective depth	Normal	170mm	0.05	8.5mm
4	B	width	Normal	1000mm	0.05	50mm
5	L	span	Normal	4500mm	0.05	225mm

TABLE 2: SAFETY INDICES OF MODELED CONCRETE SLABS

Characteristic strength of concrete , f_{cu} (N/mm²)	Safety index, β
30	3.883
25	3.407
20	2.828
15	2.081
10	1.003

5	-0.952

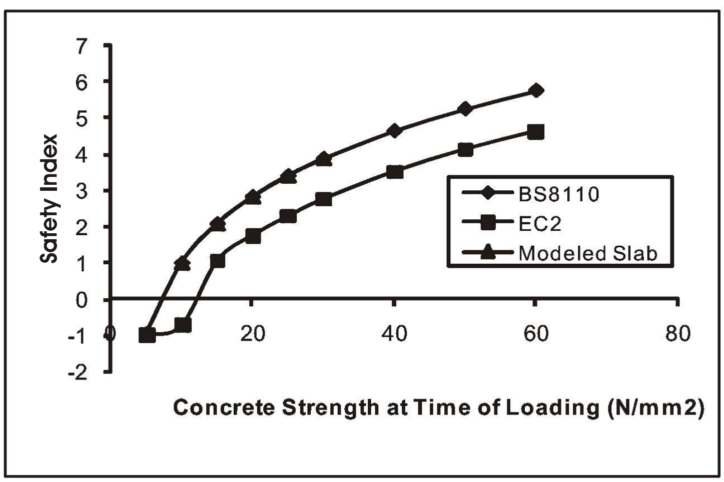

Figure 1: Implied safety of modeled prematurely loaded concrete slab with BS8110 and EC2 provisions in flexure.