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Observational Study

Comparative analysis of collapse loads of slabs supported on orthogonal Sided frames with beam/column joint fixed

Abstract

This research evaluates the collapse loads of slab supported on orthogonal sided frames with beam/column joint fixed. Two frame models were investigated (one with moment of resistance of slab (M_{RS}) > moment of resistance of beam (M_{RB}) and the other with moment of resistance of slab (M_{RS}) < moment of resistance of beam (M_{RB}).

A reinforced concrete prototype of 3m×3m×3m frame with a reduction factor of 3 was designed and constructed. A model of it constructed and cast with a micro concrete of 1:6 mix ratio. The models were allowed to cure for 28 days before being loaded directly until collapse. Loading of the RC frame model was done by a fabricated loading box of 1.0 × 1.0 × 3.0m size placed on top of its slab. Sands were poured into the panel using head pans. The weight of sand on each head pan (1.84kN). Two dial gauges were used; one was set at the center of the bottom of the slab while the other was set below the center of the bottom of the beam to monitor and measure the deflection at ten head pans of sand.

The estimated collapse load for slab and beam were 20.36kN/m and 52.27kN/m respectively. The actual collapse loads for $M_{RS} > M_{RB}$ and $M_{RS} < M_{RB}$ frame models were 69.04kN/m and 49.68kN/m respectively. The frame model failed by flexural failure at the beams/column joints. The actual collapse load of 69.92kN and 49.68kN respectively were greater than that of the estimated collapse loads of beam and slab comparably. Also the $M_{RS} > M_{RB}$ frame model is stronger than that of the $M_{RS} < M_{RB}$ frame model.

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].

Also, structural frames can be said to be composed of one-dimensional members connected together in skeletal arrangements which transfer the applied loads to the supports. While most frames are three-dimensional, they may often be considered as a series of parallel two-dimensional (plane) frames, or as two perpendicular series of two-dimensional (plane) frames (Trahair, Bradford and Nethercot, 2001). The behavior of a structural frame depends on its arrangement and loading, and on the type of connections.

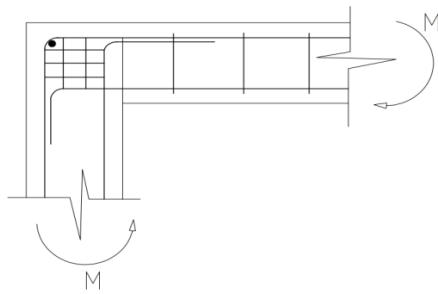
With three dimensional structures, even with quite small structures, there can be a large number of joints each with six degrees of freedom. Therefore, the number of simultaneous equations to be formed and solved is six times the number of

joints (6j), which leads to very expensive computer runs in order to get a solution for the whole structure. Hence, it is usual to adopt some form of simplification to reduce the tediousness.

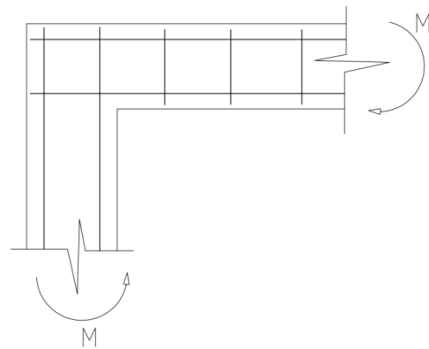
Framed reinforced concrete structures, which are to be constructed in-situ, are normally designed and detailed (as in Graph 1a) so as to be able to transfer moments and shear forces at beam-column joints. However, it is very common to see such detailing as in Graph 1b on site, where no bent bars are provided for effective transfer of moments and shear forces at the beam-column joint. This type of joint such as in Graph 1b, will behave as a hinged joint, since it has no capacity to transfer moment; while that of joint such as in Graph 1a will behave as a fixed joint [Priestley, 1997, Hakuto et al, 1999]

Challenges of research statements

The poor detailing of reinforced concrete frame structures, especially at the beam/column joint is one of the major problems facing the Nigeria industry today. This problem is due to a lot of factors such as poor workmanship, usage of unskilled workers and poor supervision.



Graph 1a: Reinforcement detailing at Column joints.



Graph 1b: Reinforcement detailing at Column joints.

Researches into the behavior and mode of failure of beam where extensively carried out; however, researched into the behavior and mode of failure of space frame reinforced concrete structures with beam/column joint fixed is rare. Hence, the secondary focus of this research work is to investigate the effect of good detailing work on the load capacity of frame structures.

Research significance

In the conventional design reinforced concrete using limit state method according to BS8110 (2001), the component structural elements are design independently of others. The issue of moment redistribution if at all considered is confined within the limit structural element along the plane being considered. Although, this approach may be safe if it is a conservative one this inherently contradicts the aim of designing a safe structure at the least possible cost.

Aim and objectives

The aim of this research is to evaluate the collapse loads of slabs supported on orthogonal sided frame models: firstly, one with M_{RS} greater than M_{RB} , and secondly one with M_{RS} less than M_{RB} with fixed joint.

The primary objective of this study is to:

- To determine the collapse load of the two frames: firstly, one with M_{RS} greater than M_{RB} , and secondly one with M_{RS} less than M_{RB} .
- To understand the mode of collapse of the two frame model.
- To gain experimental evidence of the mode of collapse of the frame model.

- To gain analytical evidence of the collapse load of the frame model.

The recent collapse of buildings in the country calls for the investigation of not only the collapsed buildings, but the behavior of the materials used for the construction of the buildings collapsed building under load. One of the ways of doing this is to carryout load test on models constructed from the same building materials used for the construction of the failed structures. In the present day construction industry in Nigeria, concrete has emerged as the most common building material. It is also worth noting that over eighty percent of the collapsed building in Nigeria as today is constructed from reinforced concrete. Hence careful consideration must be given to factors that affect the strength of reinforced concrete [2].

In his report, Adeoye (PGD 1998) noted that between December 1976 and January 1995, over 30 cases of collapse of buildings were reported across the country, with well over 250 person lost their lives with several others severely injured. Also Amanda-Ayafa (PGD 2000), noted that between May 1987 and April 2000, over 22 cases of building failure were reported in Lagos State. Also between January 2005 and August 2006, over 8 cases of building collapse were recorded in the country [2].

Akintola, Fakorede, and Osuntade (2009) [3], in their load tests of 1m square single panel space frame hinged joint models (M_{RS} greater than M_{RB}), with slab thickness equals 50mm, beam cross-sectional dimensions are 75mm by 100mm, and column cross-sectional dimensions are mm by 75mm, the collapse load was 37.4KN, while the maximum deflections at collapse are 5.7 and 5.9mm for beam and slab respectively. Investigating the same type of reinforced concrete models [4], determine the load to be 26.4KN, while deflections are 3.35mm and 7.56mm for beam and slab respectively. Also, Famoye, Majekodunmi and Olaleye (PGD 2010), determine the collapse load for the same type reinforced concrete model as 21.96KN, while the deflections are 5.85mm and 22.33mm for beam and slab respectively. In all the three cases cited above, the mode of collapse is by shear failure at the beam/column joints. This is due to the fact that the moment of resistance of slab (M_{RS}) is greater than moment of resistance of beam (M_{RB}), hence slab transfer directly the load to the column, instead of from slab to beam and beam to column (Famoye, A.A, Majekodunmi, A.S and Olaleye, O.T. 2010).

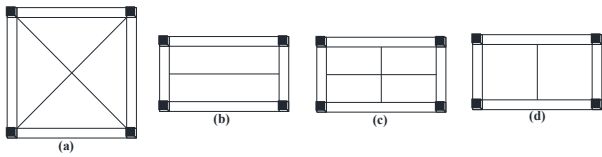
Standard collapse mechanism and collapse loads

Four standard cases of collapse mechanism for slab with edge beams as given by [5], is as shown in Graph 2(a-d). The type of collapse mechanism for a particular slab depends on the relative moments of resistance of the beams and 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 (KN/m) can be estimated from

$$n = 24M/L^2$$

Collapse mechanism b: this type of mechanism depends on M_b/ML , which is a measure of the relative magnitudes of the



Graph 2(a-d): standard collapse mechanisms for square slabs (Moy 1981).

moments of resistance of the edge beams and slab. The collapse load for this type of mechanism can be calculated using

$$n = 8M/L^2(1+2M_b/ML).....KN/m$$

Collapse mechanism c: also this type of mechanism depends on M_b/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 (KN/m) can be estimated from

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

M = the moment of resistance of the slab,

L = the length of the slab,

M_b = the moment of resistance of the beam

Material and Method

The materials used for this research work includes two RC frame models, constructed using micro concrete (i.e cement and sand in ratio 1:6) and reinforcements. Steel reinforcement characteristics strength of 250N/mm² was used. The cement and sand with adequate water was thoroughly mixed and gently poured into the formwork provided for the model starting from foundation to columns, then later to beams and slab. The RC model shall be allowed to set, harden and cure for 28days after which it was ready for loading.

After 28 days when the concrete had gained maximum strength, the RC frame model was loaded by putting a loading box with dimensions 1m* 1m* 3.0m on top of the slab of the frame. Two dial gauges was used, one was set at the centre of the bottom of the slab while the other was set below the edge beams to monitor, measure centre and edge deflections. The dial gauges was adjusted to zero before taking reading. Reading of the dial gauges was taken at every 10 head pans (1.84KN) of sand into the loading box.

Design concept

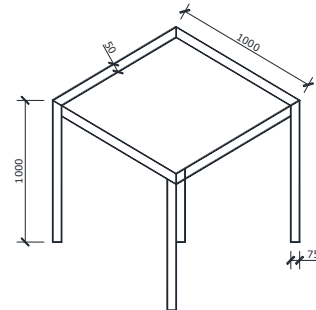
The frame was analyzed and design in accordance to BS8110

Estimation of collapse load of the frame

Using Moment of Resistance of Slab

$$F_{cc} = F_{st}$$

$$0.45 \times f_{cu} \times b \times s = 0.87 \times f_y \times A_{sprov}$$



3D description of the model with dimensions

$$0.45 \times 7 \times 1000 \times s = 0.87 \times 250 \times 142$$

$$s = \frac{0.87 \times 250 \times 142}{0.45 \times 7 \times 1000} = 9.80mm$$

$$X = \frac{s}{0.9} = \frac{9.80}{0.9} = 10.89mm$$

Hence the steel has yielded since $10.89 < 0.615d = 0.615 \times 41 = 25.23mm$

$$M_s = 0.87 f_y A_s (d - s/2)$$

$$= 0.87 \times 250 \times 142 \times (41 - 9.80/2) \times 10^{-6} = 1.12KNm$$

Hence $M_s = M_u$

Where M_s = Moment of resistance of the slab

M_u = is the Ultimate Moment.

The above equation can be written in a compressed form as stated in BS8110 part 1, we have:

$$M = \alpha n L x^2$$

From table 3.14 of the BS8110 part 1, $\alpha = 0.055$

Where Lx = length of the shorter span of slab = 1000mm

n = estimated collapse lord

$$1.12 = 0.055 \times n \times 1^2$$

$$n = 1.12/0.055 = 20.36KN/m$$

Hence the estimated collapse lord for Slab is 20.36KN/m

Using Moment of Resistance of Beam

$$F_{cc} = F_{st}$$

$$0.45 f_{cu} b s = 0.87 f_y A_s$$

$$0.45 \times 7 \times 75 \times s = 0.87 \times 250 \times 56.6$$

$$S = \frac{0.87 \times 250 \times 56.6}{0.45 \times 7 \times 75} = 52.11 \text{ mm}$$

$$X = \frac{S}{0.9} = \frac{52.11}{0.9} = 57.9 \text{ mm}$$

Hence the steel has yielded since $57.91 < 0.615d = 0.615 \times 95$
 $= 58.43 \text{ mm}$

$$M = f_{st} \times Z$$

$$M = 0.87 \times f_y \times A_s \times z$$

$$= 0.87 \times 250 \times 56.6 (85 - 52.11/2) \times 10^{-6} = 0.726 \text{ KNm}$$

Since the fixed at support we have:

$$m = wl^2/24$$

Where m is the fixed end moment

Substituting for m in the equation we have

$$0.726 = wl^2/24$$

$$W = (24 \times 0.726)/1.0^2 = 17.424 \text{ KN/m}$$

The estimated collapse load (n) will be given by

$$W = (1/3)nlx$$

Substituting the values of w and l we have

$$17.424 = 1/3 \times n \times 1$$

$$N = 17.424 \times 3 = 52.272 \text{ KN/m}^2$$

The expected collapse load of the beam is 52.272 KN/m^2

Using standard collapse mechanism

The theoretical collapse load can be calculated from the standard collapse mechanism given by:

$$n = 8Ms/L^2(1+2M_b/ML)$$

This is a measure of the relative magnitudes of the moments of resistance of the edge beams and slab.

Where Ms = the moment of resistance of the slab

Mb = the moment of resistance of the beam

L = Length of the slab

$$n = 8Ms/L^2(1+2M_b/ML)$$

$$n = 8(1.115)/1^2 \times (1 + (2 \times 0.726)/1.115 \times 1) = 20.54 \text{ KN/m}$$

Hence using standard collapse mechanism, the theoretical collapse load is 20.54 KN/m

Experimental collapse load of the frame model

After 28 days when the concrete had gained maximum strength, the RC frame model was loaded by putting a loading

box with dimensions $1\text{m} \times 1\text{m} \times 3.0\text{m}$ on top of the slab of the frame. Two dial gauges was used, one was set at the centre of the bottom of the slab while the other was set below the edge beams to monitor, measure centre and edge deflections. The dial gauges was adjusted to zero before taking reading. Reading of the dial gauges was taken at every 10 head pans (1.84 KN) of sand into the loading box.

Table 1 and 2 below shows frame models loading results and the loads were plotted against deflection at centre of beam and slab respectively. See figure 1 - 4 for more details.

Analysis and Discussions of Results

For the $M_{RS} > M_{RB}$ frame model; it was observed that through the reading in dial gauges that deflection started on the centre of the slab. Deflection was noticed also on the beams at 12.88 KN load. As the load increases, the deflections increases, deflections increase and the deflection of the slab was higher than that of the beam.

Under the load of 16.56 KN , yield line patterns were noticed on the slab and at 22.08 KN of load, cracks were noticed on the beam/columns joint across the span of the beams and laterally under the slab. Load was applied continually until there was a sudden collapse of the model at a load of 69.92 KN . See figure 5 and 6.

Also for the $M_{RS} < M_{RB}$ frame model, it was also observed that through the reading in dial gauges that deflection started on both the centre of the slab and beam respectively. The deflection increases and the deflection of the slab were also higher than that of the beam.

Under the load of 9.2 KN , yield lines patterns were noticed on the slab and at 12.88 KN of load, cracks were noticed on the beam/column joint across the span of the beams and laterally under the slab. At an applied load of 49.68 KN there was also a sudden collapse of the model.

In summary, the estimated collapsed load for the beam was 52.27 KN/m , while that of slab was 20.36 KN/m . the actual collapse load for $M_{RS} > M_{RB}$ and $M_{RS} < M_{RB}$ frame model was 69.92 KN/m and 49.68 KN/m respectively. Failure was due to Flexural failure at the beams /column joints. The actual collapse load of 69.92 KN and 49.68 KN respectively were greater than that of the estimated collapse loads of beam and slab. See figure 7 and 8.

Conclusion

In conclusion, it can be deduced that the collapse load of the space frame model when $M_{RS} > M_{RB}$ is greater than when $M_{RS} < M_{RB}$. Also, the slab of the $M_{RS} > M_{RB}$ frame model is stronger than that of the $M_{RS} < M_{RB}$ frame model, that is, the $M_{RS} > M_{RB}$ frame Model can withstand more imposed load than the $M_{RS} < M_{RB}$ frame model.

Therefore, it was observed that the collapse took place at the joint between the beam and column, and centre of the beam due to flexural failure after the formation of plastic hinges at the beam/column joints and beam centre.

Recommendation

The actual collapse load of the frame models are greater than the estimated ones, hence for a reinforced concrete frame, detailed to be fixed at beam/column joints, the tension reinforcement provided an effective shear resistance compared to an hinged beam/column joint; therefore an effective supervision of reinforcement detailing during construction should not be compromised.

Table 1: Shows the readings of MRS > MRB frame model and its corresponding deflection.

Load (KN)	Centre of slab deflection (mm)	Centre of beam deflection (mm)	Remarks
1.84	1.00	0	
3.68	2.20	0	
5.53	3.00	0	
7.36	3.71	0	
9.2	4.35	0	
11.04	5.00	0	
12.88	6.26	0.30	
14.72	7.10	0.67	
16.56	8.10	1.02	Yield line noticed on slab
18.4	9.95	1.32	
20.24	10.40	1.84	
22.08	11.08	2.43	Cracks noticed on beam/column joint
23.92	12.45	3.30	
25.76	13.40	3.80	
27.6	16.18	4.94	
29.44	18.54	5.73	
31.28	20.65	6.46	
33.12	20.70	6.84	
34.96	21.95	6.99	
36.8	22.71	7.82	
38.64	23.22	8.55	
40.48	23.90	9.20	
42.32	24.87	9.90	
44.16	25.88	10.43	
46.0	26.21	11.23	
47.84	26.89	12.56	
49.68	27.93	13.80	
51.52	28.88	14.62	
53.36	29.92	15.88	
55.2	30.79	16.82	
57.04	31.89	17.79	
58.88	32.76	18.92	
60.72	33.19	20.87	
62.56	35.08	22.03	
64.4	36.28	23.82	
66.24	38.11	26.56	
68.08	41.01	29.87	
69.92	45.50	36.08	

Table 2: Shows the readings of MRS < MRB frame model and its corresponding deflection.

Load (KN)	Centre of slab deflection (mm)	Centre of beam deflection (mm)	Remarks
1.84	0.14	0.24	
3.68	1.06	0.43	
5.53	1.45	0.83	
7.36	2.31	1.32	
9.2	3.26	1.78	Yield line noticed on slab
11.04	4.31	2.33	
12.88	5.47	3.01	Cracks noticed on beam/column joint
14.72	6.76	3.53	
16.56	8.00	4.12	
18.4	9.55	4.71	
20.24	11.20	4.80	
22.08	12.72	5.80	
23.92	14.75	6.20	
25.76	15.85	6.65	
27.6	16.00	7.00	
29.44	17.15	7.40	
31.28	18.10	7.56	
33.12	20.85	8.35	
34.96	21.90	8.70	
36.8	22.10	10.15	
38.64	24.15	10.50	
40.48	25.50	11.10	
42.32	27.52	12.14	
44.16	29.05	13.76	
46.0	31.53	16.12	
47.84	34.26	18.71	
49.68	40.50	23.80	

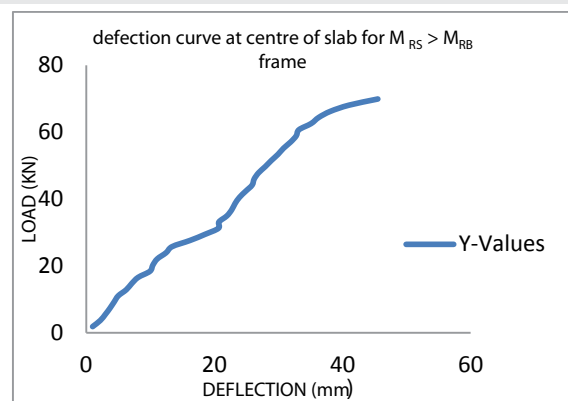


Figure 1: Loads-centre deflection graph for MRS > MRB frame.

Also, the actual collapse load of the frame models are greater than the estimated ones, hence the design formulae must be looked into so as to reflect the behavior of reinforced concrete (R.C) structures under loading.

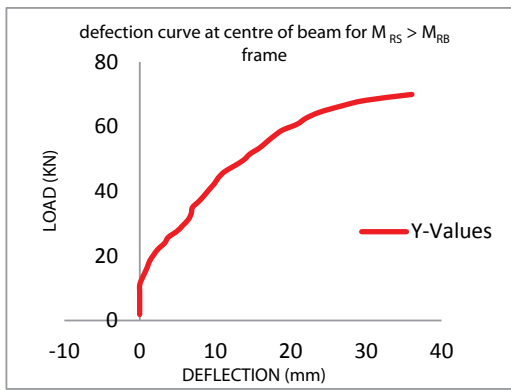


Figure 2: Loads-edge deflection graph for $M_{RS} > M_{RB}$ frame.

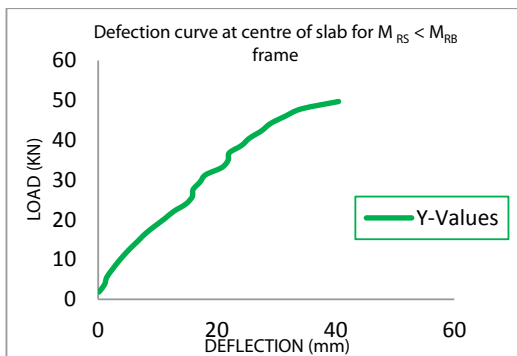


Figure 3: Loads-centre deflection graph for $M_{RS} < M_{RB}$ frame.

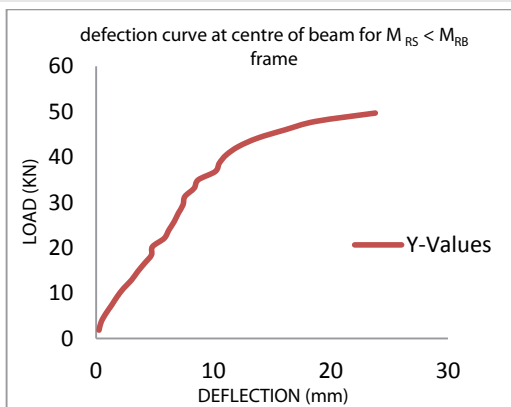


Figure 4: Loads-centre deflection graph for $M_{RS} < M_{RB}$ frame.



Figure 5: Yield line pattern noticed on slab.



Figure 6: Cracks noticed on the beam/column joint.



Figure 7: RC frame model near collapse.

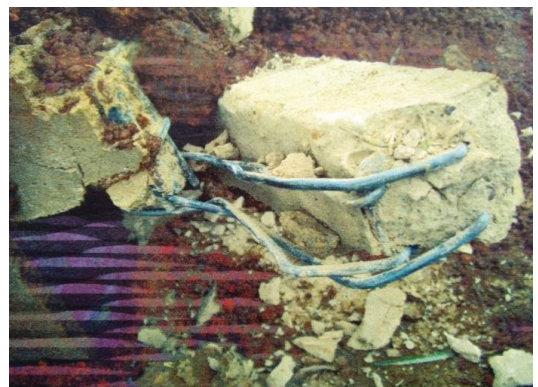


Figure 8: Collapsed RC frame model.

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