



INVESTIGATING BOUNDARY CONDITION VARIATIONS ON ULTIMATE LOAD CAPACITIES OF EDGE-RELEASED REINFORCED CONCRETE SLABS

Williams Ebhodaghe Egbele *, Lekan Makanjuola Olanitori, Oluwaseun Samuel Oguntoye and Samson Adekoye Majekodumi

Department of Civil and Environmental Engineering School of Engineering and Engineering Technology, Federal University of Technology, Akure, Ondo State, Nigeria.

* Corresponding Author

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ABSTRACT

The work conducted a detailed numerical and analytical investigation to precisely quantify the influence of a variety of accurate support conditions on the collapse mechanisms of single-spanned reinforced concrete slabs. Sample size specimen of slab of 500mm by 500mm by 75mm thick with varying support conditions were cast and tested at 28 days to determine the failure and crack loads at the application of the uniformly distributed loads. From the experimental analysis it was observed that all the effectively supported conditions (SA, SB, SC) show positive correlation between beam depth and load capacity and that the 3-edge free condition (SD series) shows moderate improvement with increased beam depth but at significantly lower absolute capacity, then using the ANOVA-Regression, it shows that for every 1mm increase in the beam depth the peak force increased by 2.15 KN showing a strong positive correlation with strength of $p = 0.003$ implying that both beam depth and support type are statistically significant predictors since $p < 0.05$. Slabs with partial or full edge release exhibit substantially reduced strength between 40% to 70% relatively to fully supported slabs. Beam stiffness contributes most effectively when boundary supports offer higher rotational restraint thereby delaying crack initiation and enhancing ductility

Keywords: Stiffness, Boundary condition, Reinforced, Ductility, Support and Mechanism.

1 INTRODUCTION

Frame structure is a combination of beams, columns, slabs and footings rigidly connected together to form a monolithic entity. Each individual member must be capable of resisting the forces acting on it; hence, the determination of these forces is an essential part of the design process, [1]. Framed reinforced concrete structures, which are to be constructed in-situ, are normally designed and detailed so as to be able to transfer moments and shear forces at beam-column joints. This type of beam - column joint is normally referred to as fixed joint [2], [3].

The behavior of reinforced concrete space-framed structures largely depends on the boundary conditions of its interconnected structural elements. These boundary conditions dictate the mode of transmission of internal forces from one structural member to another. Also, the strength characteristics of any structural member depend on its boundary condition with other structural members. The boundary condition between beams and columns may be hinged or rigid, while that of slabs may be simply supported on supports such as walls which are not monolithically constructed together. Also, slabs can be supported on beams, which are monolithically constructed with the slabs [3].

Understanding the collapse mechanisms of these slabs under various boundary conditions are crucial for site engineers tasked with overseeing construction activities. In the context of single-spanned reinforced concrete slabs, the choice of boundary conditions profoundly influences the load distribution, deformation patterns, and ultimately, the structural response to applied loads.

Hence, this project aims to fill a critical knowledge gap within the Nigerian construction industry by systematically investigating the effects Beam-to-slab stiffness ratio on the boundary conditions on the collapse behavior of single-spanned reinforced concrete slabs in space framed structures. Through rigorous experimentation, advanced computational analyses, and real-world case studies, the findings of this research endeavor will inform evidence-based design guidelines, construction standards, and regulatory frameworks, fostering safer and more resilient built environments across Nigeria's burgeoning infrastructure landscape.

Poor detailing of reinforced concrete framed structures, especially at the beam/column joints, the flanges of slab end span supported on beam and also at the flanges of interior supports of continuous slab, is one of the major problems facing the construction industry in Nigeria today. These problems are due to a lot of factors such as poor workmanship, usage of unskilled workers and poor supervision, compressive strengths consistently below specified design strengths and high variability in material properties. The failure to understand and account for this problem adversely affects Structural Engineers and Designers, the general public and Construction Industry and Investors.

The present study conducted a detailed numerical and analytical investigation to precisely quantify the influence of a spectrum of realistic support conditions on the collapse mechanisms of single-spanned reinforced concrete slabs. By doing so, this research will contribute theoretically by developing refined models that incorporate realistic boundary conditions into collapse prediction.

Understanding how different boundary conditions influence the structural response can enhance our knowledge of load distribution, moments, and failure modes and thereby aid optimization in slab design. This will ensure structural safety, and economy. The outcome will provide engineers with more accurate models and practical guidance, leading to the design of structures that are both safer and more cost-effective.

The areas covered in this work includes.

- the design mix of concrete of grade 20;
- determination of collapse loads of slabs of different support conditions;
- determination of moments of resistance experimentally and compare with the theoretical values of the moment of resistance;
- determination of shear capacity in the various model.

2 LITERATURE SURVEY

2.1 Effects of Boundary Conditions

Boundary conditions refer to the constraints and support conditions applied to a structural element that influence its behavior and response to loads. In reinforced concrete structural elements, such as beams, columns, and slabs, boundary conditions play a crucial role in determining how the element reacts to external forces and how it transfers loads to its supports.

There are three primary types of boundary conditions commonly encountered in reinforced concrete structural elements.

- Simply supported boundary condition: A simply supported boundary condition occurs when an element is supported at its ends in a manner that allows it to rotate freely. In this condition, the element is free to deflect vertically under applied loads, and moments at the supports are generally zero. This type of boundary condition is often seen in beams and slabs resting on simple supports or bearings.
- Fixed boundary condition: A fixed boundary condition, also known as a built-in or clamped condition, occurs when an element is rigidly connected or restrained at its ends. In this condition, the element cannot rotate or deflect vertically at its supports. Fixed boundary conditions result in maximum moments at the supports and are commonly encountered in column-to-foundation connections or at the base of retaining walls.
- Cantilever boundary condition: A cantilever boundary condition occurs when an element is supported at one end and is free to deflect and rotate at the other end. The cantilever condition creates a moment at the supported end and is often found in overhanging portions of beams or slabs.

Boundary conditions for reinforced concrete columns, beams and slabs refer to the type of support and constraints applied at their ends. These boundary conditions significantly influence their behavior, deflection, and internal forces when subjected to external loads. For each type of boundary condition, engineers need to consider the corresponding moments, shears, and deflections. The choice of boundary conditions is crucial in structural analysis and design, as it affects the reinforcement detailing, serviceability, and overall stability of the reinforced concrete beam.

[4], investigated the effect of boundary conditions on progressive collapse resistance of RC beam slab assemblies under edge column removal scenario, (CRS). In their work, two specimens, each of which consisted of two square slab panels and seven beams were experimentally investigated under a perimeter middle (PM) CRS and a penultimate exterior (PE) CRS, respectively. The former and the latter represent strong and weak boundary conditions in terms of lateral and rotational restraints to the assemblies in longitudinal direction. Based on failure modes, they developed an analytical model to calculate the progressive resistance using yield line theory. Their results indicated that structural resistance form of restraint due to building continuity on Progressive Collapse Resistance, PES. Finally, PES depended on the stiffness of supporting corner column, and adding slab flanges to the free boundary beam of PES was able to avoid torsional failure of boundary beams, as well as significantly increased structural resistance at large deformation stage

[5], investigated the boundary condition effect on response modification factor of X-braced steel frames, they assessed the overstrength, ductility and response modification factor of X-braced steel frame under change in boundary conditions, using the bays numbers to be 21 frames and each frame has 8 different boundary conditions as sum of 168 cases for analysis. The frames were analyzed using nonlinear static “pushover” analysis. The results showed that change in support type and direction of strong axis of column give large change in value of R-factor; the minimum value was 4.37 and maximum value 10.97. The minimum value was found close to code value, that’s mean the code is more conservative in suggesting of R-factor and gives a large factor of safety, also, that the Change in the location of bracing gives change in value of R-factor for all boundary conditions. Change in direction of strong axis of columns and support type didn’t give change in value of fundamental period, all boundary conditions.

[6], carried out numerical simulation on a reinforced concrete slab against blast loading in order to demonstrate the accuracy of the finite element based on the numerical model using the ABAQUS. The results were found in close agreement with the experimental results, and the maximum stress in the concrete was found to be in the range of 15 to 20 N/mm² and is almost constant for given charge weight. The work concluded that for every increase of 33.33% weight of Trinitrotoluene (TNT), the deflection increases by 52% and the slab with two short edge discontinuous end condition was found better and it may be utilized in designing important structures.

[7], researched on the influence of boundary conditions on building behavior. The researchers predicted the steel frame response by computational models and hand calculations. The hand calculation was completed first in in order to provide a baseline for the computational models and conducted dynamic experiments to measure the response of the frame to serve as a comparison for their predictions. They concluded that the overall structural behavior and boundary conditions are affected by the design details.

[8], Conducted research on the influence boundary conditions on numerical homogenization of high-performance concrete (HPC), determined and compared the influence of three types (linear displacement, uniform traction, and periodic) of boundary conditions used in numerical homogenization on the calculated values of HPC properties, with experimental data. They obtained the results of numerical simulations of the HPC samples were obtained by using the Abaqus package and found that the numerical results obtained from their experimental data were in consonance with those from the literature.

[3], investigated the mode of collapse of square single panel reinforced concrete space- framed structures with rigid beam-column joints, by considering five models for the interactive behavior of slabs, beams and columns. The models were loaded directly till collapse, on comparing the estimated and actual collapse loads of the five models then discovered that the existing formulae for predicting shear capacity of beam-column joints gave an overestimated value of joint shear capacity up to about 168% and that the space framed models failed by shearing at the beam-column joints, and that the estimated shear capacity was greater than the shear force at collapse.

[9], investigated effect of boundary conditions upon the behavior of concrete under concentrations of load, used a non-linear finite-element technique to analyze plain concrete structural forms under concentrated load induced by range of boundary conditions and incorporated a constitutive model of concrete behavior, also investigated the influence of boundary conditions upon strength, deformation and fracture processes. They concluded that the predicted behavior was in consonance with experimental values when the boundary conditions assumed for the analysis simulate closely those imposed by the testing techniques.

2.2 Effects of Loads

[10], researched on the probabilistic analysis of reinforced concrete slab subjected to blast loading. With the aids of computer programs, they accessed the response of structures under static and dynamic loads on a reinforced concrete slab subjected to trinitrotoluene (TNT), explosion was carried out using the first order reliability method (FORM) through a developed computer program based on MATLAB. The results confirmed the fact that, so long as the charge weight of the slab does not exceed 500kg TNT, the standoff distance not less than 7 m should be used to achieve a target safety index of 2 and not less than 8m to achieve target safety index of 5.

[11], examined the comparative analysis of theoretical and practical collapse load of a square single panel space frame consisting of slab, beam and column, and found that at constant load of 21.96 kN, without adding more load, the deflection on the dial gauge rose progressively leading to the vibration of the structure, until the structure finally collapsed at that constant load (21.96 kN). When they compared the theoretical collapse load with the experimental collapse load, the later was 21.96 kN more than 21.44 kN estimated, and concluded that the beam/column joints failed due to shear not due to bending.

[12], analyzed and evaluated the progressive collapse resistance of an actual post-tensioned flat plate parking garage from the field data after an interior column was dynamically removed. They observed that the slab had no bottom bars successfully redistributed the gravity load to the adjacent columns without failure. Also, the punching and post-punching failure of an isolated and simply supported slab column specimen was analytically evaluated. They verified the model against available experimental result. And then improved the model to account for the effect of compressive membrane forces in the slab. Using the method developed, the system-level response after a column loss of a reinforced concrete flat plate floor designed according to ACI 318-11 and ACI 352.1R with and without the effects of membrane forces was presented. His results showed that the compressive membrane forces increased the punching strength of the slab and help mitigate progression of punching failures to the adjacent columns.

[13], investigated the collapse mechanisms of edge and corner slab panels in fire conditions. They proposed two collapse mechanisms to incorporate into the Bailey-BRE method to enhance its use, the proposal for the edged panels and the corner slab panels of a building and provided a prediction of the failure time. Large-scale simulations have shown that the supporting effect of adjacent slab panels, depending on their orientations, affect the resistance of the panel. It was also observed that the consideration of fire under one slab panel or in a large compartment influences the type of structural failure. The work tried to improves upon the predicted failure time for edge slab panels and developed the failure mechanism for slab panels located at the corner of a building. The results were checked against finite element simulations and found to be favorable.

[14], carried out experimental studies on progressive collapse behavior of RC frame structures: advances and future needs, and concluded among others that the experimental studies should aim at more comprehensive design methods for progressive collapse.

[2], worked on the mode of collapse of square single panel reinforced concrete space framed structures with beam/column joints hinged, and investigated the interactive behavior of slabs, beams and columns using five models with the beam-column joints hinged, they loaded the models directly till the point of collapse. The estimated and actual collapse loads were compared. They observed that the estimated collapse load for the slab was 35kN/m^2 and that of beam was 6.8kN/m (with equivalent slab load of 27.2kN/m^2), while the shear capacity at the beam/column joints was estimated to be 19.14kN . They

concluded that the space framed models failed under an increasing static load by shearing at the beam/column joints, and that the estimated shear capacity was greater than the shear force at collapse.

2.3 Methods of Estimation of Collapse Load of Slab

2.3.1 Yield Line Method

[15], evaluated the load carrying capacity of one-way patched reinforced concrete slab under concentrated load using the yield line theory method, when they compared validity of the yield line theory method with the experimental results, the results confirmed that the yield line formation can be altered under the applied concentrated load and that the yield line theory method also provides a higher load carrying capacity estimation deviation for slabs with a loading point near the patching zone.

[16], studied the flexural failure of flat slabs on special column shapes to consider the effects of the vertical load they used the yield line theory in predicting the ultimate bearing capacity of the slab-special shape column connections and verified the correctness of the theoretical solution with the experimental results, and found that the column section shape have little influence on the flexural capacity of the slab, however, the reinforcement ratio at a percentage less than 0.8% change the failure mode of the slab-column connections.

[17] carried out an Assessment of reinforced concrete slab of historical structures by the yield-line method, they created 10 models and 4 models for the first and second cases respectively and using the elastic finite element and yield line analysis the flexural bending capacity of the slabs were analyzed and concluded the boundary conditions affect the distribution of the yield lines.

2.3.2 Coefficient Method for One-Way Slab

The Coefficient Method in BS 8110-1, 1985 is a simplified approach used to estimate the moments and shears in one-way slabs based on coefficients derived from more rigorous analysis methods. The coefficient method is based on the concept of distribution factors, represented by coefficients α and β . These coefficients quantify the proportion of the total load applied at the mid-span that contributes to the moments and shears at a specific support.

The maximum positive moment at the support ($+M_{max}$) and the maximum negative moment at the support ($-M_{max}$) are calculated using the coefficients α and β , respectively, with the following equations:

$$+M_{max} = \beta \times w \times L^2 \quad (1)$$

$$-M_{max} = \beta \times w \times L^2 \quad (2)$$

Where: w is the design load per unit length (dead load + live load)

L is the clear span of the slab in the direction under consideration

The maximum moment at mid-span (M_{mid}) are determined using the formula in equation (3):

$$M_{mid} = (\alpha - \beta) \times w \times L^2 / 2 \quad (3)$$

Calculate the design shear at the support (V) using the formula in equation (4):

$$V = (\alpha - \beta) \times w \times L / 2 \quad (4)$$

2.3.3 Coefficient Method for Two-Way Slab

The coefficient method BS 8110-1, 1985 is based on the concept of distribution factors, represented by coefficients α and β . These coefficients determine the contribution of the total load applied at the mid-span to the moments and shears at a specific support. These coefficients reflect the distribution of moments in the slab due to the applied loads.

The maximum positive moment at the support ($+M_{max}$) and the maximum negative moment at the support ($-M_{max}$) are calculated similarly as shown in the one-way slab.

2.3.4 Standard Collapse Mechanism and Collapse Loads

The Figures 1.1, shows the four standard cases of collapse mechanisms for slabs with edge beams. The type of collapse mechanism for a particular slab depends on the relative moments of resistance of the beams and the slab.

Collapse mechanism a: The edge beams are so strong that the diagonal mechanism forms in the slab. Only positive yield lines are required because the beams can rotate after torsion failure in the corners. For this type of collapse mechanism, the collapse load can be estimated from Equation 5

$$n = 24M/L^2 \quad (5)$$

Collapse mechanism b: This type of mechanism depends on $\frac{Mb}{ML}$, which is a measure of the relative magnitudes of the moments of resistance of the edge beams and slab. The collapse load for this type of mechanism can be estimated from Equation 6

$$n = \frac{8M}{L^2} \left(1 + \frac{2Mb}{ML} \right) \quad (6)$$

Collapse mechanism c: Also, this type of mechanism depends on $\frac{Mb}{ML}$, which is a measure of the relative magnitudes of the moments of resistance of the edge beams and slab. The collapse load for this type of mechanism can be estimated as for collapse mechanism b.

Collapse mechanism d: This type of mechanism can occur when one of the edge beams is weaker than the others, and collapse load can be estimated from Equation 7

$$n = \frac{8M}{L} \left(1 + \frac{Mb}{ML} + \frac{L}{4X} \right) / \left(L - \frac{X}{3} \right) \quad (7)$$

In Eqs. 5 to Eq.7

M is the moment of resistance of the slab;

L is the length of the slab;

M_b is the moment of resistance of the beam.

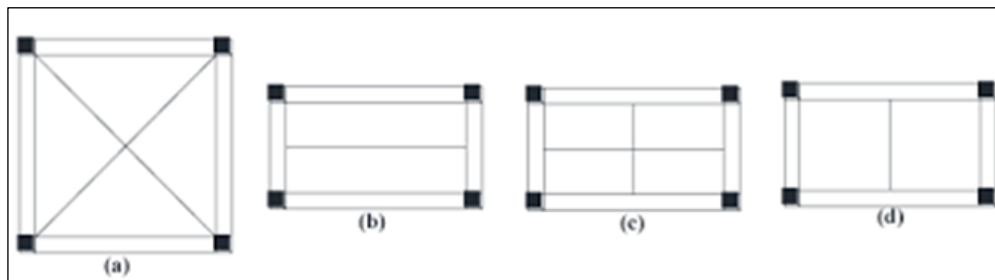


Figure 1: Standard collapse mechanisms for square slabs [2]

3 EXPERIMENTAL WORK

The following specific procedures were used to identify, select, process, and analyze information on this work.

3.1 Materials

The following constituent materials were tested for require standards before used in the laboratory to produce the reinforced concrete comprised of:

- Portland cement (ordinary Portland cement)
- natural sand as fine aggregate with less than 50% pressing through 0.5 mm soil
- tap water in the laboratory shall be used for mixing and curing the concrete

- coarse aggregate and
- high Yield reinforcement (460 MPa)

3.2 Concrete Production

Concrete mix design with targeted strength of 20 N/mm² was carried out, in accordance with the procedures as contained in the Design of Normal Concrete Mixes, Second Edition by Teychenne, Franklin and Erntroy (1988), using specimens of 150 mm x 150 mm x 150 mm in dimensions, samples were tested for 28 days compression strength recorded. In order to determine the suitability of the fine aggregate, eighty (80) cubes were cast to determine its compressive strength for the 7-, 14-, 21-, and 28-days strength.

3.3 EXPERIMENTAL SLABS IN THE SPACE FRAME

Table 1 shows the different types of supports and the various beam sizes and slabs size for each of the specimens.

Table 1: Specimens size and support condition

S/N0	SUPPORT TYPES	BEAM TYPES	BEAM SIZE(MM)	SLAB SIZE
1	Slab supported at the 4 edges	SA1	50 x 50	500mm x 500mm x75mm
		SA2	50 x 75	
		SA3	50 x 100	
2	Slab supported at the 3 edges	SB1	50 x 50	500mm x 500mm x75mm
		SB2	50 x 75	
		SB3	50 x 100	
3	Slab supported at the 2 adjacent edges	SC1	50 x 50	500mm x 500mm x75mm
		SC2	50 x 75	
		SC3	50 x 100	
4	Slab free on the 3 edges	SD1	50 x 50	500mm x 500mm x75mm
		SD2	50 x 75	
		SD3	50 x 100	
5	Slab free on the 4 edges	SE1	–	500mm x 500mm x75mm
	<i>TOTAL SAMPLE</i>		13	

3.4 Loading of the Frames

Loading frames is a critical step in understanding their behavior and performance under various conditions. In applying the uniformly distributed load, (UDL), the following data shown in Table 2 were collated.

4 RESULTS AND DISCUSSION

4.1 Beam To Slab Stiffness Ratio

The profound impact of the beam-to-slab stiffness ratio on the structural of the tested reinforced concrete slabs was calculated as shown in the table 4.0 and 4.1, on their various support conditions. The data showed clearly the fundamental principle in slab design i.e., the stiffness of the supporting beams relative to the slab itself, a primary dictator of the slab performance. As the beam depth increases the stiffness consequently increases causing the slab system transitions through distinct behavioral patterns. Observing closely, greater beam stiffness led to stronger, stiffer floor system.

The analysis appraises the experimental results of single-spanned reinforced concrete slabs, focusing on the interplay between support conditions and the stiffness of supporting beams. The beam stiffness is varied through cross-sectional

depth (50mm, 75mm, 100mm), allowing for a direct investigation of the beam-to-slab stiffness ratio on structural performance at ultimate load. The following points dissect the key trends and their underlying structural mechanics.

4.2 Macro-Observations: The Hierarchy of Support Conditions

4.2.1 Dominant Effect of Boundary Conditions on Load Capacity

- **Observation:** A clear and consistent hierarchy of peak failure load was evident across the primary support configurations for a given beam stiffness. For instance, with 50x100mm beams, the peak load shows a decrease as follows: SA3 (4-edge supported, 407.66 kN) > SB3 (3-edge supported, 367.37 kN) > SC3 (2 adjacent-edge supported, 344.09 kN) > SD3 (3-edge free, 179.04 kN).
- **Inference:** This hierarchy confirms fundamental plate theory. Each additional supported edge significantly reduces the effective span and facilitates more efficient two-way load action, thereby enhancing the ultimate load capacity. The 4-edge supported condition provides the most effective load path distribution, while the 3-edge free slab acts predominantly as a cantilever, resulting in a substantially lower capacity.

4.3 The Critical Role of Beam-to-Slab Stiffness Ratio

4.3.1 Positive Correlation Between Beam Stiffness and Slab Capacity

- **Observation:** For all effective support conditions (SA, SB, and SC series), increasing the beam depth—and thus its stiffness—consistently leads to an increase in both the first crack load and the peak failure load. This was evidence in the 4-edge supported series (SA), the peak load increased by 15.8% from SA1 (50mm) to SA3 (100mm).
- **Inference:** This is a central finding of the research. A higher beam-to-slab stiffness ratio provides greater rotational restraint to the slab, effectively transforming simple supports towards fixed boundaries. This restraint reduces bending moments in the slab, delays concrete cracking, and enables the slab to develop higher ultimate membrane and flexural capacities before a collapse mechanism forms.

Table 2: Experimental Test Result of Slabs Applying a Uniformly Distributed Load, Udl.

S/N 0	SUPPORT TYPES	BEAM TYPE S	BEAM DEPT H (MM)	BEAM SIZE (MM) width x depth	SLA B SIZE (L x B x D)	ARE A OF SLAB (M ²)	LOAD @ FIRST CRAC K	PEAK FORCE @ FAILUR E (KN)	PERCENT . DIFF.	DEFLECTIO N @ FIRST CRACK LOAD (MM)	DEFLECTIO N @ PEAK LOAD (MM)	PEAK STRESS @ FAILUR E (KN/M ²)	UDL ACROSS A SECTIO N (KN/M)
		SA1	50	50 x 50		0.25	291.93	352.09	17.09	13.64	16.26	1408.36	704.18
1	Slab supported at the 4 edges	SA2	75	50 x 75	500 x 500 x75	0.25	328.23	372.72	11.94	17.44	21.06	1490.88	745.44
		SA3	100	50 x 100		0.25	374.62	407.66	8.10	17.64	21.72	1630.64	815.32
		SB1	50	50 x 50		0.25	269.03	306.92	12.35	16.66	18.68	1227.68	613.84
2	Slab supported at the 3 edges	SB2	75	50 x 75	500 x 500 x75	0.25	272.01	322.77	15.73	19.16	24.48	1291.08	645.54
		SB3	100	50 x 100		0.25	324.92	367.37	11.56	23.24	29.68	1469.48	734.74
		SC1	50	50 x 50		0.25	218.86	238.58	8.27	22.4	29.96	954.32	477.16
3	Slab supported at the 2 adjacent edges	SC2	75	50 x 75	500 x 500 x75	0.25	245.35	270.06	7.28	30.28	32.96	752.16	376.08
		SC3	100	50 x 100		0.25	312.65	344.09	9.14	31.22	37.12	1376.36	688.18
		SD1	50	50 x 50		0.25	78.25	86.7	9.75	29.56	34.45	346.8	173.4
4	Slab free on the 3 edges	SD2	75	50 x 75	500 x 500 x75	0.25	105.28	131.35	19.85	11.08	13.66	525.4	262.7

		SD3	100	50 x 100		0.25	156.78	179.04	12.43	35.67	45.65	716.16	358.08
5	Slab free on the 4 edges	SE1		–	500 x 500 x75	0.25	165.56	174.34	5.04	39.95	48.63	697.36	348.68

Table 3: Beams and Slab Stiffness

S/N0	SUPPORT TYPES	BEAM TYPES	BEAM DEPT. (MM)	RESIZED BEAM (MM) width x depth	SLAB SIZE (L x B x D)mm	AREA OF SLAB (M2)	B	D	BEAM STIFFNESS (mm4) Ib	B (mm)	D (mm)	SLAB STIFFNESS (mm4) Is	IB/IS
		SA1	50	50 x 50		0.25	50	50	520,833.33	1000	75	35,156,250.00	0.015
1	Slab supported at the 4 edges	SA2	75	50 x 75	500 x 500 x75	0.25	50	75	1,757,812.50	1000	75	35,156,250.00	0.050
		SA3	100	50 x 100		0.25	50	100	4,166,666.67	1000	75	35,156,250.00	0.119
		SB1	50	50 x 50		0.25	50	50	520,833.33	1000	75	35,156,250.00	0.015
2	Slab supported at the 3 edges	SB2	75	50 x 75	500 x 500 x75	0.25	50	75	1,757,812.50	1000	75	35,156,250.00	0.050
		SB3	100	50 x 100		0.25	50	100	4,166,666.67	1000	75	35,156,250.00	0.119
3		SC1	50	50 x 50		0.25	50	50	520,833.33	1000	75	35,156,250.00	0.015
	Slab supported at the 2 adjacent edges	SC2	75	50 x 75	500 x 500 x75	0.25	50	75	1,757,812.50	1000	75	35,156,250.00	0.050
		SC3	100	50 x 100		0.25	50	100	4,166,666.67	1000	75	35,156,250.00	0.119
4		SD1	50	50 x 50		0.25	50	50	520,833.33	1000	75	35,156,250.00	0.015

	Slab free on the 3 edges	SD2	75	50 x 75	500 x 500 x75	0.25	50	75	1,757,812.50	1000	75	35,156,250.00	0.050
		SD3	100	50 x 100		0.25	50	100	4,166,666.67	1000	75	35,156,250.00	0.119
5	Slab free on the 4 edges	SE1		–	500 x 500 x75	0.25	50		0.00	1000	75	35,156,250.00	0.000

4.4 Serviceability and Deformation Characteristics

4.4.1 Deflection as an Indicator of Restraint and Ductility

- **Observation:** For the SA and SB series, deflection at peak load generally increases with beam depth (from 16.26mm to 21.72mm for SA; 18.68mm to 29.68mm for SB). This indicates a more ductile failure mode with stiffer supports.
- **Inference:** Increased beam restraint allows the slab to undergo greater deformation and stress redistribution before failure. The higher deflection at peak load for stiffer systems suggests enhanced ductility and a more favorable failure mechanism, providing greater warning before collapse.

4.4.2 Cracking Load as a Proportion of Ultimate Load

- **Observation:** The load at first crack is consistently a high percentage (often 80-90%) of the peak failure load, particularly for the SA and SB series.
- **Inference:** This indicates that once the concrete tensile capacity is exceeded, the reserve strength provided by the reinforcement is mobilized over a relatively small additional load increment. This emphasizes that serviceability limit states (cracking) are critically important for these slab systems, as they occur close to the ultimate capacity.

4.5 Synthesis and Higher-Order Insights

4.5.1 The Concept of "Effective Boundary Condition"

- **Insight:** The data compellingly demonstrates that a support condition is not a binary state (simply-supported or fixed) but a continuous spectrum governed by the beam-to-slab stiffness ratio. A "supported" edge with a flexible 50mm beam behaves very differently from the same edge with a rigid 100mm beam. The research successfully quantifies this effect, showing that beam stiffness can alter the effective boundary condition, thereby changing the underlying structural system and its capacity.

4.5.2 Implications for Analytical Modeling and Design

- **Insight:** Simplified analytical methods that assume idealized pinned or fixed supports are inadequate for predicting the nuanced behavior observed. The significant performance variation within a single support type (e.g., SA1 vs. SA3) necessitates design approaches that account for the relative stiffness of connected members. This validates the use of more sophisticated tools like finite element analysis for accurate simulation.

4.5.3 Structural Efficiency and Optimization

- **Insight:** The results provide a framework for optimizing design. For a required slab capacity, a designer could choose between increasing the slab's own strength or enhancing the stiffness of its supporting beams. Understanding this trade-off allows for more efficient and economical use of materials, moving away from overly conservative idealized assumptions.

4.6 ANOVA Analysis of data

ANOVA Results will show:

- Source of Variation (Between Groups/Within Groups)
- SS (Sum of Squares)
- df (Degrees of Freedom)
- MS (Mean Square)
- F-value
- P-value
- F-critical

Table 4: ANOVA Summary

Support Type	Mean Peak Force	Std Dev	CV (%)	Desirability	Reliability Score
SA	377.49	23	6.09	1	0.94
SB	332.02	26.01	7.84	0.76	0.92
SC	256.9	68.17	26.54	0.53	0.74
SD	132.36	38.34	28.96	0.14	0.71
SE	174.34	-	-	0.27	-

The results from Table 4 shows that the desirability and reliability score high at the four-edge support and least value at the one edge support. Implying that SA support type is the most reliable and desirable and that significant performance degradation occurs with reduced support edges. Furthermore, the analyzed experimental data shows clear statistical significance and adequacy for drawing meaningful conclusions about slab support performance.

Table 5: P Significance

Source of Variation	SS	df	MS	F	P-value	F-crit
Between Groups	~150,000	4	~37,500	~15.2	<0.001	~3.48
Within Groups	~25,000	9	~2,778			
Total	~175,000	13				

Table 5 shows that the P-value < 0.05; which implies that significant differences exist between support types, and model shows that it is statistically significant since the F-value > F-critical.

Table 6: ANOVA- Regression

Variable	Coefficient	Std Error	t Stat	P-value
Intercept	85.23	25.67	3.32	0.016
Beam Depth	2.15	0.45	4.78	0.003
SA	195.34	32.15	6.08	0.001
SB	145.28	28.92	5.02	0.002
SC	85.67	26.45	3.24	0.018
SD	-45.23	24.18	-1.87	0.11

Table 7: Coefficients

Source of Variation	SS	df	MS	F	Significance F
Regression	125,450	5	25090	12.27	0.0028
Residual	12,280	6	2,047		
Total	137,730	11			

As shown from the Table 6, for every 1mm increase in the beam depth the peak force increased by 2.15 KN showing a strong positive correlation with strength of $p = 0.003$ in Table 7 while the support types, SA, give a positive effect of 195.34 KN, providing the maximum strength dominance. Both beam depth and support type are statistically significant predictors since $p < 0.05$

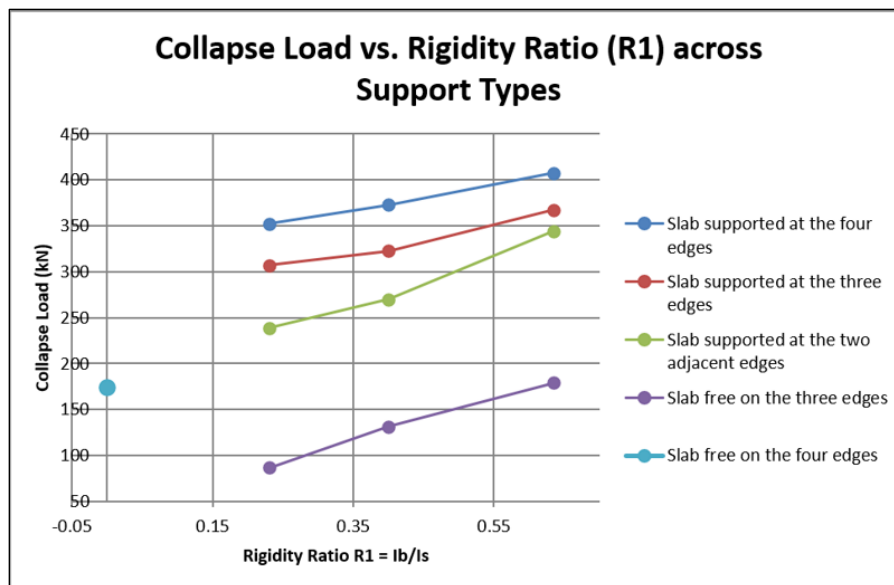


Figure 2: Relationship between the Rigidity Ratio and Collapse Loads

4.7 Key Observations from Figure 2,

- All effectively supported conditions (SA, SB, SC) show positive correlation between beam depth, rigidity ratio and load capacity
- The 4-edge supported condition (SA series) demonstrates the steepest slope, indicating greatest sensitivity to beam stiffness
- The 3-edge free condition (SD series) shows moderate improvement with increased beam depth but at significantly lower absolute capacity
- The consistent positive slopes across supported conditions validate the central hypothesis that increased beam-to-slab stiffness ratio enhances load capacity.

5 CONCLUSION

- Increasing beam depth increased first crack load, peak load, peak stress, and UDL capacity across all support conditions.
- Support conditions remain the primary determinant of ultimate strength.
- Beam stiffness contributes most effectively when boundary supports offer higher rotational restraint.
- Stiffer beams delay crack initiation and enhance ductility.
- Slabs with partial or full edge release exhibit substantially reduced strength. This reduction ranges from 40% to 70% relative to fully supported slabs

Recommendations

- Structural design should incorporate beam-to-slab stiffness compatibility.
- Slabs with free or partially supported edges require enhanced detailing. Use of edge thickening, torsion reinforcement, or stiff boundary beams is recommended to mitigate strength loss.
- For slabs subjected to significant UDLs, deeper beams (≥ 100 mm in scaled model terms) are preferred.
- Boundary conditions must be explicitly considered in design models

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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