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Original Research

Statistical Analysis of Ultimate Deflection and Load Assessment for One-Way Voided Slabs under Static Loads

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ABSTRACT

This study aimed to propose new formulas for predicting the ultimate deflection and load of reinforced concrete voided one-way slabs subjected to static loads. Since a predictive equation was not available in design codes, and the scarcity of statistical investigations offering predictive equations for this type of slab, a statistical analysis involving 86 specimens from the literature review was conducted using three methods: Stepwise Regression (SR) analysis, fitted line plot, and Pearson correlation. This study included twelve input variables that significantly affected the performance of the voided one-way slab: length of specimen (L), width of specimen (w), thickness of specimen (H), number of voids (N), longitudinal and transverse distances between voids (St and Ld), diameter of voids to slab thickness ratio (D/H), volume of voided slab to the volume of solid slab (Vvs/Vss), weight reduction ratio ($Wred\%$), shear span (a), shear span to effective depth ratio (a/d), and the square root of compressive strength of concrete $\sqrt{fc}$. Based on the input parameters, the ultimate deflection and load formulas were predicted, considering the output parameters. The result showed that the SR formulas exhibited greater accuracy than the other two regressions, with a determination coefficient (R^2) of 0.99 and 0.87 for ultimate deflection and load, respectively. The results of the Pearson correlation coefficient demonstrated that the correlation between the input and output variables ranged from strong to moderate or showed no statistical correlation.

Keywords: Stepwise regression, Fitted line plot method, One-way, Void slabs, Ultimate deflection

1. Introduction

Recently, there has been a growing demand for lightweight construction due to its many benefits, such as reducing self-weight, material consumption, costs, and CO_2 emissions, without compromising structural strength. Therefore, Jørgen Breuning in 1990 [1] introduced the voided slabs technique by removing ineffective concrete, resulting in a reduction in the weight of supporting members such as beams, columns, and footings. Load transfer occurs primarily in one direction through one-way voided slabs, and sudden failure can occur if the continuous load transfer is interrupted by voids in this direction. To ensure voided one-way slabs are properly supported and transfer loads correctly in one direction, their design requirements must be carefully considered. Therefore, the regression method used in this study significantly assists engineers in the early stages of design. Jabir et al. 2021 [1] investigated the influence of the shear span to effective depth (a/d) ratio on the behavior of one-way voided slabs under repeated loading. They concluded that, regardless of the a/d ratio, the presence of voids causes sudden shear failure. Additionally, they stated that increasing the a/d ratio decreased the strength, stiffness, and toughness of the slabs. The study also evaluated sustainability, confirming that voided slabs are more environmentally friendly than solid slabs. It was observed that voided slabs emitted about 14% less CO_2 and consumed roughly 10% less embodied energy than solid slabs. In 2019, Al-Gasham et al. [2] examined the relationship between void size and the structural response of one-way slabs under four-point loading. They stated that optimal performance was achieved when voids were half the thickness of the slab, with no significant reduction in strength. In 2014, Ali Oukaili et al. [3] investigated the behavior of prestressed one-way voided slabs with a void-to-slab thickness ratio of 0.67. The experimental results showed a significant increase in ultimate load and a decrease in deflection compared to non-prestressed slabs. Kim et al. 2011 [4] examined the influence of various void shapes on the performance of a voided one-way slab. The results indicated that doughnut-shaped voids had a more favorable effect on ultimate load capacity and stiffness than round box-shaped voids. Similarly, Chung et al. in 2022 [5] emphasized the importance of void shape, demonstrating that doughnut voids offer the greatest advantages. Construction incorporating steel fibers significantly improved the slabs' performance, increasing the ultimate load [6, 7]. Some researchers employed the same statistical method as in the current study to predict the buckling performance of castellated steel beams, the maximum lateral and vertical temperature gradient, and to evaluate the shear capacity of SFRC beams. They indicated that the accuracy rate and the coefficient of determination were high for applying these equations in practice [8-10].

Since no previous statistical studies were found to evaluate the behavior of a one-way voided slab subjected to static loads, and there are currently no specific rules or calculations for this type of slab in design codes, the experimental work also requires a high cost and time. Therefore, this study adopted three different statistical methods (stepwise regression, Pearson correlation analysis, and fitted line plot regression) to generate precise formulas for predicting the ultimate deflection and load. This research contributed to identifying which of these three methods offered the most reliable analysis, serving as a useful guide to help engineers select the best analysis method.

2. Research significance

The precise prediction of ultimate deflection and load of RC voided one-way slabs under static loads has not been the focus of prior research. Therefore, this study aims to fill a gap in previous investigations by employing three comprehensive statistical methods, including a multivariate regression approach (stepwise regression), a fitted line plot, and Pearson correlation to evaluate the behavior of one-way voided slabs. It also determined which of these methods provided the most reliable analysis according to the largest coefficient of determination obtained from these methods. Additionally, this research highlighted the most influential parameters on ultimate deflection and load based on Pearson correlation analysis.

3. Methodology

A total of 86 samples with 1,204 parameters were collected from previous studies [2-4, 6-12]. Considering all effective variables on the ultimate load and deflection, twelve parameters were selected as input variables for the regression models. Nine of these, including geometrical parameters such as specimen length (L), width (w), and thickness (H), specify the dimensions and shape of the slab, which directly influence the distribution of stress, strain, and load-bearing capacity. The longitudinal and transverse distances between voids (SL and ST) affect the load transfer paths, thereby impacting the loading capacity, while the void number (N) directly influences the distribution of materials within the cross-section, affecting the slab's resistance to bending and shearing. The volume of voided slab relative to the volume of the solid slab (Vvs/Vss) impacts structural behavior and self-weight. The ratio of void diameter to slab thickness (D/H) influences the effectiveness of the cross-sectional area. The weight reduction ratio ($Wred\%$) is closely linked to design efficiency and dead load reduction due to void formation, as well as its influence on slab behavior under loads. Two parameters relate to loading conditions: shear distance (a), which indicates the critical area subjected to shear forces, and the shear span to effective depth ratio (a/d), which reveals whether the slab behavior is dominated by flexure or shear. The remaining variable related to material properties is the square root of the compressive strength ($\sqrt{fc}$), which indicates material quality and significantly affects the slab's bearing capacity. The ultimate load (pu) and ultimate deflection (Δu) serve as the output variables for the models. The SR creation was performed using the Minitab software. Finding an appropriate function with a well-modified constant coefficient is the most crucial aspect. Therefore, a sensitivity analysis was conducted to examine the effects of the variables on the targets (ultimate deflection, ultimate load) by combining the variables used in established equations with the same variables but expressed in different mathematical forms that could influence the results, to enhance the accuracy of the equations, as shown in Table 1.

Table 1. Stepwise Regression Formulas (Inputs vs Equations)

Model	Input	Equation	R^2
Δu	$L, H, W, \frac{Vvs}{Vss}, N, \sqrt{fc}, a, St, Sl, \frac{D}{H}, \frac{a}{d}, Wred\ \%$	$\Delta u = -72.3 + 0.05865\, L + 0.0567\, W - 68.7\, \frac{Vvs}{Vss} - 0.442\, St + 0.204\, Sl + 170.5\, \frac{D}{H} - 5.033\, Wred\ \%$	0.87
Δu	$L, H, W, \frac{Vvs}{Vss}, N, \sqrt{fc}, a, St, Sl, \frac{D}{H}, \frac{a}{d}, Wred\ \%, L^2, H^3, W^3, \left(\frac{Vvs}{Vss}\right)^2, N^3, a^2, St^3, Sl^3, \left(\frac{D}{H}\right)^4, \left(\frac{a}{d}\right)^3, (Wred\ \%)^2$	$\Delta u = -163.9 - 0.1788\, L + 1.631\, H + 18.83\sqrt{fc} + 0.1338\, St + 25.40\, \frac{D}{H} + 33.47\, \frac{a}{d} + 0.000005\, L^2 + 0.000000\, H^3 - 6.32\left(\frac{Vvs}{Vss}\right)^2 + 0.000021\, N^3 - 0.03207\left(\frac{a}{d}\right)^3 - 0.01369\,(Wred\ \%)^2$	0.99
pu	$L, H, W, \frac{Vvs}{Vss}, N, \sqrt{fc}, a, St, Sl, \frac{D}{H}, \frac{a}{d}, Wred\ \%$	$pu = -1518 - 0.2173\, L + 6.66\, H + 0.630\, W + 138.3\sqrt{fc} - 1.702\, St + 241\, \frac{D}{H} + 31.9\, \frac{a}{d} - 4.27\, W\, red\ \%$	0.85
pu	$L, H, W, \frac{Vvs}{Vss}, N, \sqrt{fc}, a, St, Sl, \frac{D}{H}, \frac{a}{d}, Wred\ \%, L^2, H^3, W^3, \left(\frac{Vvs}{Vss}\right)^2, N^3, a^2, St^3, Sl^3, \left(\frac{D}{H}\right)^4, \left(\frac{a}{d}\right)^3, (Wred\ \%)^2$	$pu = -801 + 1.706\, W + 60.8\sqrt{fc} - 0.2364\, a - 0.000001\, W^3 - 98.1\left(\frac{D}{H}\right)^4$	0.87

To assess the precision of the predicted formulas, several accuracy metrics were used: R-squared coefficient of determination, average absolute error (AAE), and root mean square error (RMSE):

$$RMSE = \sqrt{\frac{\sum (Xpred - Xexp)^2}{n}} \tag{1}$$

$$AAE = \frac{\sum (Xpred - Xexp)}{n} \tag{2}$$

Where n is the number of records, $Xpred$ is the expected value, and $Xexp$ is the matching experimental record at the same time step [13].
R-squared coefficient (R^2): Measures the proportion of variance. Its value always ranges from 0 to 1.

4. Stepwise regression (SR) types

SR is a powerful statistical method to determine the connection between independent and dependent variables [14]. It determines the best fit between input and output variables to determine the optimal combinations of input variables. This can be discovered by changing variables that impact the remaining sum of squares. In 1963, Marquardt introduced the stepwise procedure as a powerful technique that considers adding and deleting variables at each step [15]. The two main methods of SR are forward selection and backwards elimination. Forward stepwise regression selection starts using the first input parameter, and with the process of forwarding, each parameter is investigated and its significance is measured, and if identified as unimportant, it is eliminated until they are removed. Conversely, the backwards remaining starts using all parameters at one time and then removes the least important variable before the other variables become important. The two methods can be used simultaneously.

5. Correlation of the experimental data

This section presents Pearson correlation analysis between the output parameters' ultimate deflection (Δu) and ultimate load Pu, with input parameters as well as the strength of the correlation for each relationship, as shown in Tables 2 and 3.

Table 2. The Strength of the Correlation between Δu and the included parameters

Relationship	Pearson Correlation	Strength of Correlation
Between Δu and L	0.701	Strong
Between Δu and H	0.486	moderate
Between Δu and w	0.390	weak
Between Δu and $\frac{Vvs}{Vss}$	-0.139	no correlation
Between Δu and N	-0.040	No correlation
Between Δu and $\sqrt{fc}$	-0.063	No correlation
Between Δu and a	0.255	weak
Between Δu and ST	0.426	Moderate
Between Δu and SI	0.424	Moderate
Between Δu and $\frac{D}{H}$	0.101	Very weak
Between Δu and $Wred\%$	0.043	No correlation
Between Δu and $\frac{a}{d}$	0.000	No correlation

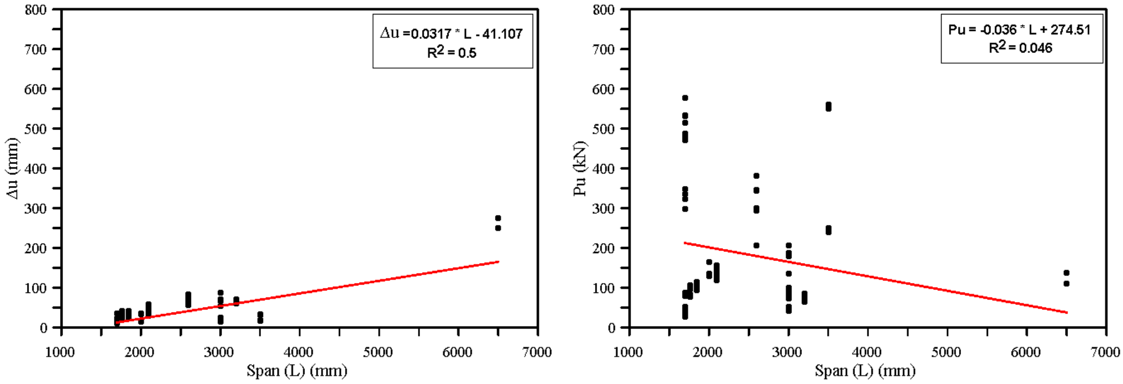
Table 3. The Strength of the Correlation between Pu and the included parameters

Relationship	Pearson Correlation	Strength of Correlation
Between Pu and L	-0.215	Weak
Between Pu and H	0.105	Very weak
Between Pu and w	0.435	moderate
Between Pu and $\frac{Vvs}{Vss}$	0.338	weak
Between Pu and N	0.184	Very weak
Between Pu and $\sqrt{fc}$	0.342	weak
Between Pu and a	-0.481	moderate
Between Pu and ST	-0.034	No correlation
Between Pu and SI	0.010	No correlation
Between Pu and $\frac{D}{H}$	0.738	strong
Between Pu and $Wred\%$	-0.610	strong
Between Pu and $\frac{a}{d}$	-0.552	strong

A positive correlation signifies that an increase in the predictor variable corresponds to an increase in the response variable. On the other hand, a negative correlation indicates that an increase in the predictor variable causes a decrease in the response variable [16]. The results showed that the most influential variable on the ultimate deflection was L, followed by thickness H, ST, and SI, with moderate strength. This demonstrates that these variables play an important role in determining the value of the deflection. The less significant or non-influential parameters affecting Δu were N, $\sqrt{fc}$, $\frac{Vvs}{Vss}$, $\frac{a}{d}$, and $Wred\%$. This could be attributed to several reasons: the relationship may be non-linear, Pearson's correlation measures only linear relationships, and these variables may not impact the deflection in this analysis. While the result between the ultimate loads and the input variables showed that the $\frac{D}{H}$ have the greater positive influence on $Wred\%$, and $\frac{a}{d}$ gave the most negative influence, on the behavior of the one-way voided slab, and the other parameters ranged from moderate to very weak influence on the ultimate loads, for the same reason mentioned above.

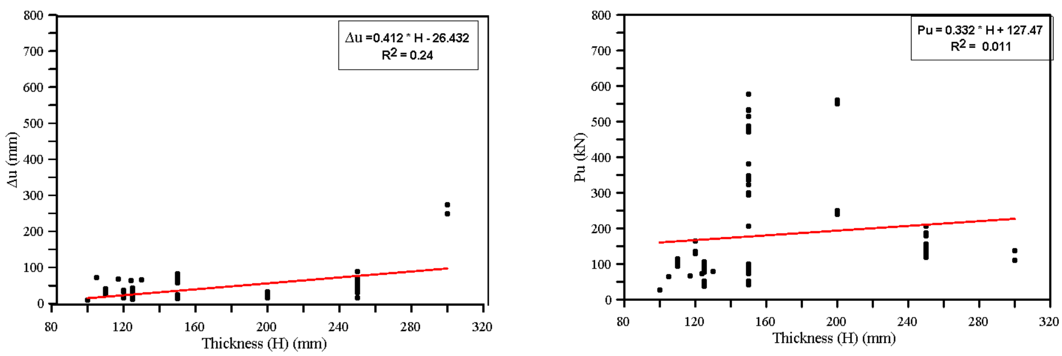
6. Fitted line plot (The scatter plot)

A fitted line plot is a graphical analysis used to show the relationship between two numerical parameters. All points on a scatter plot represent individual data points [16]. Its primary function is to identify patterns, trends, or correlations, whether positive, negative, or absent, between the two variables. It also helps in detecting outlier data points. Often, the formula of the fitted line is displayed on the plot, indicating the slope and intercept. These equations enable engineers to modify their structural designs to meet the required performance and safety standards. To evaluate the model's accuracy and reliability, the coefficient of determination R^2 is calculated. This metric provides a dependable indicator of the regression model's effectiveness by measuring how well it fits the experimental data. A high R^2 value shows that the model accurately captures the underlying trends and variations, confirming its suitability for structural design. Additionally, the accuracy of the model was assessed using S, the standard deviation of the actual distance between the fitted line and data points. A lower S value indicates that the model more precisely describes the response [17]. As shown in Figs. 1 through 12.



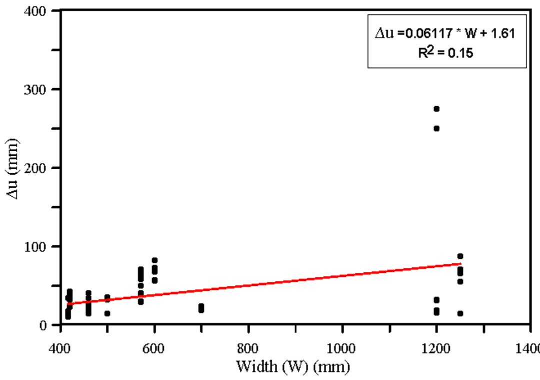
(a) Δu-L (b) Pu-L

Figure 1. Effect of Span (L) on the Scattering of Ultimate Deflection and Ultimate Load

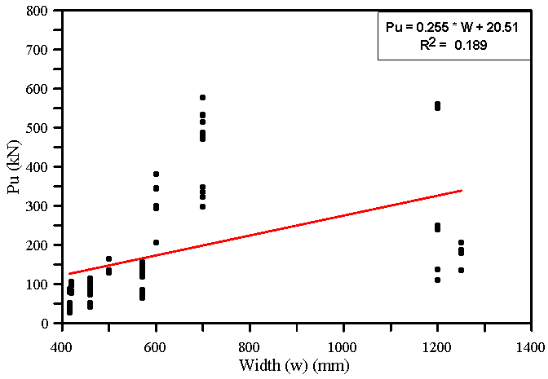


(a) Δu-H (b) Pu-H

Figure 2. Effect of Thickness (H) on the Scattering of Ultimate Deflection and Ultimate Load

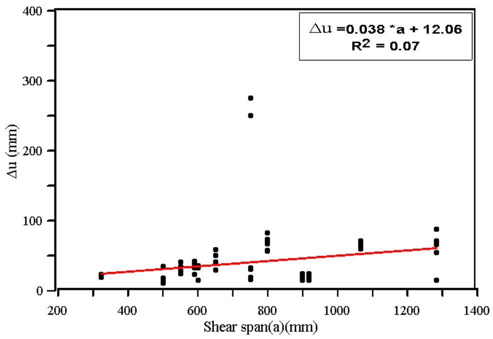


(a) Δu-W

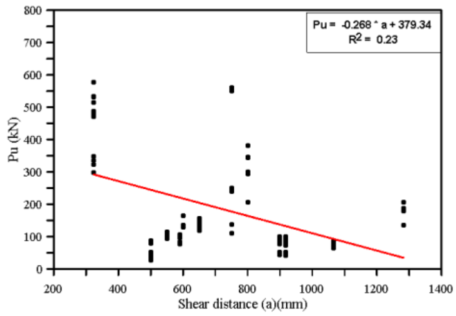


(b) Pu-W

Figure 3. Effect of Width (W) on the Scattering of Ultimate Deflection and Ultimate Load

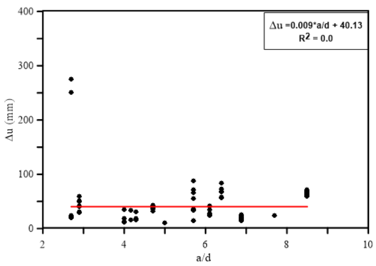


(a) Δu-a

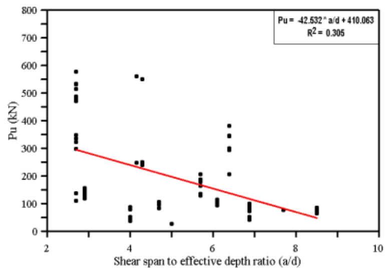


(b) Pu-a

Figure 4. Effect of Shear Span (a) on the Scattering of Ultimate Deflection and Ultimate Load

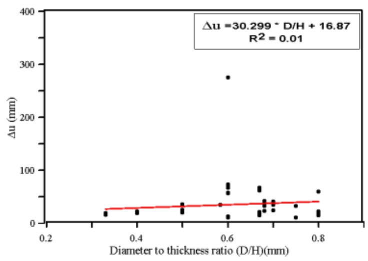


(a) Δu-$\frac{a}{d}$

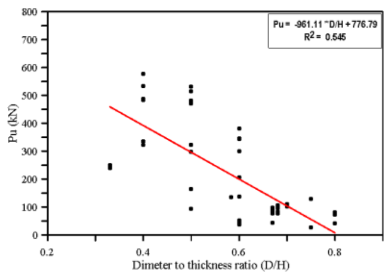


(b) Pu-$\frac{a}{d}$

Figure 5. Effect of Shear Span (a) on the Scattering of Ultimate Deflection and Ultimate Load

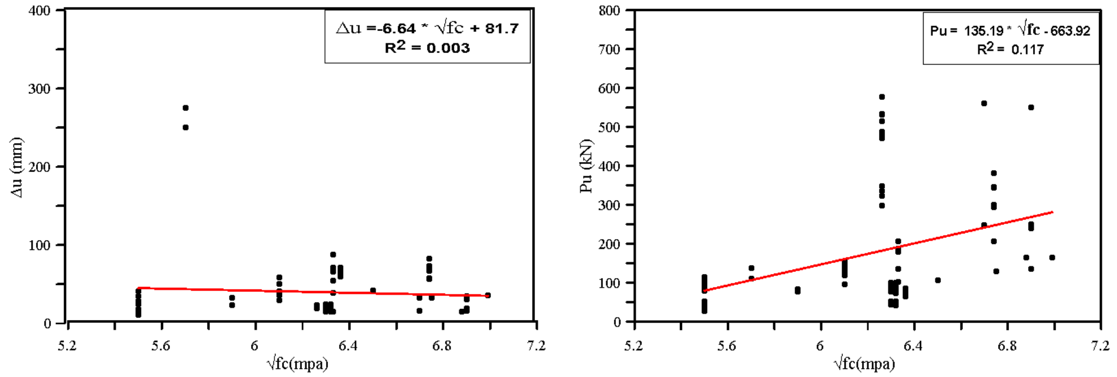


(a) Δu-$\frac{D}{H}$



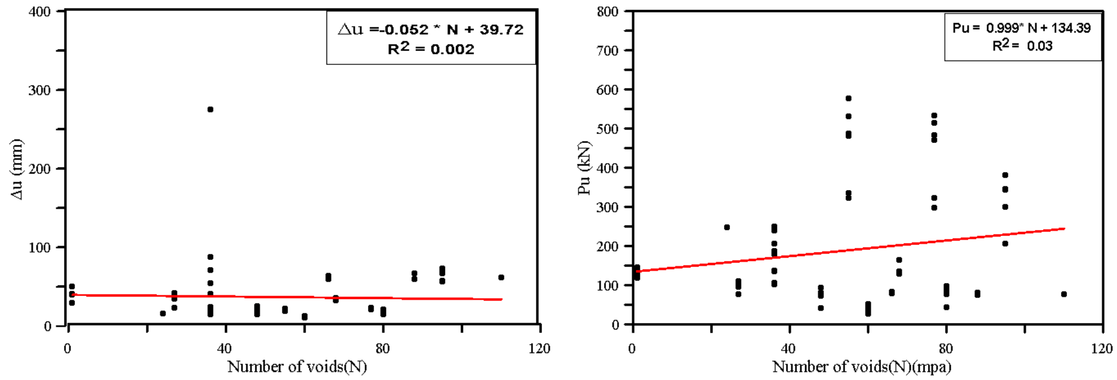
(b) Pu-$\frac{D}{H}$

Figure 6. Effect of Diameter-to-Thickness Ratio $\frac{D}{H}$ on the Scattering of Ultimate Deflection and Ultimate Load



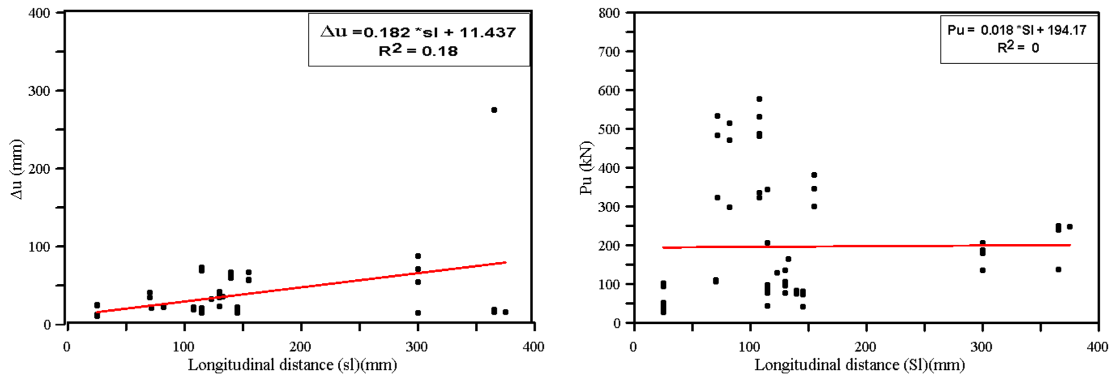
(a) Δu-$\sqrt{fc}$ (b) Pu-$\sqrt{fc}$

Figure 7. Effect of Compressive Strength Square Root on the Scattering of Ultimate Deflection and Ultimate Load



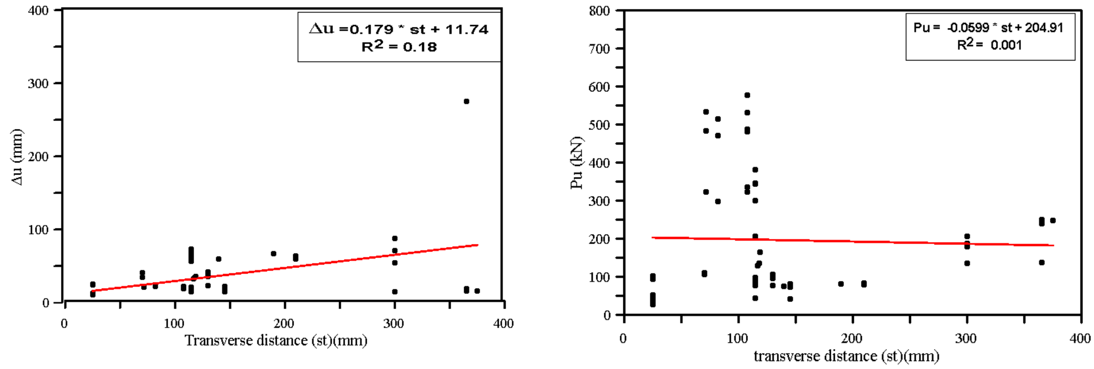
(a) Δu-N (b) Pu-N

Figure 8. Effect of the Number of Voids on the Scattering of Ultimate Deflection and Ultimate Load



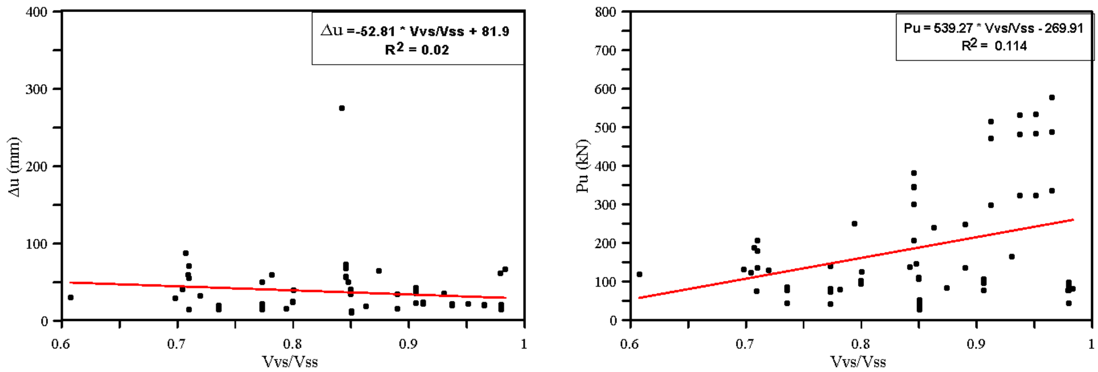
(a) Δu-Sl (b) Pu-Sl

Figure 9. Effect of Longitudinal Distance between Voids on the Scattering of Ultimate Deflection and Ultimate Load



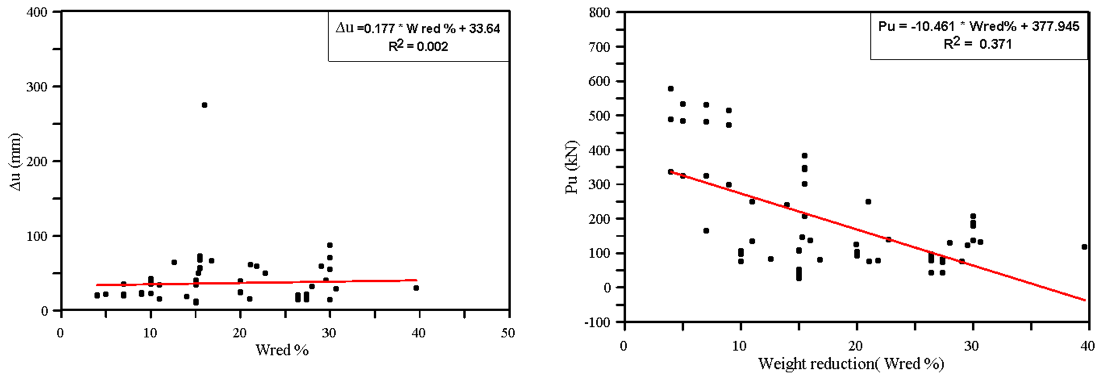
(a) Δu-St (b) Pu-St

Figure 10. Effect of Transverse Distance between Voids on the Scattering of Ultimate Deflection and Ultimate Load



(a) Δu-$\frac{Vvs}{Vss}$ (b) Pu-$\frac{Vvs}{Vss}$

Figure 11. Effect of Void Volume / Solid Volume on the Scattering of Ultimate Deflection and Ultimate Load



(a) Δu-$Wred\%$ (b) Pu-$Wred\%$

Figure 12. Effect of Weight Reduction on the Scattering of Ultimate Deflection and Ultimate Load

A positive relationship was shown between slab span and ultimate deflection, with an R^2 value of 0.5, indicating a moderate linear relationship between ultimate deflection and slab length. This suggests that some of the variability in ultimate deflection can be attributed to changes in length. The regression line, with a positive slope ($\Delta u = 0.0317L-41.107$), indicates that as the span increases, the ultimate deflection also increases. This behavior is expected both practically and theoretically in structural elements. The standard deviation ($\sigma = 28.7$) reflects a medium level of variability within the dataset, as illustrated in Fig. 1a. Conversely, the linear relationship between ultimate load and slab length was weak, with an R^2 value of only 0.046. The fitted line's negative slope

(-0.03641) indicates that the ultimate load decreases as the length of the one-way voided slab increases, signifying a reduced load-carrying capacity for longer slabs. Additionally, the higher standard deviation (σ = 147.28) suggests greater variability in ultimate load for a given slab length, as shown in Fig. 1b. The thickness of the slab has a minor effect on the variability of ultimate deflection, evidenced by the low R^2 value of 0.237 and a standard deviation of 35.2209. The equation indicates that the ultimate deflection increases by 0.4119 units for each unit increase in slab thickness (H), as illustrated in Fig. 2a. The correlation between ultimate load and slab thickness was very weak, as suggested by the low R^2 of 0.011, a high standard error (149.970), and a nearly horizontal slope in the fitted line plot. The equation implies that increasing slab thickness slightly increases the ultimate load, as shown in Fig. 2b. The fitted line plot between ultimate deflection and slab width demonstrated a weak relationship between them, due to minimal R^2 and high standard deviation. The equation suggests that increasing slab width leads to an increase in ultimate deflection. Similarly, the correlation between ultimate load and slab width is shown in Fig. 3. The remaining Figs. 4-12 show low R^2 values and nearly horizontal lines, indicating no significant effect of the remaining variables, N, $\frac{Vvs}{Vss}$, $\sqrt{fc}$, a, $\frac{a}{d}$, $ST, SL\ \ D/H$, and $Wred\%$ on the variation of both ultimate deflection and ultimate load. Furthermore, the standard deviation signifies a higher average distance between the fitted regression line and the data points.

7. Predicted ultimate deflection formula

Stepwise regression was conducted as a primary step to provide a simple formula with a high determination coefficient and variables raised to different powers, including $L, H, W, a, SL, FC, ST, D/H, a/d, Vvs/Vss\ , N, Wred\%$. Furthermore, the stepwise regression additionally incorporated their multipliers. Among the factors mentioned above, a simple equation was created with a high R^2, which equals 0.99 [2], as shown in Fig. 13. The suggested formula of ultimate deflection is:

$$\Delta u = -163.9 - 0.1788\,L + 1.631\,H + 18.83\sqrt{fc} + 0.1338\,St + 25.40\,\frac{D}{H} + 33.47\,\frac{a}{d} + 0.000005\,L^2 + 0.000000\,H^3 - 6.32\left(\frac{Vvs}{Vss}\right)^2 + 0.000021\,N^3 - 0.03207\left(\frac{a}{d}\right)^3 - 0.01369\,(Wred\,\%)^2 \quad (3)$$

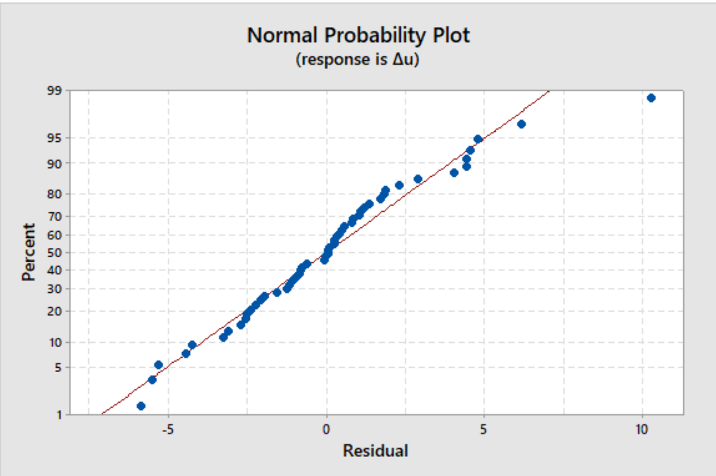


Figure 13. Normal Probability Plot of Ultimate Deflection Response

8. Predicted ultimate load formula

The correlation between the experimental ultimate loads from previous studies and the predicted values shows a strong agreement with an R^2 of 0.87 [14], as shown in Fig. 14. The suggested formula for the ultimate load is:

$$Pu = -801 + 1.706\,W + 60.8\sqrt{fc} - 0.2364\,a - 0.000001\,w^3 - 98.1\left(\frac{D}{H}\right)^4 \quad (4)$$

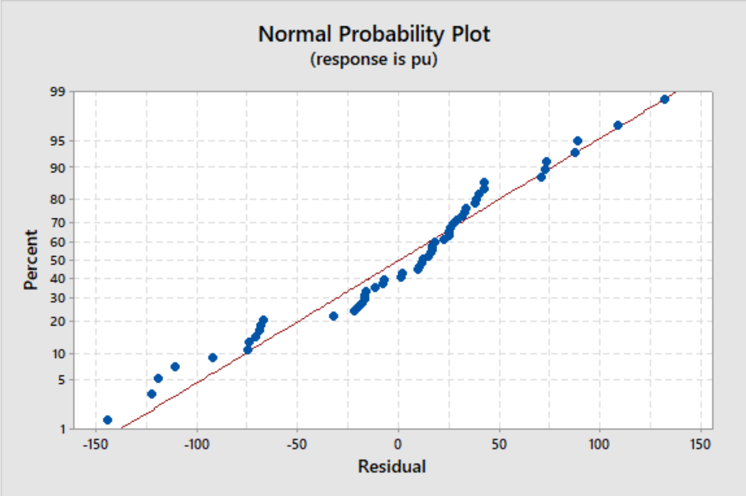


Figure 14. Normal Probability Plot of Ultimate Load Response

9. Conclusion

The current study collected 86 samples from previous studies to examine the ultimate deflection and load of the RC voided one-way slabs under static loads. A parametric study included twelve input variables, with the most influential ones on the performance of the one-way voided slab (ultimate deflection and load), which were considered as output variables. This analysis used various statistical methods (SR, fitted line plot, and Pearson correlation) to develop accuracy formulas and explore the relationships between ultimate displacement and load with input variables. The results showed :

1. It is obvious from the obtained R^2 value that the stepwise regression model exhibited more accurate prediction than the fitted line plot, with 0.99 and 0.87 R^2 for ultimate deflection and load, respectively. This outcome can be attributed to the ability of the multivariate regression method SR to identify and select the most significant predictors. This conclusion helped engineers select the suitable accuracy formulas for practice.
2. The strength and direction of correlation between input and output parameters were assessed using the Pearson correlation technique. A strong correlation was observed between Δu and L due to the person correlation being more than 0.4. A weak relationship was found between Δu and a/d due to the Pearson correlation equaling 0.00. Furthermore, a strong correlation was identified between Pu and D/H, as well as between Pu and $Wred\%$. In contrast, the relationships between Pu and the remaining variables were weak, in accordance with this analysis.
3. The regression model was visually represented through a fitted line plot. A nearly horizontal line in the plot indicates a weak relationship between the two variables. Conversely, a steep slope in the line signifies a strong relationship. The weak correlation between variables may be attributed to the non-linear relationships, and the fitted line plot analysis primarily examines linear trends.
4. It has been concluded that the combined influence of input variables is greater than the individual influence of input variables on the performance of voided one-way slabs; therefore, stepwise regression enhances the overall fit and predictive accuracy of the model.

5. Declaration of Competing Interest

6. The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

7. Funding Information

8. No funding was received from any financial organization to conduct this research.

9. Author Contributions

All authors proposed the research problem, in addition to authors Awad F.H. and Jabir H.A., who collected recent articles and organized them in simple shapes. Authors Awad F.H. and Jabir H.A. verified the recommendation in the proposed work. Author Awad F.H. designed and proposed the work. Authors Awad F.H. and Jabir H.A. discussed the proposed design. All the authors discussed the results and the final version of this paper.

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