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Reliability Assessment of Cracked Reinforced Concrete Slab and Verification using a Full-Scale in-Situ Load Test

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Abstract

This paper presents a case study focused on the deterministic and probabilistic structural assessments of a cracked reinforced concrete (RC) slab and evaluation using in-situ load testing. The case study explores the practical application of in-situ load testing as a diagnostic tool for evaluating the condition of the slab and determining its ultimate load-carrying capacity in the presence of cracks, and service loads are used to verify its serviceability. Through comprehensive analysis and interpretation of test results, this study aims to provide valuable insights into the structural performance of cracked reinforced concrete slabs and inform effective repair and rehabilitation strategies. The building under examination is a G+4 reinforced concrete structure constructed using ready mix concrete transported to the construction site. Upon inspecting the slab, which had a total thickness of 170 mm, numerous deeply mapped cracks were evident, visible from the slab's surface and extending through its entire depth. Structural analysis indicated that the design included sufficient reinforcement and that the loads acting upon the slab were not expected to induce the cracking. Factors such as poor construction practices, potential issues with the cement used, and excessive evaporation may have contributed to the occurrence of these cracks, necessitating repairs. A full-scale in-situ load test was performed following ACI 318-08 testing procedures and results show that the slab under investigation is reasonably safe against serviceability and strength requirements with "no evidence" of failure.

Keywords: Structural assessment, RC slab, cracks, in-situ load test, load-carrying capacity

1. Introduction

Reinforced concrete slabs may develop cracks due to various factors such as loading conditions, shrinkage, temperature variations, and material deterioration. Assessing the condition of cracked RC slabs is crucial for ensuring structural safety, durability, and serviceability [1]. The occurrence of excessive evaporation from the concrete mix in the plastic stage is a factor that could lead to shrinkage in the concrete matrix. Such excessive loss of water may result in related plastic shrinkage cracks [2]. Concrete surface starts to dry on direct sun exposure and as a general rule at evaporation rates greater than 1.0 kg/m^2 and immediate protection/covering becomes necessary. However, drying may occur at much lesser rates of evaporation depending on the concrete mix ratio [3]. The other reason of cracks in concrete is drying shrinkage that results from the loss/evaporation of water from the concrete after hardening stage [2]. These types of cracks are known to penetrate full depths of structural members.

Cracks which affect the structural integrity of RC structures need to be treated. For such purposes, different retrofitting and/ or strengthening techniques were experimentally tested using cement grout, epoxy injection, ferrocement layer, carbon fiber strip and section enlargement. Results showed that all repair techniques are found to be able to enhance the structural capacity of cracked concrete slabs where section enlargement gives 130% higher ultimate load capacities compared to the control slab [4].

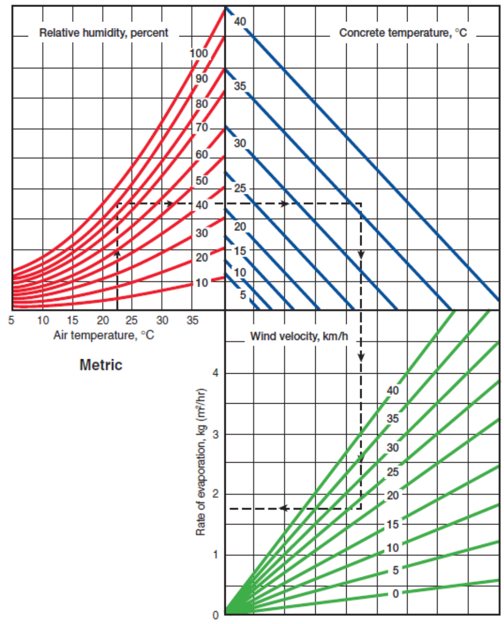


Fig. 1. Estimation of rate of evaporation [3]

Ensuring the structural integrity of existing structural slabs with limited material data and various defects, such as multiple cracks, poses a significant challenge. In-situ load testing has emerged as a valuable verification technique for addressing this challenge [5–9]. The study conducted by Saleem, Abbas, and Nehdi demonstrates that a straightforward approach involving distributed in-situ loading using cement bags, in conjunction with finite element modeling, can offer reliable insights into appraising such existing structures. These findings hold promise for assisting practitioners in effectively managing a substantial portfolio of RC slabs affected by construction defects, thereby facilitating the process of condition rating. Once the condition of cracked RC slabs is assessed, appropriate rehabilitation and strengthening strategies can be implemented to restore or enhance their structural integrity. Common repairing techniques may include crack injection, fiber reinforced polymers (FRP) strengthening, steel plate bonding, and external post-tensioning [7].

A static and dynamic analysis of an industrial hall with a reinforced concrete slab was conducted to assess the capacity of the cracked slab. The slab exhibited lots of cracks, with a maximum crack width of 1.6 mm, penetrating to depths ranging from 30 to 125 mm. The analysis results indicated that the slab's capacity remained safe, provided the service load is limited to a lower permissible limit of 4 kN/m² [6].

A five-story concrete building that was partially burned was evaluated using a non-destructive load test. According to the test results, the affected portions need retrofitting to restore the original design load carrying capacity of the as the structure's has a reduced strength [10]. Moreover, a load test was conducted on a garage structure and it was determined that the structure was adequate [11,12]. For several reasons, including determining the impact of construction and design defects and omissions, in-situ load testing is important. For the structures considered in the load test, finite-element technique models were developed to facilitate the design of the load test. The field observations were confirmed by the computational simulations [13].

In situ load testing of RC slabs in parking garage structures was performed using both cyclic and 24-hour load test approaches. Cyclic loading was applied to the structural members in a quasi-static manner over at least six loading and unloading cycles at regular intervals. Both methods produced the same result: two identical RC slabs failed to meet the acceptance criteria [11]. These findings suggest that conducting a 24-hour load test is a practical approach for in situ testing of existing RC slabs. Similarly, in situ load tests were conducted on RC and prestressed concrete (PC) slabs, with measurements taken for deflection and crack width. The results were compared against the limits specified in ACI 318 and ACI 437 standards. The paper also presented the evaluation criteria and findings from two field projects: one involving a post-tensioned concrete slab with structural deficiencies due to tendon and mild reinforcement misplacement, and another concerning a floor bay of a two-way RC slab showing cracks in both the positive and negative moment regions. The testing revealed that, in some cases, the ACI 437 requirements were not met [8].

Several studies have attempted in situ load testing on RC slabs. Among them, W.J. Gold and A. Nanni conducted an in situ load test by varying the load magnitude, applying cyclic loads over a short period to address the lack of having accepted standardized design and construction specifications for new structural repairs. The test results demonstrated that the performance of the strengthening system using bonded carbon fiber-reinforced polymer (CFRP) sheets was found effective [14].

Different codes and standards provide the minimum magnitude of loads to be used for load test in buildings. As per the requirement of ACI 318-08, the intensity of the load to be applied to the slab is specified that the total test load including dead load already in place shall not be less than the magnitude given in Eq. (1) and the load shall be applied in not less than four approximately equal increments [15].

$$LI_{min} \geq 0.85(\gamma_D D + \gamma_L L) \tag{1}$$

where LI_{min} is the minimum load intensity (kN/m^2), D, L are dead and live load effects, respectively (kN/m^2) , γ_D and γ_L are dead and live load factors, respectively.

The maximum deflection of the slab during test load shall satisfy one of the following conditions given in Eqs. (2) and (3) [15].

$$\Delta_{max} \leq \frac{L_1^2}{20{,}200h} \tag{2}$$

$$\Delta_{r,max} \leq \frac{\Delta_{max}}{4} \tag{3}$$

where Δ_{max} is the measured maximum deflection (mm), L_1 is the shorter span for two-way slab systems (mm), h is the overall thickness of member (mm) and $\Delta_{r,max}$ is the measured residual deflection (mm)

In this study, evaluation of an RC slab is made analytically and by in-situ load testing. After a year of construction, a field test is carried out on a RC floor slab to confirm the findings of the design review and probabilistic assessment, thereby ensuring its safety. The results show that the slab is reasonably safe against serviceability and strength requirements, even with cracks.

2. Methodology

The structure under investigation in this research comprises five floors, encompassing the ground level and four stories above it. At the time of examination, construction had progressed up to the third story. During the construction process, cracks were observed within two days in the newly cast slabs on the third story, prompting a halt in work. This pause was necessary to assess the safety and viability of continuing construction and future occupation of the building. Decisions regarding whether the structure could support further construction and future occupation or if partial or complete demolition and reconstruction were required hinged on this evaluation.

The verification includes strength and durability aspects. This is to assess whether the deflection requirement of the slab is exceeded or not. Moreover, load carrying capacity of the slab was assessed. Deterministic and reliability-based assessment of the structure are carried out to evaluate the safety of the structure. For the load test, the most defective slab with maximum span dimensions is selected as the panel is critical (2nd floor slab between Axis 1-2 and Axis A-B). Fig. 2 presents the floor plan of the building, indicating the locations of the observed cracks.

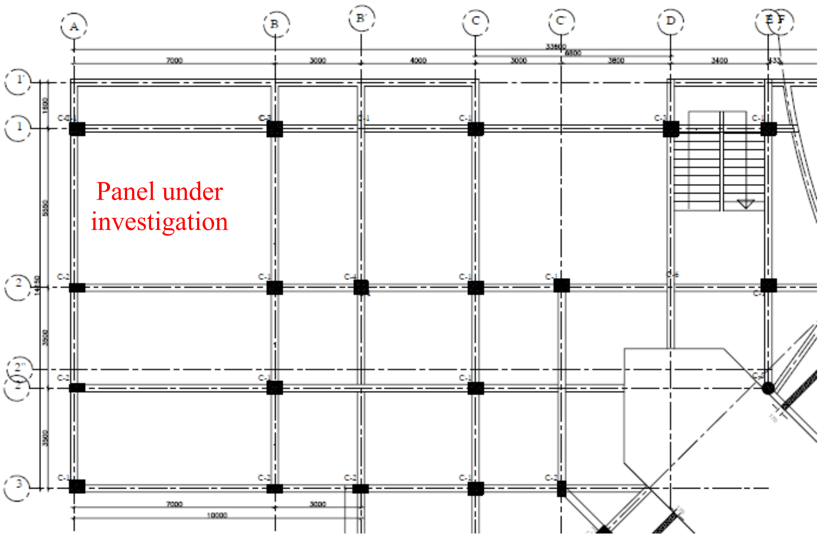


Fig. 2. Typical floor plan of the building

2.1 Construction Information

Materials used for the construction, actual dimensions of the slab, reports on the proportions and properties of the concrete mixtures are checked following ACI 437 standard [16]. Moreover, for the purpose of this study, to get the actual material strengths, tests are performed. The reinforcement steel bar utilized for the work was having a yield strength of 420 MPa and the concrete's average compressive strength of the core was recorded at 24.9 MPa, 26.8 MPa and 29.6MPa sampled at three different deliveries. The thickness (170mm) and dimension of the slab (center to center spacing of 7m×5.5m) are measured at site. Review of the original design was made in accordance with ES-EN 1992-2015 design code [17]. From the inspection report, it was verified that reinforcing bars are placed as per the original design.

2.2 Equipment and Instruments

Test equipment from the Construction Materials and Structures Laboratory of Addis Ababa Institute of Technology (AAiT) were mobilized. The tools, equipment and instrumentation used for the field test include; Schmidt hammer, core drilling machine, data logger - for digital data acquisition - 500 data points per second, transducers - measurement of vertical displacement (digital), crack scale to measure crack widths, UPS - power storage and power extension cables. The field test is designed to assess the performance of the selected slab and solely targeted on the strength, stiffness, and geometry aspects. In the investigation three tests are carried out; hammer test, core test (compressive strength of concrete) and in-situ load test.

2.2.1 Test set-up

For the test setup, the slab to be investigated was first selected, with existing cracks, damages, or deformations documented. Instrumentation such as displacement transducers (LVDTs) was installed to measure deflections at the mid point and crack width scale was used to measure cracks. Before loading began, initial measurements of deflections, crack widths, and the slab’s condition were taken for comparison throughout the testing process. The loading test was conducted using the setup presented in Fig. 3.

(a) (b)

Fig. 3. Set-up for loading test (a) slab deflection measurement and (b) data logger

2.2.2 Load intensity

As the slab was already in place (weight of existing slab is 4.25kN/m^2), the superimposed dead load to be applied during the test was determined to be the finishing and design live loads. For the load test, additional dead load of 2.96kN/m^2; i.e., weights of cement screed (0.8kN/m^2), floor finish (0.21kN/m^2), ceiling plaster (0.45kN/m^2) and partition walls (1.5kN/m^2), and a live load of 3.0kN/m^2 are considered, resulting in a test load of 6.06kN/m^2. In this study, a test load of 8.0kN/m^2 was applied to the slab; i.e., 5 layers of cement bags, each weighing 1.60kPa (40qtl with an effective loaded area of 5.75×4.35m^2). The slab has a total dead load of 7.21kN/m^2, which includes the weight of the concrete (4.25kN/m^2) and additional dead loads of 2.96kN/m^2. The minimum test load required by ACI 318-08 based on Eqn. (1) becomes 12.13kN/m^2, taking into account γ_D of 1.35 and γ_L of 1.5 as the slab was designed following ES-EN 1992-2015 [17]. Therefore, the load requirement of ACI 318-08 is satisfied, i.e., the total load intensity applied in the slab, including its weight (12.25kN/m^2 =8.0+4.25) was not less than the minimum requirement of 12.13kN/m^2.

2.2.3 Loading steps and measurements

During the test, the behavior of load-deflection response of the slab was checked at each loading step. The test load was applied incrementally in five layers as recommended by ACI 318 [15] up to the maximum load intensity of 8.0kN/m^2 and deflection is measured using LVDT [16]. In addition to the deflection measurements, any possible cracks formation, opening/closure of flexural cracks were tested and taken after each load increment to monitor the slab's response. The test continued until the slab showed signs of failure, which could include excessive deflection, significant crack widening, material distress (such as spalling or crushing), or instability in the form of a rapid increase in deflection without a corresponding increase in load. Fig. 4 shows a loaded RC slab with cement bags. Finally, the loads are removed immediately after all response measurements (deflection and crack widths) are made. In each loading and testing steps, safety provisions are properly followed.

(a) (b)

Fig. 4. Surface loads used for loading test a) three layers b) five layers

3. Results and Discussion

3.1 Crack Formation

Fig. 5 presents the cracks seen on top surface of the deck; they are found to be of random pattern and distributed in the panel fully indicating a non-structural cause i.e., contraction of the paste. The site observations showed that the concrete has been leaking water through the cracks indicating crack opening running deep to the depth of the slab. To confirm this, two core samples were taken at locations where cracks were visible on the surface. The core samples verified that the cracks observed on the top surface extended to the depth of the slab, as illustrated in Fig. 6. For the cracked slab under investigation, a maximum crack width of 0.6mm has been measured.

Fig. 5. Cracks observed at deck top surface

Fig. 6. Core samples reaching the full depth of the slab

Fig. 7 below shows plastic settlement cracks which run along the directions of top restraints. By their nature settlement cracks are known to occur primarily while the concrete is plastic and bleed water is still rising and covering the surface. They tend to roughly follow restraining elements such as reinforcement bars (see Fig. 8) or change in depth of members. To avoid formation of such cracks it is recommended to use mixes with lower bleeding characteristics and increase the ratio of cover depth. Bleed of concrete may result from excessive water to cement ratio (greater than 0.50) or excessive water reducer dosage that causes free water to rise to the top surface. It is also suggested that the finishers wait to proceed until the water evaporates or re-trowel the surface to close the settlement crack openings while the concrete is still plastic.

Fig. 7. Plastic settlement cracks

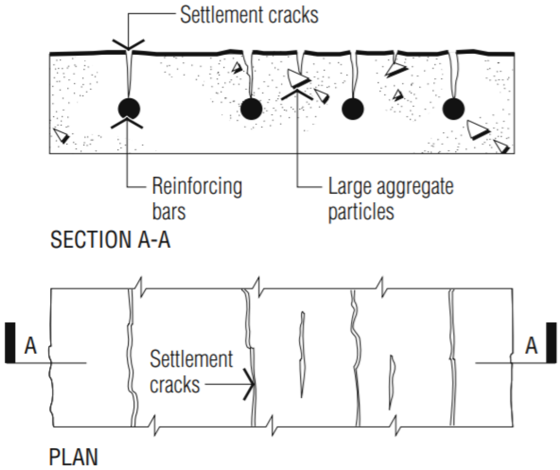


Fig. 8. Settlement cracking concept [18]

Estimation of the water evaporation from the slab surface per area can be made by taking the weather information presented in Table 1 and from the chart presented in Fig. 1. Nevertheless, it is worth noting that the data presented may not be exactly represent the site situation. Data as reported by the National Metrological Data and Climatology Directorate is presented in Table 1 [19].

Table 1. Weather data of Addis Ababa during the concrete casting dates

Date	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)	Wind speed (m/s)
22	25.7	13.0	0	0.54
23	25.5	11.2	0	0.41

3.1.1 Possible causes of cracks

From the information collected, the concrete slabs on the 2nd floor were casted on February 22 and 23, 2021 and multiple cracks were noticed within 24 hours. These cracks are most likely caused by one or a combination of the following reasons:

i. The concrete was casted in February 2021, when the temperature and humidity were 25.5°C and 44%, respectively (which is the maximum temperature and minimum relative humidity in the year 2021). This would have resulted in early aged slab cracking due to rapid and excessive evaporation of water from the concrete.

ii. Poor cement quality which can also cause a volumetric shrinkage in the produced concrete. However, this cannot be verified without conducting a chemical composition test and physical tests on the cement. No sample of the utilized cement was availed to test its quality neither did the investigators find a report on its quality by the suppliers.

iii. Problem in mix proportion of concrete: chemical composition and fineness content of cement, excessive use of water to cement ratio, large size of course aggregates and presence of excessive fine aggregates are major causes for early-stage shrinkage cracking. As per the mix design data provided by the contractor, the concrete mix used in this project is in good agreement with the design. However, test results for the constituent materials used for the construction of the slabs were not provided and could not be verified. The reported mix design followed for making C-25 concrete is presented in Table 2.

Table 2. Reported concrete mix design

Weight (kg/m^3)	Water	Cement (OPC 42.5 N)	Fine aggregate	Coarse aggregate (max. size)		Retarding Admixture
				10 mm	20 mm	
	147	335	693	236	767	0.6

The specific materials used in making the concrete were said to have been fully utilized, making it impossible to extract samples for additional laboratory investigations.

iv. The contractor may not have used the proper slab curing procedure. As a result of this, excessive evaporation of water from the concrete was accelerated and hence the section has cracked. Rapid drying of the surface of the concrete due to high temperature caused the slab to shrink and crack. Further drying shrinkage resulted a full-depth cracking of the concrete slab which propagated to the slab soffit.

3.1.2 Investigation of curing condition

Beam and column curing involved the application of water sprinkling, while wet burlap was used to cover the slabs. However, based on site observations the assurance of consistent burlap saturation through intermittent sprinkling was lacking. Inadequate moisture distribution caused by inconsistent burlap saturation could have resulted in non-uniform curing of the concrete. This non-uniform curing possibly contributed to differential shrinkage and stress within the concrete, which in turn increased the likelihood of cracks forming. Moreover, insufficient moisture during curing likely caused the surface of the concrete to dry out too quickly, leading to surface cracks.

3.1.3 Core strength

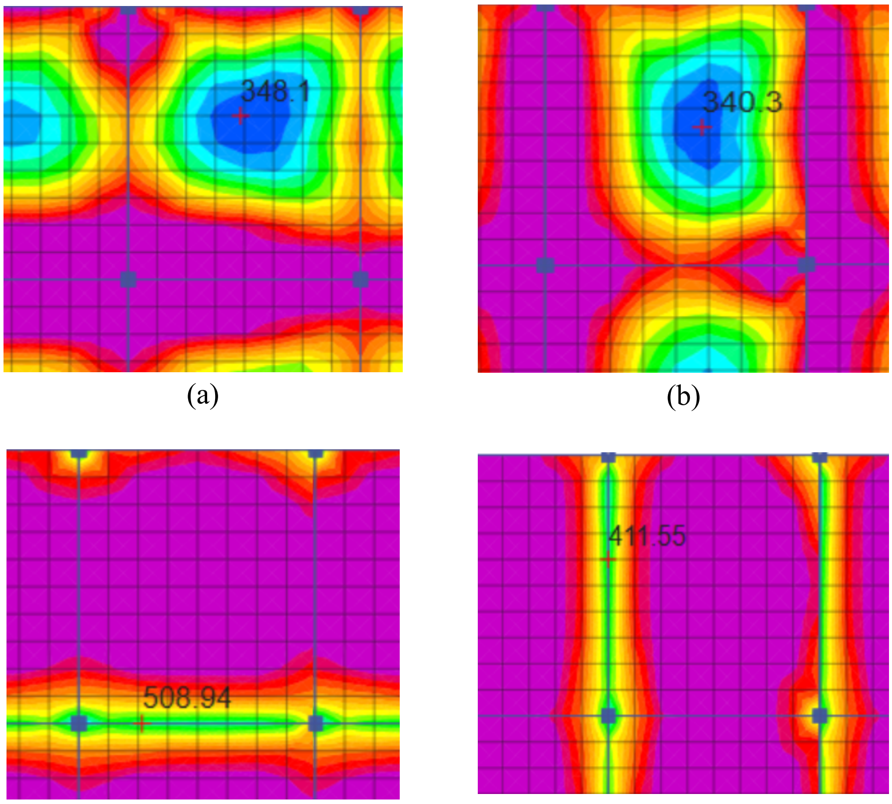
The strength of the core was made in accordance with testing procedures of ACI 214.4R-03 [20] and the results showed that the cylindrical strength of the samples complies with the design strength of concrete.

3.2 Performance Assessment of RC Slab

Structural performance assessment can be carried out using a deterministic or probabilistic approach. A deterministic analysis is a conservative method of assessment that determines whether or not the structure is safe by taking mean values of all variables with the appropriate factors mentioned in the codes [21–23]. On the other hand, a reliability-based analysis of structures is challenging as there are lack of design information and uncertainties in random variables [21,23,24].

3.2.1 Deterministic analysis

In this section, design review and performance assessment process of the slab under investigation is made deterministically. First, the design was checked using an Extended Three-Dimensional Analysis of Building System (ETABS V21.1.0 [25]) software and the results are compared with the actual drawings used in the construction. The summary of design review output is shown in Fig. 9 and the results are summarized in Table 3.



(a) (b)

(c) (d)

Fig. 9. Rebar intensity (mm^2/m) (a) bottom, x- direction (b) bottom, y-direction (c) top, x- direction and (d) top, y-direction

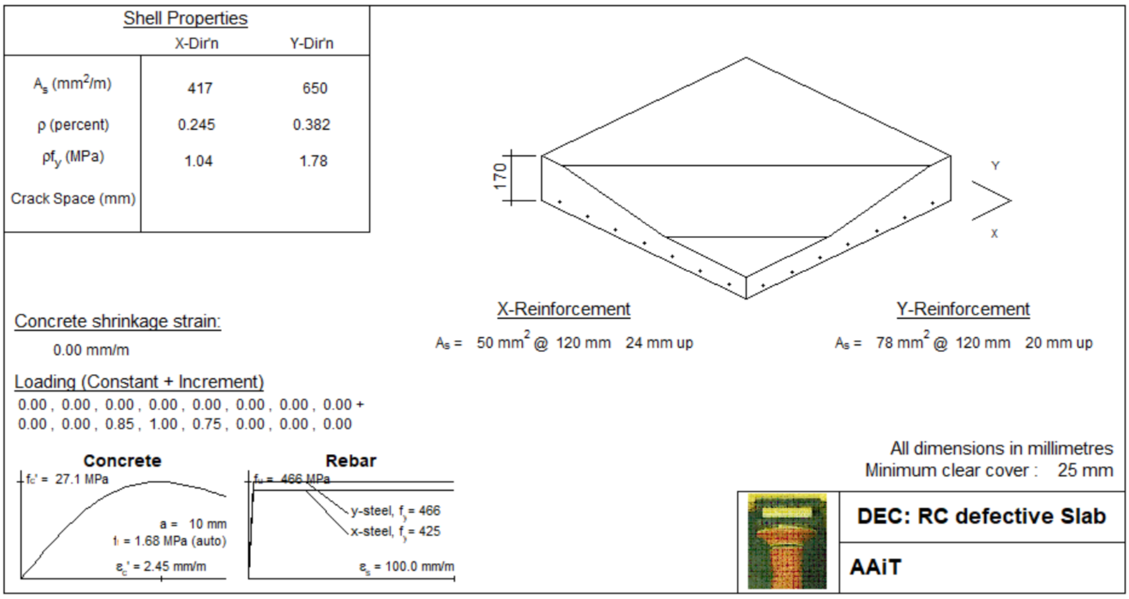
Table 3. Review of reinforcements in slab

Description	Reinforcement areas (mm^2/m)			
	Support		Span (field)	
$A_{s,required}$ (mm^2/m)	506.94	411.55	348.10	340.30
$A_{s,provided}$ (mm^2/m)	628.15	628.15	650.10	417.25

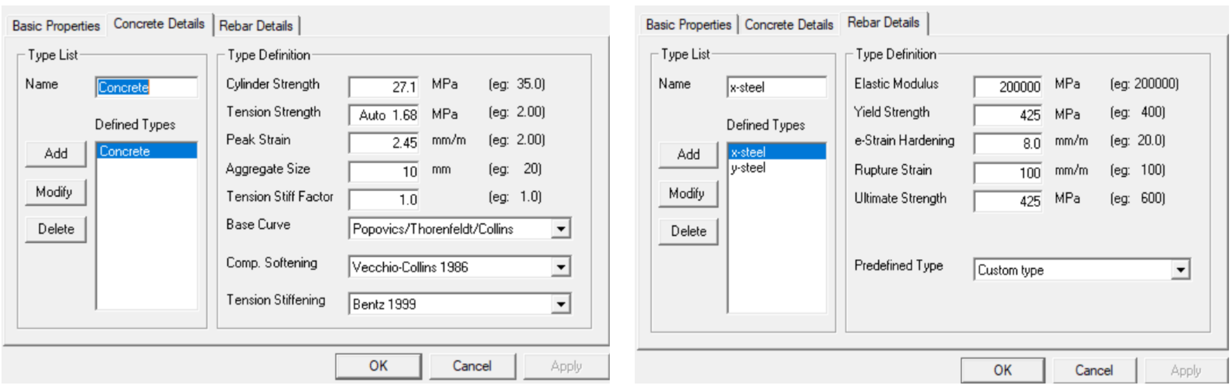
As shown in Table 3, the actual reinforcements provided in the construction of the 2nd floor slab satisfy the requirement and are adequate. Moreover, material properties used in the construction are in line with the design values. The section capacity for the defective slab was carried out using a finite element tool, SHELL-2000 (Reinforced Concrete Sectional Analysis using the Modified Compression Field Theory). The geometric and material characteristics are taken from design data and field test results. Fig. 10 below shows the geometric and material properties of the defective slab. The section is analyzed for its moment capacity for both in the x- and y- directions. The output of the software is shown in Fig. 11. In the analysis, as the concrete was cracked at its early stage, shrinkage and temperature strains are also considered. The evaluation of the RC slab's flexural capacity is summarized in Table 4, where it is evident that the capacity to demand ratio is greater than one, indicating that the slab has no substantial structural deterioration and has enough resistance to flexural action as indicated in ACI 562 [26].

Table 4. Assessment of flexural capacity of RC slab

Moment (kN-m/m)	M_{xf}	M_{yf}
Design moment, demand (1)	17.60	12.90
Section capacity (Software output)	25.77	19.33
Design capacity, (multiplied by 0.9) (2)	23.19	17.40
Capacity to demand ratio (2)/(1)	1.32	1.35



(a)



(b)

Fig. 10. (a) Geometric properties and (b) Material properties for concrete and steel

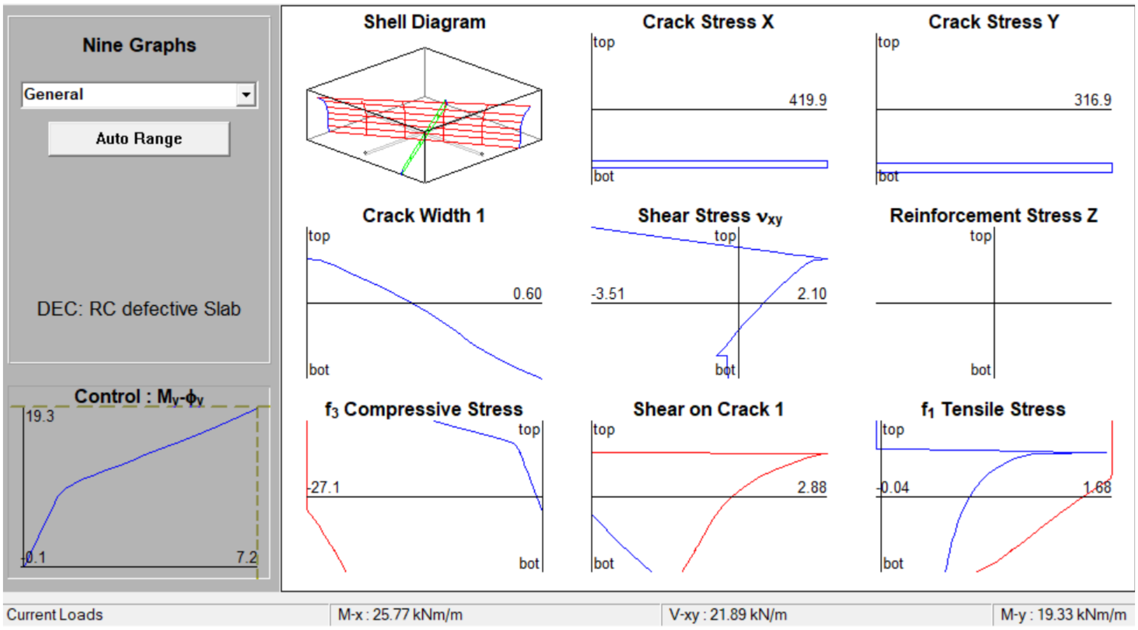


Fig. 11. Analysis Output

3.2.2 Reliability analysis

A reliability analysis of the cracked slab under investigation is done by considering different variations in material properties (especially compressive strength of concrete and yield strength of reinforcing bars), concrete overlay (floor finish), live loads and etc. Furthermore, as construction errors affect section capacity, errors in its section dimensions are considered which accounts the defects in construction caused by lack of skilled manpower and quality of formworks [27]. In a general case, the probability of failure P_f is defined by the limit state function, $g(x) < 0$ and it is given in Eq. (4) [28]:

$$P_f = P\,(g(x) < 0) \tag{4}$$

where P_f is the probability of failure, $g(x)$ is the limit state function, design margin = $R(x)$-$S(x)$, $R(x)$ is the resistance of the section and $S(x)$ is effect of loads. Since bending resistance has a lognormal (LN) distribution and load effects have normal (N) distributions [29], the reliability index of the structure is estimated using Rackwitz and Flessler expressions given in Eqs. (5) and (6), respectively [30].

$$\beta = \frac{\mu_R\left(1 - k\frac{\sigma_R}{\mu_R}\right)\left[1 - ln\left(1 - k\frac{\sigma_R}{\mu_R}\right)\right] - \mu_s}{\sqrt{\left(\mu_R\left(1 - k\frac{\sigma_R}{\mu_R}\right)\left(\frac{\sigma_R}{\mu_R}\right)\right)^2 + \sigma_S^2}} \tag{5}$$

$$k = (\bar{R}^e - r^*)/\sigma_R^e \tag{6}$$

where β is the reliability index, μ_R, σ_R are mean and standard deviation of the resistance, respectively, μ_s, σ_S are mean and standard deviation of total-load effect, respectively, $\bar{R}^e$,σ_R^e are mean and standard deviation for the resistance of the approximating normal distributions (equivalent normal parameters), respectively, k is a multiplication factor of the standard deviation, and r* is a design point on the failure boundary.

Table 5. Statistical distribution of random variables

No.	Random variables	Mean values	CoV (%)	Std. dev.	Distribution	References
1	Yield strength for flexural reinforcement steel, f_y (MPa)	420	5	21	LN	[21,27,29,32]
2	Cylindrical compressive strength of concrete, f'_c (MPa)	27	10	2.7	LN	[29,32]
3	Longitudinal bars x-direction, A_{sx} (mm^2/m)	650	2	13	N	[29]
4	Longitudinal bars y-direction, A_{sy} (mm^2/m)	417	2	8.3	N	[29]
5	Live load	1.00	25	0.25	N	[23,29,32]
6	Permanent loads (finishing and partition loads)	1.00	10	0.10	N	[23,29]
7	Analysis Variable for DL and LL; Avdl and Avll	1.00	5	0.05	LN	[29,33]
8	Resistance factor, ϕ	0.90	10	0.09	N	[29]
9	Model uncertainty for the resistance and load effects, N_R	1.00	4.6	0.046	LN	[29]
10	Slab thickness, t_s (mm)	170	0.5	0.85	N	[29,32]
11	Concrete cover, c (mm)	15	10	1.50	N	[23]

The statistical variations of random variables considered in this study is shown in Table 5. Their statistical distributions are obtained from literatures, standards, codes and manuals [21,23,27,29,31–33].

To determine the number of possible combinations of random variables, Latin Hypercube Sampling (LHS) method is used. LHS method is selected as it permits a limited number of simulations with acceptable level of accuracy [21]. The number of possible combinations is computed using Eq. (7) [34,35].

$$n = 2^k \tag{7}$$

where n is the number of possible combinations (runs), k is the number of input variables, and it is a power of 2; ($k = 2^m$) and m is an integer.

Table 4 considers 11 input variables (k) where m varies from 3 to 4, resulting in k values of 8 and 16. The possible combinations of random variables should not be less than 2^8=256 [34]. This satisfies the minimum number of samples required by [36], which specifies that the sample size must be at least four times the number of input random variables (in this study, it is 44 = 4×11) if the correlation algorithm is used. Hence, in this study, using a built-in LHS design function in MATLAB with mean and standard deviation criterion, LHS of 11 factors (random variables) in 256 combinations is generated [37] and some of which are shown in Table 6. The data is filtered from erroneous combinations using the concept of constrained LHS [38,39], i.e., for instance, the flexural resistance factor (strength reduction factor, ϕ) as specified in [15] does not exceed one.

Table 6. LHS of 11 factors in 256 runs

runs	Random variables (factors)										
	f'_c	f_y	NR	A_{sx}	A_{sy}	LL_f	DL_f	A_{vll}	ϕ	t_s	c
1	26.25	426.15	1.02	638.93	412.70	0.88	0.99	1.05	0.83	169.69	12.67
2	24.06	398.27	0.93	635.41	417.69	0.81	0.91	0.99	0.87	169.09	11.84
3	24.30	427.23	1.01	647.91	406.34	1.17	1.10	1.02	0.95	168.87	11.50
4	29.95	380.31	1.00	638.18	413.88	0.95	1.08	0.98	0.94	169.83	14.29
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256	23.62	382.14	0.96	633.31	416.02	0.97	1.05	0.89	0.90	170.60	16.21

The probabilistic assessment results in terms of design margin for bending moment in x- and y- directions are computed and the corresponding probabilistic distribution graphs are presented in Fig. 12. The reliability indexes of the slab under investigation for bending moments in x- and y- directions are computed using Eqn. (5) and they are found to be 5.52 (β_{Mx}) and 4.17 (β_{My}), respectively. Thus, the safety index of the slab structure becomes 4.17 with a probability of failure of 10^{-6} [21]. The slab is found to fulfill the minimum requirements for ultimate limit states with medium consequence of failure (office and public buildings), with a reliability index limit of 3.8 (for a 50-year return period) [21,40]. Furthermore, it satisfies the minimum target reliability index requirement of 2.5 for a slab element subjected to bending [41].

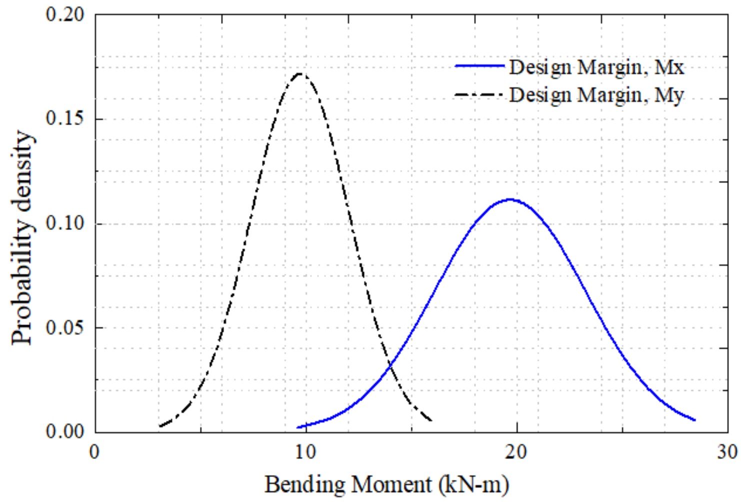

Fig. 12. Probabilistic distribution of design margin for moment

3.3 Verification of capacity of slab by load test

3.3.1 Load deflection results

Time-history and record of mid-span deflection of RC slab due to external surface loads are shown in Figs. 13 and 14, respectively. From Fig. 14, under the action of various loading steps, it is observed that the load-displacement relationship is linear and no opening or closure of cracks have been noticed. As there was no nonlinear load-deflection was observed at each loading step, the slab was loaded up to the maximum load (8kN/m^2). As can be observed from the deflection curve of the RC slab, the structure's deflection due to additional dead and live loads (6.06kN/m^2) was found to be 6.81mm. The deflection of the slab for 5 layers of surface load was measured as 8.68 mm.

The maximum deflection of the slab, computed from Eqn. (2) becomes 8.89 mm [15]. In all cases, the deflection limit is not exceeded making the slab is reasonably safe against serviceability and strength requirements. The result showed that the slab is verified to be safe as it achieved to resist the desired load of 8 kN/m^2. Furthermore, it was observed that, the residual deflection of the beam after removal of the test loads was measured as 0.71mm. This is one-third of the residual deflection limit (=2.23mm), which was computed using Eqn. (3). It shows that there was "no evidence of failure" as more than 90% of the deflection of the slab was recovered [15]. As a result, even with cracks, the structure's strength is satisfactory.

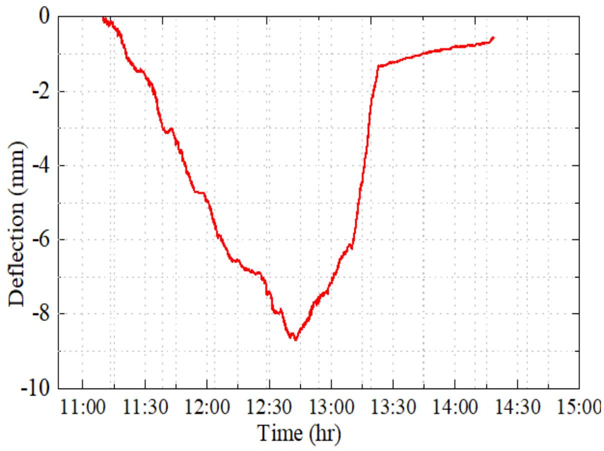

Fig. 13. Time-history of deflection

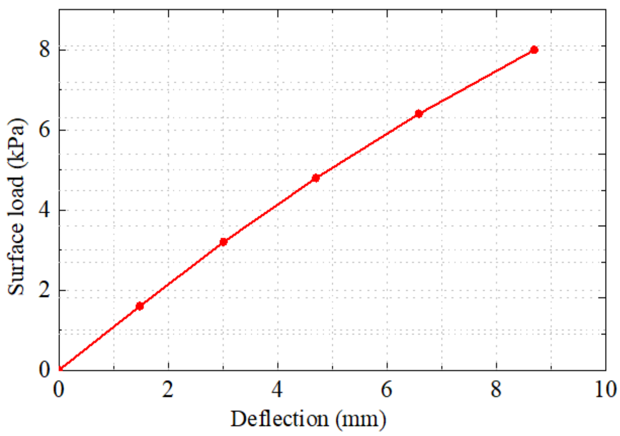

Fig 14. Mid-point deflection under surface loads

3.3.2 Crack widths

During the load test, it was observed that the behavior of the cracks remains unchanged and no further movement of cracks was visualized (no opening and closure of cracks: stabilized cracks). Thus, the cracks are classified as non-structural cracks and there will not be durability issues of the structure, if they are properly treated.

4. Conclusions

Even if the RC slab under investigation has many cracks, "no evidence" of failure was observed. The adequacy of the slab was verified using numerical analysis and a full-scale load test. Hence, the defective reinforced concrete slab is safe against stiffness and strength limits. An overlay with the intended thickness indicated in the original drawing is to be constructed by placing mortar over a cracked concrete surface, and ACI 224R [42] application procedures should be followed. Alternate suitable filler materials should also be used before applying finishing materials to the cracked slab and the cracks should not be left untreated.

The findings of this study provide critical insights into the structural performance of damaged slabs under real-world conditions. By assessing the slab's ability to carry loads in a damaged state, this research highlights the impact of cracks and other imperfections on structural integrity, and helps establish whether repairs or reinforcements are needed to maintain safety and functionality. The results can also influence design guidelines for dealing with pre-existing damage in concrete structures, suggesting that certain levels of damage may still allow the structure to meet safety standards. This research offers a valuable tool for civil engineers, structural inspectors, and facility managers who are responsible for assessing the condition of aging or damaged structures. In-situ load testing can be applied to buildings, bridges, and other critical infrastructure to determine whether they can continue to be used safely without costly, large-scale interventions. This method can also be used to validate the effectiveness of repairs or retrofitting by comparing pre- and post-repair load-carrying capacity. It's particularly useful in situations where visual inspections or non-destructive testing alone are not sufficient to assess the true condition of the slab.

The study advances the understanding of how in-situ load testing can be applied in practical settings, especially in scenarios involving damaged or cracked slabs. It contributes to the body of knowledge by demonstrating how this method can be used not only to evaluate structural capacity but also to monitor the progression of damage under load. Additionally, it offers a framework for using numerical simulations alongside experimental data to provide more comprehensive evaluations of concrete structures. The research also underscores the importance of developing tailored guidelines for in-situ load testing in damaged conditions, potentially influencing future building codes and standards. Future research is recommended to focus on the influence of loading conditions and the long-term monitoring and performance evaluation of cracked RC slabs.

Conflict of Interest

The authors declare that there is no conflict of interest.

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Author Contributions

Yisihak Gebre: Concept, Design the structure, Methodology, Writing the manuscript, Performed the analysis, and Revision of the manuscript.
Biruktawit Taye: Concept, Collected the data, Methodology, and Designed the analysis.
Abrham Gebre: Concept, Design the structure, Collected the data, Writing sections 3.1 and 3.2, Designed the analysis, Performed the analysis and Revision of the manuscript.
Asmerom Weldegerima: Collected the data, Methodology, Analysis and Revision of the manuscript.

References

[1] Mehndi, S. M., Khan, M. A., Ahmad, S., Causes and Evaluation of Cracks in Concrete Structures. *International Journal of Tech. Research and Applications,* 2(5), 29-33, 2014.

[2] Sayahi, F., Plastic Shrinkage Cracking in Concrete: Mitigation and Modelling. Doctoral Thesis, Luleå University of Technology, Department of Civil, Environmental and Natural Resources Engineering, Luleå, Sweden, 2019.

[3] ACI 305R-20, Guide to Hot Weather Concreting. *American Concrete Institute,* ACI Committee-305, 1999.

[4] Thanoon, W. A., Jaafar M. S., Kadir, M. R. A., Noorzaei, J., Repair and Structural performance of initially cracked reinforced concrete slabs. *Construction and Building Materials*, 19(8), 595-603, 2005.

[5] De Luca, A., Zadeh, H. J., Nanni, A., In-situ Load Testing of a One-Way Reinforced Concrete Slab as per ACI 437 Standard. *Journal of Performance of Constructed Facilities,* 28 (5), 04014022, 2014.

[6] Dmochowski, G., Berkowski, P., Schabowicz, K., Wójcicki, Z., Grosel, J., Dłucik, Ł., Failure Analysis of RC Floor Slab in Industrial Hall. In *Modern Building Materials, Structures and Techniques. Proceedings of the International Conference*, Vilnius Gediminas Technical University, 10, p.587, 2010.

[7] Saleem, M. A., Abbas, S., Nehdi, M. L., Assessment of Reinforced Concrete Slabs Using In-situ Load Testing: A Case Study. *Journal of Building Engineering*, 25, p.100844, 2019.

[8] Ziehl, P. H., Galati, N., Nanni, A., Tumialan, J. G., In-situ Evaluation of Two Concrete Slab Systems. II: Evaluation Criteria and Outcomes. *Journal of Performance of Constructed Facilities,* 22(4), 217-227, 2008.

[9] Abu-Khajil, A., Reliability Assessment of Load Testing for Concrete Buildings. M.Sc Thesis, University of Waterloo, Ontario, Canada, 2015.

[10] Calisang, S.R., Non-destructive Evaluation of an Existing Concrete Structure using Load Test. *International Journal of Scientific Engineering and Research (IJSER)*, 6(11), 63-71, 2018.

[11] Casadei, P., Parretti, R., Nanni, A., Heinze, T., In situ Load Testing of Parking Garage Reinforced Concrete Slabs: Comparison between 24 h and Cyclic Load Testing. *Practice Periodical on Structural Design and Construction,* 10(1), 40-48, 2005.

[12] Matysek, P., Witkowski, M., Analysis of the Causes of Damage to the RC Floor Slab in the Underground Garage, *MATEC Web of Conferences*, 284, p. 06004, 2019.

[13] Galati, N., Nanni, A., Gustavo, T. J., Ziehl, P. H., In-situ Evaluation of Two Concrete Slab Systems. I: Load Determination and Loading Procedure. *Journal of Performance of Constructed Facilities,* 22(4), 207-216, 2008.

[14] Gold, W.J., Nanni, A., In-situ Load Testing to Evaluate New Repair Techniques. In *Proc., NIST Workshop on Standards Development for the Use of Fiber Reinforced Polymers for the Rehabilitation of Concrete and Masonry Structures*, 102-112, 1998.

[15] ACI 318. Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary, *American Concrete Institute*, 2008.

[16] ACI 437R. Strength Evaluation of Existing Concrete Buildings. *American Concrete Institute*, ACI Committee-437, 2019.

[17] ES EN 1992-1-1:2015. Design of Concrete Structures- Part 1-1: General Rules and Rules for Buildings. Ministry of Construction, Addis Ababa, Ethiopia, 2015.

[18] Plastic Settlement Cracking. Cement Concrete & Aggregates Australia (CCAA), Data Sheet, Australia, 2005.

[19] http://www.ethiomet.gov.et/data_access/information, accessed on May 02, 2024.

[20] ACI-214.4R. Guide for Obtaining Cores and Interpreting Compressive Strength Results.

American Concrete Institute, ACI Committee-214, 2003.

[21] Rücker, W., Hille, F., Rohrmann, R., Guideline for the Assessment of Existing Structures, *Federal Institute of Materials Research and Testing*, Final Report-F08a, 2006.

[22] Gebre, A., Gebreyouhannes, E., Gebre, Y., Probabilistic Assessment and Field Test Verification for Strength Evaluation of Bridge with Defective Girder. *Zede Journal of Ethiopian Engineers and Architects,* 41(1), 17-28, 2023.

[23] Muhammed, J. J., Deterministic and Probabilistic Approaches in the Analysis of the Bearing Capacity of a Bridge Foundation on Undrained Clay Soil. *Slovak Journal of Civil Engineering*, 27(2), 44-51, 2019.

[24] Rezaee, R., Brown, J., Augenbroe, G., Kim, J., Assessment of Uncertainty and Confidence in Building Design Exploration. *AIEDAM*, 29(4), 429-441, 2015.

[25] ETABS V21.1.0. Structural and Earthquake Engineering Software. *Computers and Structures, Inc. (CSI)*, 2023.

[26] ACI 562-19. Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures. *American Concrete Institute*, 2019.

[27] Seo, D., Shin, S., Han, B., Reliability-based Structural Safety Evaluation of Reinforced Concrete Members. *Journal of Asian Architecture and Building Engineering*, 9(2), 471-478, 2010.

[28] Nguyen, H. A. T., Probabilistic Assessment of Bending Strength of Statically Indeterminate Reinforced Concrete Beams. *International Journal of Engineering*, 35(4), 837-844, 2022.

[29] Van Coile, R., Caspeele, R., Taerwe, L., The Mixed Lognormal Distribution for a More Precise Assessment of the Reliability of Concrete Slabs Exposed to Fire. *Proceedings of ESREL*, 29(9), 02-10, 2013.

[30] Rackwitz, R.,, Flessler, B., Structural Reliability under Combined Random Load Sequences. *Computers & Structures*, 9(5), 489-494, 1978.

[31] ACI 214R. Guide to Evaluation of Strength Test Results of Concrete. *American Concrete Institute*, ACI Committee-214, 2011.

[32] ASCE-02. Minimum Design Loads for Buildings and other Structures, *American Society of Civil Engineers,* 2nd edition, 2002.

[33] Tarekegn, A. G., Time-Dependent Reliability Analysis for Deflection of a Reinforced Concrete Box Girder Bridge. *International Journal of Engineering and Applied Sciences*, 15(2), 60-74, 2023.

[34] Steinberg, D. M., Lin, D. K., A Construction Method for Orthogonal Latin Hypercube Designs. *Biometrika*, 93(2), 279-288, 2006.

[35] Cronvall, O., Structural Lifetime, Reliability and Risk Analysis Approaches for Power Plant Components and Systems. *VTT Publications* 775, Finland, 2011.

[36] Pleming, J., Manteufel, R., Replicated Latin Hypercube Sampling. In *46th*

AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, *American Institute of Aeronautics and Astronautics,* p.1819, *Austin, Texas*, 2005.

[37] MATLAB. Programming Language, R2021a. The MathWorks, Inc., Natick, Massachusetts, USA, 2021.

[38] Shields, M. D., Zhang, J., The Generalization of Latin Hypercube Sampling. *Reliability Engineering & System Safety*, 148, 96-108, 2016.

[39] Petelet, M., Iooss, B., Asserin, O., Loredo, A., Latin Hypercube Sampling with Inequality Constraints. *AStA Advances in Statistical Analysis*, 94, 325-339, 2010.

[40] Stanojev, M. L., Stojic, D., Reliability Analysis of Structures. *Facta Universitatis, Series: Architecture and Civil Engineering*, 12(3), 265-272, 2014.

[41] Viegas, C. H. H., Real, M. D. V., Reliability Analysis of Reinforced Concrete Slabs Designed according to NBR 6118. *International Journal of Advanced Engineering Research and Science (IJAERS),* 9(7), 286-297, 2022.

[42] ACI 224-R. Control of Cracking in Concrete Structures. *American Concrete Institute,* ACI Committee-224, 2001.