Proceedings of the 9h World Congress on Civil, Structural, and Environmental Engineering (CSEE 2024)
London, United Kingdom – April 14-16, 2024
Paper No. ICSECT 143
DOI: 10.11159/icsect24.143

Nonlinear FE Analysis and Life Prediction of RC Slabs under High-Cyclic Loading

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Abstract - Engineering structures, such as bridges, highways, airport pavements, and offshore platforms, are constantly exposed to varying degrees of fatigue loading. The accumulation of fatigue loads can result in structural damage well before reaching their ultimate load capacity. Consequently, a comprehensive assessment of fatigue performance and service life prediction for these structures is paramount. This study focuses on a parametric investigation of the fatigue performance of reinforced concrete slabs under high cyclic fatigue loading, employing the nonlinear finite element method. The research scrutinizes the influences of load levels, concrete grades, and reinforcement ratios on several key parameters, including structural deflection, reinforcement stresses, cumulative damage, and natural frequency degradation. This study develops the three-dimensional finite element models based on experimental data, with rigorous verification of the model's accuracy. The findings emphasize the considerable impact of load levels, concrete grades, and reinforcement ratios on deflection, reinforcement stress, and cumulative damage in fatigued reinforced concrete slabs. Notably, the main form of structural fatigue damage is fatigue fracture of steel reinforcement, but high load levels, low concrete strength and reinforcement rates can cause concrete fatigue damage. Increasing concrete strength and reinforcement ratio can increase the initial natural frequency of the structure and slow down the fatigue degradation at the natural frequency. Additionally, the study proposes a practical life prediction equation for engineering designers. This equation offers valuable tools for predicting the fatigue life of reinforced concrete slabs, aiding in the design and maintenance of durable engineering structures.

***Keywords*:** Nonlinear analysis; Life prediction; Reinforced concrete slab; Fatigue performance.

1. Introduction

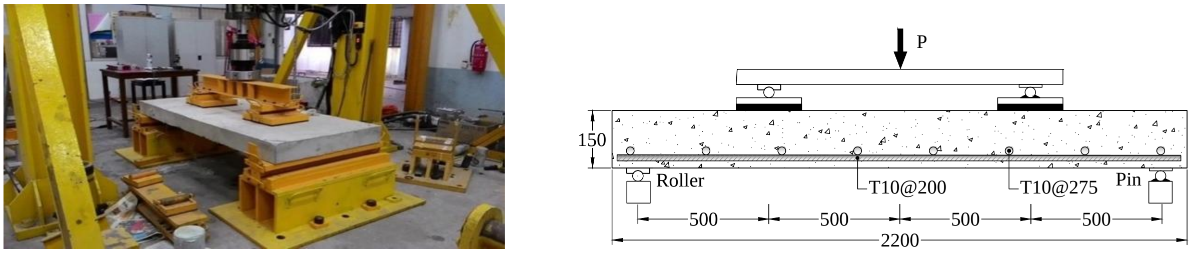
Fatigue is a phenomenon characterized by the degradation of material strength due to repeated application of loads. Essentially, fatigue can be considered as the propagation of damage [1]. Reinforced concrete structures such as roads, bridges, offshore platforms, dams, and airport runways are inevitably subjected to the invasion of fatigue loads [2, 3]. For instance, annual reports from the U.S. Department of Transportation [4, 5] indicate that from 1996 to 2017, the total number of bridges in the United States increased from 591,707 to 615,002, with the proportion of bridges with structural defects growing to 7.74%. In Japan, more than 50% of the total expenditure on highway maintenance is allocated to the repair and renewal of reinforced concrete bridge decks [6], primarily due to high cyclic moving loads and material-related issues [7, 8].

Unlike static loading-induced failures, fatigue loads often lead to catastrophic structural failures at loads significantly lower than the yield load. Previous research has primarily focused on the characteristics of structural fatigue failure. For example, Holmen's study [9] indicates that the elastic modulus of concrete continuously degrades with an increasing number of fatigue load cycles, proposing relevant calculation methods. Researchers such as Hsu [10], Sima [11], Aslani [12], Guo [13], and Zou [2] consider the monotonic stress-strain curve of concrete under static loading as the envelope curve for the stress-strain curve under axial cyclic loading, putting forth formulas for residual concrete strength [2, 13]. Barsom's research [14] demonstrates that the elastic modulus of steel remains constant under fatigue loads, while Feng [15] measures steel damage by the reduction in the effective cross-sectional area after fatigue. Jamadin [16] uses comprehensive dynamic response techniques to assess the stiffness degradation characteristics of reinforced concrete slabs with increasing fatigue loads.

As mentioned earlier, despite numerous studies analyzing the effects of cyclic loads on the elastic modulus, strength, and stiffness of reinforced concrete structures, there is limited research on the dynamic behavior and life prediction of reinforced concrete slabs. This study employs numerical methods to comprehensively assess the fatigue behavior of reinforced concrete slabs, proposing corresponding life prediction methods to better provide valuable information for the fatigue performance and design of RC slabs.

2. Experimental Overview

The comparative experiments conducted in this study draw inspiration from recent research by Jamadin [15, 16]. As depicted in Figure 1, Jamadin [15, 16] explored the fatigue behavior of reinforced concrete (RC) slabs subjected to 1, 1.5, and 2 million cycles of high cyclic loading, along with the corresponding variations in dynamic characteristics, structural stiffness, and residual load-carrying capacity. The tested RC slabs had dimensions of 2200 mm (length) × 1000 mm (width) × 150 mm (thickness). The compressive strength of the concrete, obtained through compression strength tests, was determined to be 40 MPa. Standard high-yield ribbed steel reinforcement with a diameter of 10 mm, an elastic modulus of 200 GPa, and a Poisson's ratio of 0.3 was employed to reinforce tension. The manufacturer's specifications indicate a yield strength of 500 MPa for the steel reinforcement. The average yield strength of the steel, as tested according to BS 4449 (2005) [17], was determined to be 550 MPa.



(a) Experimental test set-up [16]

(b) Schematic view of the test up

Fig. 1: Test set-up and the support system with a hinged support at one end and a roller support at the other end.

3. Finite element modelling

This section describes the mechanical behavior of the material and finite element modelling details.

3.1. The constitutive relationship of concrete

The compressive constitutive relationship of concrete proposed by Kent and Park [18] is used as the initial constitutive relationship, as follows:

$$\sigma_c = \begin{cases} f_c'(2x - x^2) & (x \leq 1) \\ f_c'[1 - Z\varepsilon_0(x - 1)] & (1 < x) \end{cases} \tag{1}$$

Where $= \varepsilon_c/\varepsilon_0$, $Z = 0.5/(\varepsilon_{50u} - \varepsilon_0)$, $\varepsilon_{50u} = (3 + 0.29f_c')/(145f_c' - 1000)$. σ_c and ε_c are compressive stress and compressive strain respectively. ε_0 is the strain corresponding to σ_c to reach the uniaxial compressive strength f_c' of the concrete cylinder.

The residual strength of the concrete $\sigma_c(N)$ was calculated using a formula previously developed by the authors [2] as follows:

$$\sigma_c(N) = f_c'\{1 - Z\varepsilon_0(\lg \mathrm{N} / \lg N_f)[x(N_f) - x(1)]\} \tag{2}$$

The elastic modulus E_n for any cycles n_i is calculated using the following equation [9, 19]:

$$E_n = (1 - 0.33n_i/N_{ci})E_c \tag{3}$$

Where E_c is the initial elastic modulus, and N_{ci} is the fatigue life of concrete which can be calculated by [20]:

$$S_{ci} = 0.9885 - 0.0618 \lg N_{ci} \tag{4}$$

Where $S_{ci} = \sigma_{ci} / f_c^{'}$ is the ratio of the maximum compressive stress σ_{ci} at *i*th cycle and the uniaxial compressive strength f_c' of concrete.

3.2. The constitutive relationship of steel bars

The fully elastic-plastic model [21] is used to describe the stress-strain behavior of steel bars.

$$\sigma_s(\varepsilon) = \begin{cases} E_s\varepsilon_s & (\varepsilon_s \leq \varepsilon_y) \\ f_y & (\varepsilon_s > \varepsilon_y) \end{cases} \tag{5}$$

where E_s is the modulus of elasticity of the steel, $\sigma_s(\varepsilon)$ and ε_s are the stress and the corresponding strain, respectively, and f_y and ε_y are the yield stress and the yield strain, respectively.

Fatigue life of steel rebar N_s is calculated by [22]:

$$\log N_s = 7.253 - 0.0056\,\Delta\sigma \tag{6}$$

where $\Delta\sigma$ is the stress amplitude of steel rebar.

3.3. FE modelling details

In order to accurately characterize the fatigue performance of reinforced concrete slabs, the concrete damaged plasticity model (CDPM) is employed in Abaqus to replicate the mechanical behavior of concrete. The chosen element type for this analysis is the 3-D reduced integrated hexahedral element with 8 nodes (C3D8R). The CDPM model relies on various input parameters to define concrete behavior, including the dilation angle (ψ), eccentricity (e), the ratio between equal biaxial and initial uniaxial compressive yield stresses (fb0/fc0), the ratio of the second stress invariant on the tensile meridian to the compressive meridian (K_c), and viscosity parameters (υ). These key input parameters are detailed in Table 1 [3]:

Table 1. The CDP model parameters [3].

ψ	e	f_{b0}/f_{c0}	K_c	υ
31°	0.1	1.16	0.67	0.001

The reinforcement is described using an elastic-plastic model, with the element type chosen as 3-D truss elements with 2 nodes (T3D2). The consideration of bond-slip relationships between the reinforcement and concrete is omitted. The material properties of both concrete and reinforcement have been detailed in the preceding section. The mesh partition and boundary conditions for the established model are illustrated in Figure 2.

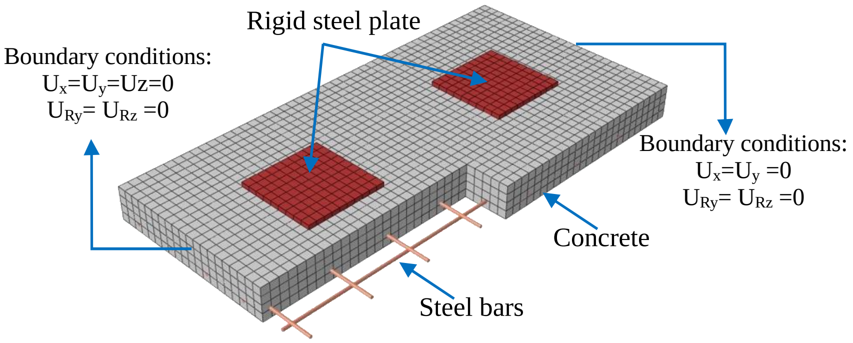
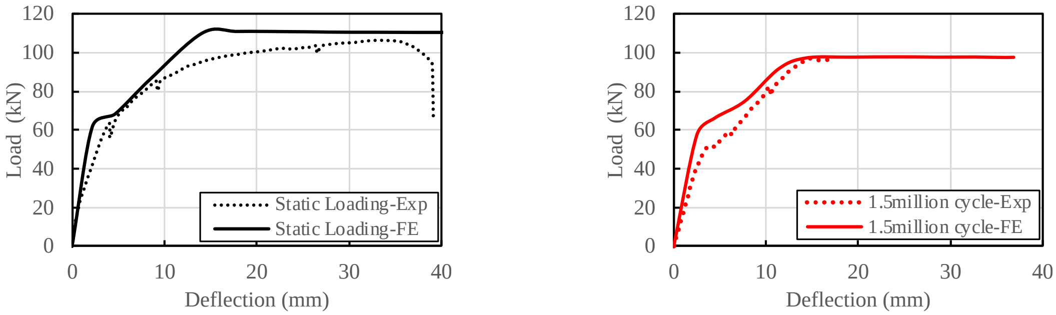


Fig. 2. Meshing configurations and boundary conditions.

4. Validation of the numerical simulation

Figure 3 presents the load-deflection curves of the reinforced concrete slab for 1 cycle and 1.5 million cycles. It is evident that the shape of the load-deflection curves obtained from finite element analysis closely aligns with experimental results. The average ratio, standard deviation, and coefficient of variation for the yield load (P_u) between numerical analysis and experiments, as detailed in Table 2, are 1.030, 0.0246, and 0.0240, respectively. These values indicate the model's high accuracy.



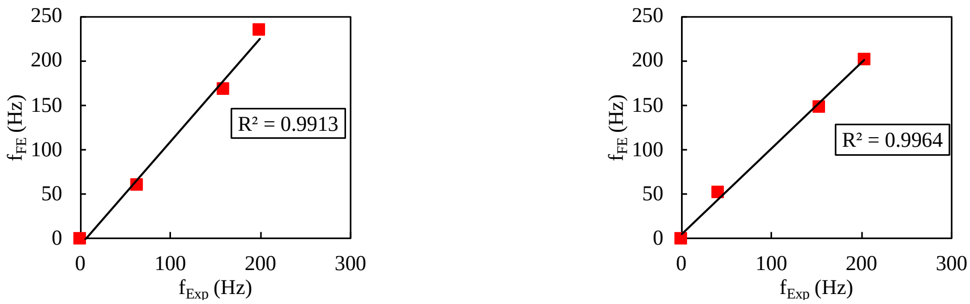
(a) At first cycle (b) At 1.5 million cycles

Fig. 3. Comparison of FE and tested [16] load-deflection histories under different fatigue levels.

Table 2. Comparison of residual strength between FE and experimental test [16] of RC slabs.

Specimen	$P_{u,FE}$ (kN)	$P_{u,Exp}$ (kN)	$P_{u,FE}/P_{u,Exp}$	Mean	Standard deviation (SD)	Coefficient of variation (CoV)
S1	110.9	106	1.05	1.03	0.0246	0.0240
F1.5M	97.8	96.7	1.01			

In Figure 4, a correlation analysis between the natural frequencies obtained through numerical analysis and experimental testing for the RC slab is conducted for undamaged and fatigued states (1.5 million cycles). It is observed that the coefficients of determination R^2 for undamaged and fatigued reinforced concrete slabs are 0.9913 and 0.9964, respectively. This signifies a strong correlation between finite element analysis and experimental results. Therefore, the established finite element model effectively captures the static and fatigue behavior of the RC slab, enabling parametric analysis for design-oriented purposes. This facilitates a comprehensive assessment of the impact of concrete strength, reinforcement ratio, and load levels on the fatigue performance of the reinforced concrete slab.



(a) Undamaged slab (b) Fatigued slab

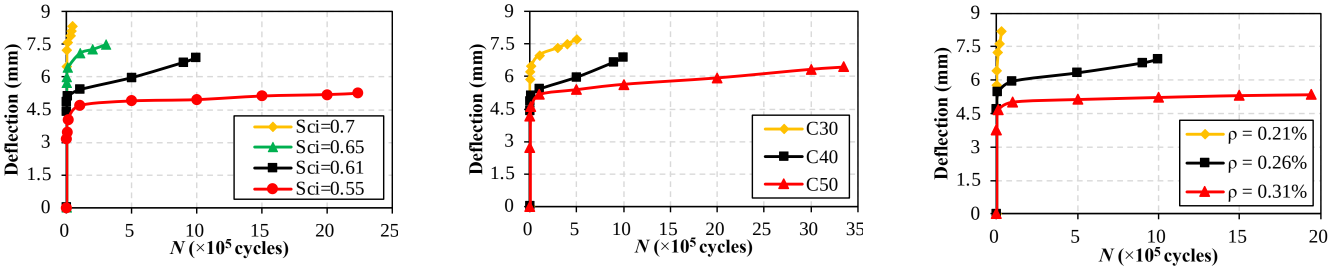
Fig. 4. Correlation of FE and tested [16] natural frequencies of undamaged and fatigued RC slabs.

5. Results and discussion

This section discusses the fatigue performance of reinforced concrete slabs under four different load levels S_{ci} (0.55, 0.61, 0.65, and 0.7), three concrete grades (C30, C40, and C50), and three reinforcement ratios ρ (0.21%, 0.26%, and 0.31%).

5.1. Deflection variation

The relationship between deflection and cycles for reinforced concrete slabs under different load levels, concrete strengths, and reinforcement ratios is illustrated in Figure 5. As observed in Figure 5(a), higher fatigue load levels correspond to larger midspan deflections and shorter fatigue life. Under the same load level, slabs with higher concrete strength exhibit smaller deflections and longer fatigue life, as depicted in Figure 5(b). Notably, the increase in fatigue life is not linear with the increase in concrete strength. For instance, when the concrete strength increases from 30 MPa to 40 MPa, the structural fatigue life doubles, while an increase from 40 MPa to 50 MPa results in a 2.36 times longer fatigue life. Under otherwise identical conditions, increasing the reinforcement ratio reduces deflection and extends fatigue life, as shown in Figure 5(c).

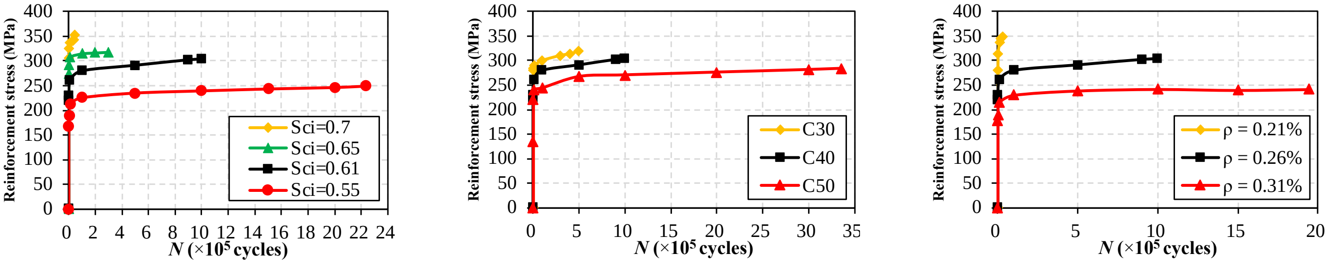


(a) Different loading level (b) Different concrete strength (c) Different reinforcement ratio

Fig. 5. The relationship between deflection and fatigue cycles for reinforced concrete slabs.

5.2. Reinforcement stress variation

Figure 6 illustrates the relationship between reinforcement stress and cycles under different load levels, concrete strengths, and reinforcement ratios. Generally, reinforcement stress undergoes rapid development during the initial cycles, followed by a gradual progression. None of the reinforcement stresses reach the yield strength (500 MPa). Similar to deflection, both load level and reinforcement ratio have a notable impact on reinforcement stress. High load levels and low reinforcement ratios result in a rapid development of fatigue stress in the reinforcement over cycles.

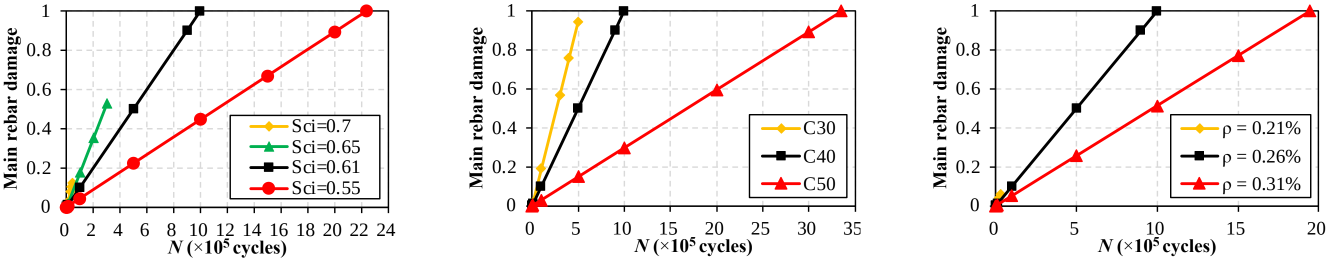


(a) Different loading level (b) Different concrete strength (c) Different reinforcement ratio

Fig. 6. The relationship between reinforcement stress and fatigue cycles for reinforced concrete slabs.

5.3. Accumulated damage in reinforcement

The evolution of accumulated damage in the reinforcement over fatigue cycles is presented in Figure 7. The accumulated damage in the reinforcement exhibits a linear relationship. Since the reinforcement does not reach the yield strength, its failure is induced by the cumulative damage. From Figure 7, it is evident that increasing the load level, reducing concrete strength, and decreasing the reinforcement ratio accelerate the accumulated damage in the reinforcement. Common failure modes for reinforced concrete slabs include concrete crushing and reinforcement rupture. For load levels at 0.7 and 0.65, as well as a reinforcement ratio of 0.21%, the accumulated damage in the reinforcement is relatively small, indicating that the predominant failure mode is concrete crushing. In contrast, for other load levels and reinforcement ratios, the accumulated damage in the reinforcement reaches 1, suggesting structural failure is predominantly caused by reinforcement rupture.

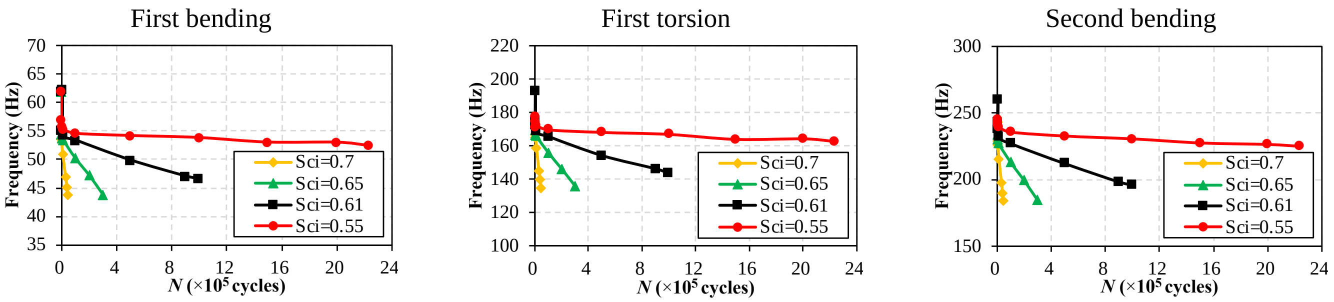


(a) Different loading level (b) Different concrete strength (c) Different reinforcement ratio

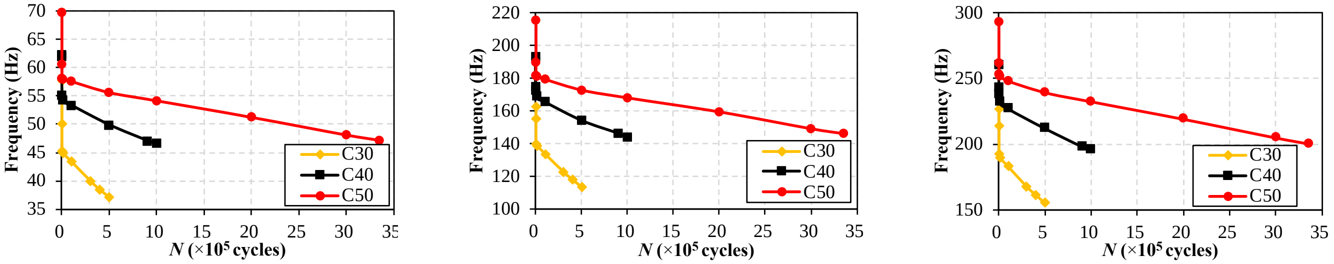
Fig. 7. The evolution of accumulated damage in the reinforcement over fatigue cycles of RC slabs.

5.4. Variation in natural frequencies

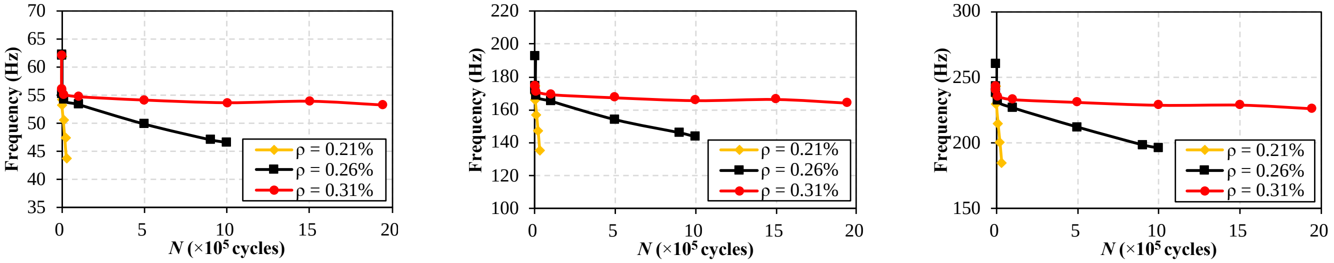
The evolution of the first bending, first torsion, and second bending’s natural frequencies of the reinforced concrete slab over fatigue cycles is depicted in Figure 8. From Figure 8(a), it is evident that, at each load level, the degradation of the structure's natural frequencies follows a pattern of rapid degradation followed by a stable decline. The degradation rate of the first three natural frequencies is significantly higher at high load levels than at low load levels, indicating a notable influence of load levels on the degradation rate of natural frequencies. Notably, the reduction in the natural frequencies of reinforced concrete slabs subjected to different load levels is relatively small in the initial cycles. For instance, at the first cycle, increasing the load level from 0.55 to 0.7 results in a reduction in the first bending’s natural frequency of less than 5.78%. As depicted in Figure 8(b), increasing the concrete strength substantially enhances the natural frequencies of the structure. For instance, at the first cycle, elevating the concrete strength from C30 to C50 increases the first three natural frequencies of the reinforced concrete slab by 21.00%, 22.22%, and 22.19%, respectively. Furthermore, with the development of fatigue cycles, the degradation of natural frequencies in high-strength concrete slabs is more gradual than in low-strength concrete slabs. The impact of reinforcement ratio on the degradation of natural frequencies is similar to that of load levels, as illustrated in Figure 8(c). Additionally, it is observed that increasing the reinforcement ratio enhances the initial natural frequencies of the structure and mitigates the degradation of natural frequencies.



(a) Different loading level



(b) Different concrete strength



(c) Different reinforcement ratio

Fig. 8. Fatigue evolution of natural frequencies.

6. Fatigue life prediction

The fatigue life of reinforced concrete slabs with different concrete strengths is predicted using the least squares method, and the results are presented in Figure 9. The R^2 values for slabs with concrete strength grades C30, C40, and C50 are 0.9519, 0.9691, and 0.9956, respectively. These values indicate sufficient reliability, enabling the use of the predictions for structural fatigue life. The formulas for predicting $P_{max} - N$ for reinforced concrete slabs with concrete strength grades C30, C40, and C50 are as follows:

$$\text{For C30: } P_{max} = 114.69 - 3.801\ln(N) \tag{7}$$

$$\text{For C40: } P_{max} = 116.76 - 3.671\ln(N) \tag{8}$$

$$\text{For C50: } P_{max} = 115.83 - 3.24\ln(N) \tag{9}$$

These predictive formulas demonstrate the relationship between maximum load P_{max} and the number of cycles to failure N for reinforced concrete slabs with different concrete strengths.

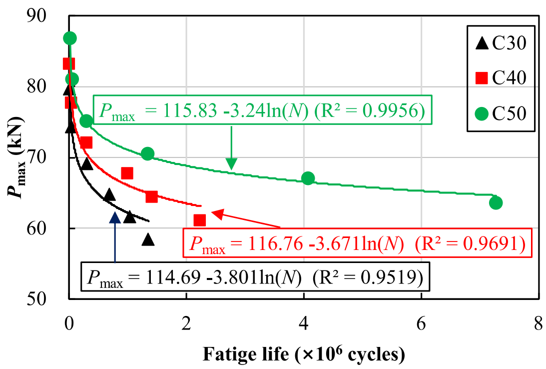


Fig. 9. Fatigue life prediction for RC slabs with different concrete strengths.

According to ACI 215R-74[23], the fatigue load corresponding to a fatigue life of $N = 2 \times 10^6$ cycles is considered as the fatigue limit. Therefore, by substituting $N = 2 \times 10^6$ into formulas (7) to (9), the fatigue limit for reinforced concrete slabs with different concrete strengths can be predicted, as shown in Figure 10. It can be observed that the fatigue limits for reinforced concrete slabs with concrete strengths C30, C40, and C50 are 59.54 kN, 63.50 kN, and 68.68 kN, respectively. Compared to C30, the fatigue limits of reinforced concrete slabs with C40 and C50 have increased by 6.6% and 15.6%, respectively. These results indicate a significant influence of concrete strength on the fatigue limit of reinforced concrete slabs.

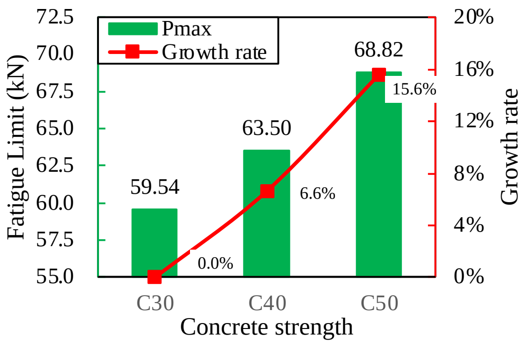


Fig. 10. Relationship between fatigue limit and concrete strength.

7. Conclusion

This study conducted a parametric analysis of the fatigue behaviour of reinforced concrete slabs using finite element analysis. A comprehensive evaluation of the effects of load level, concrete strength, and reinforcement ratio on structural deflection, reinforcement stress, and accumulated damage was performed. Additionally, a fatigue life prediction method was proposed. The key conclusions are as follows:

1. Fatigue load level, concrete strength, and reinforcement ratio significantly influence the deflection, reinforcement stress, and accumulated damage of reinforced concrete slabs. The primary form of structural fatigue failure is reinforcement fatigue rupture, but high load levels, low concrete strength, and reinforcement ratios can induce fatigue failure in concrete.
2. High load levels result in a faster degradation of structural natural frequencies. Increasing concrete strength and reinforcement ratio enhances the initial natural frequencies of the structure and mitigates the fatigue degradation of natural frequencies.
3. Predictive methods for the fatigue life of concrete slabs with different strengths were proposed. The fatigue limit is notably influenced by concrete strength.

Acknowledgements

The authors would like to acknowledge the supports of Ministry of Higher Education, Malaysia, through the Fundamental Research Grant Scheme (FRGS/1/2020/TK0/UM/02/27), Basic Ability Improvement Project for Young and Middle-aged Teachers in Colleges and Universities in Guangxi (2022KY1776), China.

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