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Research Article

Theoretical and Practical Collapse Load of a Single Panel Space Frame: A Comparative Analysis Approach

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Abstract: This research examines the comparative analysis of theoretical and practical collapse load of a square single panel space frame consisting of slab, beam and column. A reinforced concrete proto type of 3m×3m×3m space frame with a reduction factor of 3 was designed, a model of it constructed and casted with a micro concrete of 1:6 mix ratio. It was cured and crushed after 28 days strength. The micro concrete compressive strength was 7N/mm^2 which satisfied average compressive strength of 1:2:4 reinforced micro-concrete. The theoretical collapse load was 21.44 kN. The model was put under load; at 18.3 kN an orthogonal yield line was observed at the slab soffit, as the load increases to 20.3kN cracks were noticeable at the beam/column joints. Further increase in load made the beam/column slab joint cracks much more pronounced. At constant load of 21.96 kN, without adding more load, the deflection on the dial gauge continued to rise, vibration of the structure occurred, until the structure finally collapse at that constant load (21.96 kN). Comparing the theoretical collapse load with the experimental collapse load, the later was 21.96 kN more than 21.44 kN estimated. It was observed that the beam/column joints failed due to shear not due to bending.

Keywords: Collapse load, compressive strength, micro-concrete, yield line

INTRODUCTION

Structural frame 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 (Mosley and Bungey, 1993). A frames structure 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 (Trahir *et al*., 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. Horne (1956) developed a method for analysis and design of three-dimensional braced rigid frames in which it could be assumed that plastic hinges form at all major and minor axes beam ends. Thus, when plastic analysis is used, columns which do not participate in the collapse mechanism may be designed as isolated beam-columns against flexural-torsional buckling. In his later publications, Horne (1964) extended this method so that the occurrence of plastic hinges at one or both ends of the column (instead of in the beams) could be allowed for. These above methods basically reduce space frame to two-dimensional (plane) frames. As the assumption of plastic hinges at all the beam-column joints is only valid for frames with vertical loads, the analysis for lateral loads must be carried out independently.

The primary actions in a two-dimensional (plane) frame in which the members support vertical/horizontal loads are usually flexural and often accompanied by significant axial actions. The structural behavior of a frame is influenced by the behavior of the member joints, which are usually considered to be simple, semi-

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rigid, or rigid, according to their ability to transmit moment (Trahir *et al*., 2001).

Furthermore, Nethercot (1986), Nethercot and Chen (1988) and erson *et al.* (1991) and Couchman (1997) showed the economy effect of the type of joint between beam and column in a frame. Rigid-jointed frames are statically indeterminate and basically can be analysed manually using first order approach (Coates *et al*., 1988). According to Owens and Knowles (2003) the above method is tedious; hence they suggested a more simple approximate method or available solutions for specific frames. The division of space frames to series of plane frames reduces the number of equations to be solved at a time to three times the number of joints (3j) (Astill and Martin, 1982). The practical interpretation of this is that one of the transverse plane frames is selected, analyzed and designed for and assumed to be typical of all other plane frames that make up the structure. Since there has been no popular and simplified approach, that takes the space nature of space frame into consideration, the above simplified approach of breaking space frame into series of plane frame still remains popular among structural engineers.

From the foregoing, the study intends to achieve the objective of this research by determining the collapse load of the square space frame, the mode of collapse as well as comparing the collapse load with the estimated collapse load.

THEORETICAL FRAMEWORK

Concrete technology: Concrete and steel are the most commonly used structural materials. They sometimes complement one another and sometimes compete with one another so that structures of a similar type and function can be in either of these materials. And yet, the engineer often knows less about the concrete of which the structure is made than about the steel. Concrete could be made from a mixture of cement, fine aggregate, coarse aggregate and water. The proportions of each material control the strength and quality of the resultant concrete. For concrete to be made to meet the required crushing strength, there are two overall criteria: the concrete has to be satisfactory in its hardened state and also in its fresh state while being transported from the mixer and placed in the formwork. The requirements in the fresh state are that the consistence of the mix be such that it can be compacted by the means desired without excessive effort and also that the mix be cohesive enough for the method of placing used not produce segregation with a consequent lack of homogeneity of the finished product. The usual primary requirement of a good concrete in its hardened state is a satisfactory compressive strength. This is aimed at not only so as to ensure that the concrete can withstand a prescribed compressive stress but also because many other desired properties of concrete are concomitant with high strength, such as density, durability, tensile strength, impermeability, resistance to abrasion, resistance to sulphate attack and many others.

Reinforced Concrete (RC) is concrete in which reinforcement bars ("rebars"), reinforcement grids, plates or fibers have been incorporated to strengthen the concrete in tension. The term Ferro Concrete refers only to concrete that is reinforced with iron or steel. Other materials used to reinforce concrete can be organic and inorganic fibers as well as composites in different forms. Concrete is strong in compression, but weak in tension, thus adding reinforcement increases the strength in tension. In addition, the failure strain of concrete in tension is so low that the reinforcement has to hold the cracked sections together. For a strong, ductile and durable construction the reinforcement shall have the following properties:

- High strength
- High tensile strain
- Good bond to the concrete
- Thermal compatibility
- Durability in the concrete environment

In most cases reinforced concrete uses steel rebars that have been inserted to add strength. Concrete is reinforced to give it extra tensile strength; without reinforcement, many concrete buildings would not have been possible.

Reinforced concrete can encompass many types of structures and components, including slabs, walls, beams, columns, foundations, frames and more.
Reinforced concrete can be classified as precast or cast in-situ concrete

Concrete constituents: Concrete is a mixture of cement, fine aggregate (sand), coarse aggregate (gravel), admixtures and Water. Concrete mixes can be expressed as volume ratio thus: 1:2:4 = 1 part cement, 2 parts fine aggregate, 4 parts coarse aggregate.

Cement: Cement is the setting agent of concrete and the bulk of cement used in this country is Portland cement. This is made from chalk or limestone and clay and is generally produced by the wet process. In this process the two raw materials are washed, broken up and mixed with water to form slurry. This slurry is then pumped into a steel rotary kiln which is from 3-4 m in diameter and up to 150 m long and lined with refractory bricks. While the slurry is fed into the top end of the kiln a pulverized coal is blown in at the bottom end and fired. This raises the temperature at the lower end of the kiln to about 1400°C. The slurry passing down the kiln first gives up its moisture and then the chalk or limestone is broken down into carbon dioxide and lime and finally forms a white hot clinker which is transferred to a cooler before being ground. The grinding is carried out in a ball mill which is a cylinder some 15 m long and up to 4.5 m in diameter containing a large number of steel balls of various sizes, which grind the clinker into a fine powder. As clinker is being fed into the ball mill, gypsum (about 5%) is added to prevent a flash setting off the cement. The types are:

- Rapid-hardening Portland cement
- High alumina cement
- Portland blast-furnace cement
- Sulphate-resisting cement
- Low heat blast-furnace cement
- Super-sulphate cement

Water: The water used in the making of concrete must be clean and free from impurities that could affect the concrete. It is usually specified as being of a quality fit for drinking. A proportion of the water will set up a chemical reaction which will harden the cement. The remainder is required to give the mix workability and will evaporate from the mix while it is curing, leaving minute voids. An excess of water will give porous concrete of reduced durability and strength.

The quantity of water to be used in the mix is usually expressed in terms of the water/cement ratio, which is:

$$= \frac{\text{The total weight of water in the concrete}}{\text{Weight of cement}}$$

For most mixes the ratio is between 0.4 and 0.7

Admixtures: Admixtures are substances introduced into a batch of concrete during or immediately before its mixing, in order to alter or improve its properties in the fresh and the hardened state. It is different from the term additives; additives refer to the materials used by the cement manufacturers to modify the properties of cement.

The use of admixtures are used to effect influences in the concrete in the areas of hydration, liberation of heat formation of pores and the formation of the gel structure. They should only be considered for use when required modification in concrete cannot be achieved by varying the mix proportion or when the admixtures can produce the required effect more economically. Various types of admixtures according to BS 5075: part1: 1974 are:

- Accelerating admixture
- Retarding admixture
- Normal water-reducing admixture
- Accelerating water-reducing admixture
- Retarding water-reducing admixture
- Calcium Chloride ($CaCl_2$)

The addition of calcium chloride to the mix increases the rate of development of strength and this accelerator is, therefore, sometimes used when concrete is to be placed at low temperatures (in the region of 2 to 4°C (35 to 40°F)) or when urgent repair work is to be done.

Calcium Chloride increases the rate of heat liberation during the first few hours after mixing, the action of $CaCl_2$ being probably that of a catalyst in the reaction of hydration of C_3S and C_2S; it is possible that the reduction in the alkalinity of the solution promotes the hydration of the silicates. The hydration of C_3A is delayed somewhat, but the normal process of hydration of cement is not changed.

Aggregates: An aggregate is a material in granular or particle form, such as sand or gravel, which is added to the class of materials known as binders (e.g., cement, hydraulic limes, plasters and bitumen) to produce a solid mass on hardening. Since most aggregates are inert and undergo no chemical action with the binder, the strength of the combined mass depends on the specific adhesion or bond which develops between aggregate and binder. The mechanical interlock which develops between the constituent particles in virtue of their shape, size and surface texture, the strengths of the aggregate and binder respectively.

They are materials which are mixed with cement to form concrete and are classed as a fine or coarse aggregate. Fine aggregates (Sand) are those which will pass a standard 5 mm sieve and coarse aggregates (gravel) are those which are retained on a standard 5 mm sieve. All- in aggregate is a material composed of both fine and coarse aggregates. A wide variety of materials (for example, gravel, crushed stone, brick, furnace slag and lightweight substances, such as foamed slag, expanded clay and vermiculite) are available for making of concrete. In making concrete aggregates must be graded so that the smaller particles of the fine aggregate fill the voids created by the coarse aggregate. The cement paste fills the voids in the fine aggregate thus forming a dense mix. Aggregates from natural sources are covered in BS 882.

Deleterious substances in aggregate: There are three broad categories of deleterious substances that may be found in aggregates:

- Impurities which interfere with the processes of hydration of cement
- Coatings preventing the development of good bond between aggregate and the cement paste
- Certain individual particles which are weak or unsound in themselves

All or part of an aggregate can be harmful through the development of chemical reactions between the aggregate and the cement paste.

Micro-concrete: In RC modeling, accurate simulation of both service and ultimate load behavior of structural concrete requires the use of a concrete mix with a reduced aggregate size (micro concrete). Micro concrete is a concrete in which the coarse aggregate has been substituted with fine aggregates. Hence for concrete of mix ratio 1:2:4, its equivalent micro concrete mix ratio will be 1:6.

The determination of a suitable micro concrete mix has been the subject of many studies (Johnson, 1962; Ruiz, 1966; Chowdhurry *et al.*, 1977; Hughes and Chapman, 1966; Muller, 1985). Whilst the required cube strength may be obtained by the normal method of varying the aggregate-cement, a/c and water/cement, w/c, ratios, the similitude of other mechanical properties cannot be obtained so easily. Mild steel of diameter 6mm is used for the construction of the micro-concrete structural models.

Mix design: As defined by Neville and Brooks (1987) as the process of selecting suitable ingredients of concrete and determining their relative quantities with the object of producing as economically as possible concrete of certain minimum properties, notably consistence, strength and durability.

The process of mix design: There are variations in the exact method of selecting the mix proportions. For instance, in the excellent method of the American Concrete Institute, the water content in kilogrammes per cubic metre or pounds per cubic yard of concrete is determined direct from the workability of the mix (given the maximum size of aggregate) instead of being found indirectly from the water/cement and aggregate/cement ratios, as is done in the method of Road Note No. 4.

It should be explained that a design in the strict sense of the word is not possible: the materials used are essentially variable and many of their properties cannot be assessed truly quantitatively, so that we are really making no more than an intelligent guess at the optimum combinations of the ingredients on the basis of the relationships established. It is not surprising, therefore, that in order to obtain a satisfactory mix; we not only have to calculate or estimate the proportions of the available materials but must also make trial mixes. The properties of these mixes are checked and adjustments in the mix proportions are made; further trial mixes are made until a fully satisfactory mix is obtained. Factors to be considered in the choice of mix proportions are:

- Mean strength
- Minimum strength

METHODS OF STRUCTURAL ANALYSIS

The mathematics involved in the analysis of indeterminate structures. The classical approach is based on the assumption that the stress in the structure caused by the applied loads are within the elastic limit of the materials used and thus deflection are small. The approach of course, widely used. However, an alternative has gained increasing support over the past ten years or so.

Structural analysis follows, in general, traditional lines, the recognized route being static, simple bending theory, virtual work and finally the analysis of rigid jointed structures. The main barrier that has to be crossed is from statically determinate structures (which must be effectively analyzed by a combination of static and compatibility of deformations). There are two method of structural analysis, these are:

- Convectional method
- Plastic method

Convectional method of structural analysis: Since twentieth century, indeterminate structures are being widely used for its obvious merits. It may be recalled that, in the case of indeterminate structures either the reactions or the internal forces cannot be determined from equations of statics alone. In such structures, the number of reactions or the number of internal forces exceeds the number of static equilibrium equations. In addition to equilibrium equations, compatibility equations are used to evaluate the unknown reactions and internal forces in statically indeterminate structure. In the analysis of indeterminate structure it is necessary to satisfy the equilibrium equations (implying that the structure is in equilibrium) compatibility equations (requirement if for assuring the continuity of the structure without any breaks) and force displacement equations (the way in which displacement are related to forces). We have two distinct method of analysis for statically indeterminate structure depending upon how the above equations are satisfied:

- Force method of analysis (also known as flexibility method of analysis, method of consistent deformation, flexibility matrix method)
- Displacement method of analysis (also known as stiffness matrix method)

In the force method of analysis, primary unknown are forces. In this method compatibility equations are written for displacement and rotations (which are calculated by force displacement equations). Solving these equations, redundant forces are calculated. Once the redundant forces are calculated, the remaining reactions are evaluated by equations of equilibrium.

In the displacement method of analysis, the primary unknowns are the displacements. In this method, first force -displacement relations are computed and subsequently equations are written satisfying the equilibrium conditions of the structure. After determining the unknown displacements, the other forces are calculated satisfying the compatibility conditions and force displacement relations. The displacement-based method is amenable to computer programming and hence the method is being widely used in the modern day structural analysis.

Plastic method of structural analysis: This new philosophy taints the problem on the head, it is obvious that any structure can be made to fall down that is, collapse by applying load of sufficient magnitude. The purpose of the new analysis is to find that magnitude which requires the knowledge of what happen at collapse and how structures behave when stresses in the material exceed the elastic limit.

This philosophy is embodied in the plastic method of analysis and design. One important reassuring feature of the plastic methods is that the mathematics involved is usually formidable than with the traditional methods.

Condition of plastic analysis:

- **Mechanism condition:** There are sufficient plastic hinge for the structure to be become a mechanism. The load factor at which a structure becomes mechanism is called the collapse load factors.
- **Yield condition:** the Bending Moment (BM) nowhere exceed the plastic moment of the members.
- **Equilibrium conditions:** The distribution of BM's is in equilibrium with the applied load.

Methods of finding collapse loads:
The virtual work method: This method of determine collapsed load based on the principle of virtual work has proved to be a powerful tool because it is readily applied to frames. The method is based on two premises, when framed structures collapsed, all deformation of the structure occurs by rotation at the plastic hinges. The principle of virtual work can be applied to these deformations. There are other methods that can be used to find collapse loads, such as:

- Free and reactant BM method
- Limit Analysis
- Hilerborg strip method

Yield line method to describe theoretical collapse load of the slab: In general, any pattern of yield line has to be postulated from experienced and useful set of rules. There is no guarantee that the chosen pattern is the correct one, it will satisfy the mechanism and equilibrium condition, but not necessarily the yield condition. Unfortunately, it is difficult, if not possible, to check this, which means that in general any yield line solution will be upper bound. Theoretically, yield line analysis is unsafe because an upper bound is an over-estimate of the strength of the slab. Physically it is safe because the analysis ignores two important factors:

- Moment of resistance of slab is calculated ignoring strain hardening in the reinforcement.
- Yield line theory is very much an idealization of slab behavior i.e., if assumes that the vertical loads are carried by only bending action.

Experimentally this is not so. For a slab which is subjected to increasing load, cracking and reinforcement yield will first occur in the most highly stressed zone. This is will act as plastic hinge as subsequent load are distributed to other region of the slab. Crack will develop to form a pattern of 'yield lines' until a mechanism is formed and collapse is indicated by increasing deflections under loads. When a slab is on the verge of collapse owing to the existence of a sufficient number of real plastic hinges to form a mechanism axies of rotation will be located along the line of support or over point supports such as columns. The slab segment can be considered to rotate as rigid bodies in space about this axis of rotation. The yield line between any two adjacent slab segments is a straight line. Being the intersection of two essentially plane surfaces. Since the yield line (as a line of intersection of two planes) contains all points common to these two planes, it must contain the point of intersection of the two axes of rotation, which is also common to the two planes. That is, the yielding (or yield line extended) must pass through the point of intersection of the axes of rotation of the two adjacent slab segments. The terms positive yield line and negative yield line are used to distinguish between those associated with tension at the bottom and tension at the top slab respectively.

Rules for postulating yield line patterns: The five rules below will help in finding yield line patterns:

- Yield line is straight and is axes of rotation
- Yield line must end at a slab boundary
- Axes of rotation lie along supported edges cut unsupported edges and pass over columns
- The axes of rotation of adjacent rigid regions have a point of intersection (which may be at infinity)
- There are often negative yield lines along at least past of a fixed edge.

Advantages of yield line method:

- The method is simple
- Information is provided on the real load carrying capacity of slab
- Principle used is familiar to structural engineers and is therefore usable in practice despite the complexity in seeking for maximum yield loads
- For reinforced concrete slab, close agreement exists between experimental and yield line method solutions.

MATERIALS AND METHODS

Study area: This research study was conducted at the Federal University of Technology Akure Ondo State, Nigeria. It was carried out in 2010 where a single panel space frame model was designed, casted and loaded to failure. A comparison between the theoretical designed load and practical collapse load were investigated. It also involved the substitution of coarse aggregate with fine aggregate to form a micro-concrete. The execution of this research was in stages as follows:

- Structural analysis and design of a single panel space frame RC prototype of 3×3×3 m. These comprised of structural elements such as slab, beams, columns and foundation. The prototype structure was scaled down by factor 1/3 to form the model.
- Estimation of the theoretical collapse load of the space frame using moments of resistance of the beam, slab, shear capacity of the frame and theoretical collapse using standard mechanism.
- Construction of a square single panel space frame RC model of 1:2:4 micro- concrete mix ratios of (1:6), with 6mm diameter mild steel reinforcements.
- Loading of the RC model was done by loading box of 1 m×1 m×2.4 m size.
- The cracks, yield lines formed on the slab and mode of collapse were noticed.
- The estimation of practical collapse loads of the frame compare with the theoretical collapse load.

Analysis and design of a single panel space frame: The space frames shown in Fig. 1 consist of the following components:

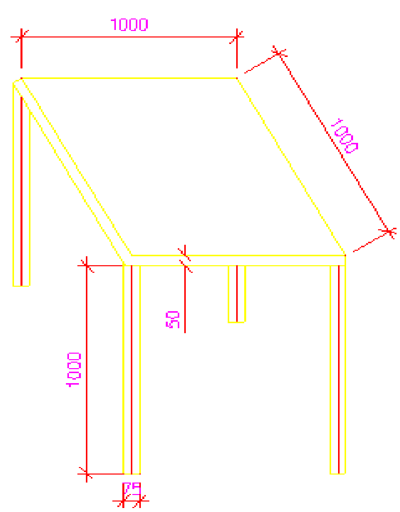


Fig. 1: Single panel space frame

Table 1: Design information

Relevant codes	BS8110, part, (1985)
Design stresses	Concrete G_K = 1.2KN/m^2
Fire resistance	One hour for all elements
Exposure condition	Mild for all element
	Cover = 6 mm, slab = 50 mm,
	Beam = 100 mm by 75 mm, column = 75 mm by 75 mm
General loading condition	Column height-1m
	Live load Q_K = 1KN/m^2
	Dead load G_K = 1.2KN/m^2
Design data	K_U = 0.156
	$K = \frac{M}{F_{CU}bd^2}, La = 0.5 + \sqrt{0.25 - \frac{k}{0.9}} \leq 0.95$
	$A_S = \frac{M}{0.95F_Y Z}, K \leq Ku$
	$A_S' = \frac{(K - Ku)F_{CU}bd^2}{0.95F_Y(d - d')}$
	$A_S = \frac{K_U F_{CU} bd^2}{0.95F_Y Z} + A_S'$
	$Z = d(0.5 + \sqrt{(0.25 - \frac{k_u}{0.9}})$

- The slab
- Beam
- Column and
- The foundation

Summary of design (Table 1):
Slab design: The slab panel was designed as a two ways spanning slab and the loading was as shown in Table 2. The following reinforcements were obtained:

- At short span, provide Y6 @ 200mm c/c at the bottom.
- At long span provide Y6 @ 200mm c/c near the bottom.

Beam design: The load from the slab and self weight of the beam were added together and designed as simply supported beam (Table 3). Provide 3Y6mm bar with total area of 56.5mm^2).

Column: The slab and beam load now constitute the total load to be carried by the column. Provide 4-Y6 bars Area 113.1mm2 for the column (Table 4).

Foundation: A nominal reinforcement of 4-Y6 mm diameter bars, top and bottom was used for the foundation.

Estimation of collapse loads of the frame using moments of resistance of the slab, beam, shear capacity and theoretical collapse using standard mechanism:

Table 2: Slab design

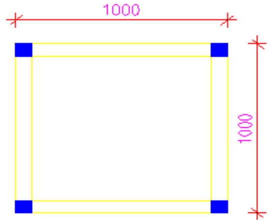
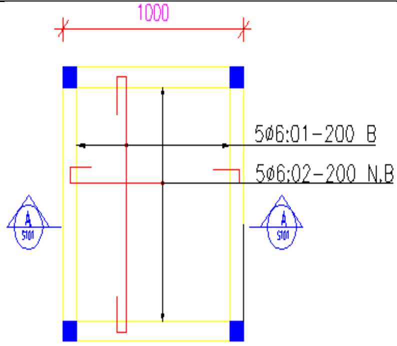
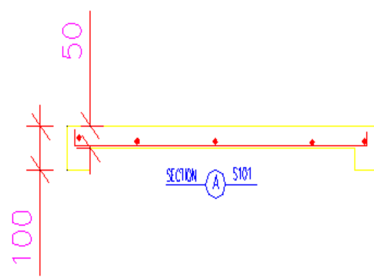
Member ref	Calculation	Output
	 Slab panel The slab can be design as a two way slab L_y = 1m, L_x = 1m therefore $\frac{L_Y}{L_X} < 2 = k = 1$ Loading; u.d.l (Fk); Concrete own weight = 0.05x24 = 1.2KN/m^2 finishes say = 0.5KN/m^2 Total G_k 1.7KN/m^2 Live load Q_k 1KN/m^2 Hence, total design load at ultimate limit state $F = 1.4G_k + 1.6Q_k$ = 1.4x1.7 +1.6x1 = 2.38+1.6 = 3.98KN/m^2 According to BS8110 part 1. Section 3.13, the bending moment coefficient for rectangular panel support on four edges with provision for torsion at corners: $\beta_{sx} = 0.055, \beta_{sy} = 0.056$	
Short span	At the short span: $M = \beta_{sx} w L_X{}^2$ $M = 0.055 \times 3.98 \times (1.0)^2 = 0.2189KNm$ $h = 50mm, d = 50 - 6 - 3 = 41mm$ $K = \frac{M}{f_{cu} bd^2} = \frac{0.2189 \times 10^6}{7 \times 1000 \times (41)^2}$ $k = 0.0186, La = 0.95$ $A_S = \frac{M}{0.95 f_y z} = \frac{0.2189 \times 10^6}{0.95 \times 250 \times 0.95 \times 41}$ $A_S = 23.66mm^2$ Provide Y6 @200mm c/c Btm 141mm^2	Y6@200 mm c/c Btm
Long span	At the long span $M = \beta_{sy} w L_X{}^2$ $M = 0.056 \times 3.98 \times (1.0)^2 = 0.2229KNm$ $h = 50mm, d = 50 - 6 - 3 = 41mm$ $K = \frac{M}{f_{cu} bd^2} = \frac{0.2229 \times 10^6}{7 \times 1000 \times (41)^2} = 0.0189$ $k = 0.0189, La = 0.95$ $A_S = \frac{M}{0.95 f_y z} = \frac{0.2229 \times 10^6}{0.95 \times 250 \times 0.95 \times 41}$ $A_S = 24.09mm^2$ Provide Y6@200mm c/c near Btm (141mm^2) Deflection fs $= \frac{2}{3} \times 250 \times \frac{42.67}{141} = 50.02$ $M.F = 0.55 + \frac{(477 - 50.02)}{120(0.9 + (\frac{0.2189 \times 10^6}{1000 \times (41)^2}}} = 3.45$ $d_{req} = \frac{1000}{20 \times 3} = 16.66$ Detailing this is shown in (a) and (b) below:	Y6@ 200mm c/c near Btm 3Y6mm Bar

Table 2: Continue

Long span	At the long span	Y6@ 200mm c/c near Btm



(a)



(b)

Table 3: Beam deign

Member ref	Calculation	Output
	Loading:	
	$n = \frac{1}{3}WL_x = \frac{1}{3} \times 3.98 \times 1 = 1.327\,KNm$	
	Beam wt :	
	$= 0.075 \times 0.1 \times 24 \times 1.4 = 0.252\,KNm$	
	$N = 1.327 + 0.252 = 1.579\,KNm$	
	$d = 100 - 6 - 3 = 91\,mm$	
	Case 1 beam simply supported:	
	$Moment(M) = \frac{WL^2}{8} = \frac{1.579 \times 1^2}{8} = 0.19\,KNm$	
	$K = \frac{M}{F_{cu}bd^2} = \frac{0.19 \times 10^6}{7 \times 75 \times (91)^2} = 0.043$	4–Y6 bars
	$K = 0.043, La = 0.95$	
	$A_S = \frac{M}{0.95 f_y lad} = \frac{0.19 \times 10^6}{0.95 \times 250 \times 0.95 \times 91} = 9.2$	
	Provide 3Y6 mm bar (56.5 mm^2)	
	The details are shown below:	

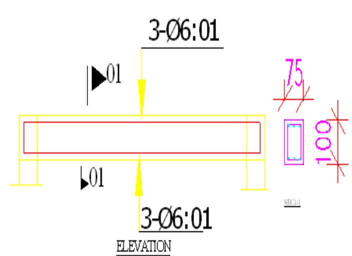


Table 4: Column design

Calculation:
Slab load = 3.98 x0.5x0.5 = 0.995KN
Beam load = 0.1x0.075x1x24x1.4 = 0.252
N = 0.995+0.252 = 1.247KN
$\frac{l_{ex}}{h} = \frac{1000}{75} = 13.3$
$\frac{l_{ey}}{b} = \frac{1000}{75} = 13.3$
Both $\frac{l_{ex}}{h}$ and $\frac{l_{ey}}{b}$<15
Therefore the column is a short braced axially loaded column:
$N = 0.4F_{cu}A_c + 0.8F_yA_{sc}$
$1.247\times10^3 = (0.4\times20\times75\times75) + (0.8\times250\times A_{sc})$
$A_{sc} = \frac{1.247\times10^3 - (0.4\times20\times75\times75)}{0.8\times250}$
$A_{sc} = \frac{-43753}{200} = -218.76mm^2$
Thus for this case:
$A_{sc} = 0.4\% \times 75\times75 = 22.5 \approx 23mm^2$
Provide 4 – Y6 bars (113.1 mm^2)

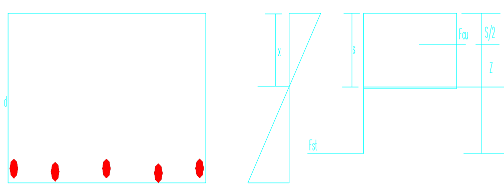


Fig. 2: Strain and stress distribution across the rectangular slab section at collapse

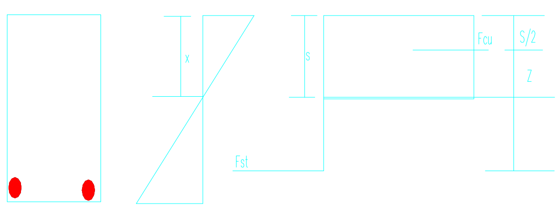


Fig. 3: Strain and stress distribution across the rectangular beam section

Moment of resistance of slab (Fig. 2):

Fcc = Fst

0.45 x Fcu x b x S = 0.87 x Fy x As

0.45 x7 x1000 x S = 0.87 x 250 x 141

$$S = \frac{0.87x250x141}{0.45x7x1000} = 9.74mm$$

$$x = \frac{s}{0.9} = \frac{9.74}{0.9} = 10.82mm$$

Therefore, 10.82<0.615d = 0.615x41 = 25.2 mm

The tension steel has yielded.

M_R = 0.87 FyAs (d –S/2)

(1- $\frac{7}{250}$)×7×10^{-3} = 8.35KN where M_R is the Moment of resistance of the slab.

M_R = M_U, the collapse load can be estimated.

M_U is the Ultimate moment.

According to BS8110-1 Eq. (14) and (15) can be written in a compressed form, thus having:

$M = \alpha n L_x^2$

According to BS 8110-1, α = 0.055

L_X = Length of the short span of the slab = 1000 mm

n = The ultimate or estimated collapse load in KN/m^2

$$1.1 = 0.055\times N\times1^2$$

$$\frac{1.1}{0.055\times1^2} = N$$

$$N = 20KN/m$$

Hence the expected or estimated collapse load for slab $N = 20KN/m$

Moment of resistance of beam (Fig. 3):

$$F_{CC=}F_{st}$$

$$0.45F_{CU}bS = 0.87F_yA_s$$

$$0.45\times7\times75\times S = 0.87\times250\times56.5$$

$$S = \frac{(0.87\times250\times56.5)}{0.45\times7\times75} = 52.1mm$$

$$\chi = \frac{52.1}{0.9} = 58mm$$

χ = 58 mm< 0.615d = 0.615x95 = 58.4 mm

Hence the steel has yielded:

$$M = F_{st}\times\mathbf{Z}$$

$$= 0.87\ F_Y\ A_S\ Z$$

where,

M = The moment of resistance

F_{ST} = The resultant tensile force in the tension reinforcement.

Z = The lever-arm

A_S = The area of reinforcement provided = 56.5 mm^2

F_Y = The characteristic strength of steel

F_Y = 250N/mm^2 for mild steel

Substitute for A_S, F_Y and Z in equation above, we have:

M = 0.87x 250x56.5 (91-52.1/2) x 10^{-6}

M = 0.79KNm

In order to estimate the expected collapse or ultimate load. The beam will be considered as a simply supported. The average value of the collapse load is taken therefore, when the beam is assumed to be simply supported. Then:

$$M = \frac{WL^2}{8}$$

Substituting for M and L, we have:

$$0.79 = \frac{WL^2}{8}$$

$$W = \frac{0.79 \times 8}{1^2} = 6.32KN/m$$

Hence the expected or estimated collapse loads for beam N= 6.32KN/m

Estimation of the shear capacity of the frame: The expected collapse load of the slab will be used to determine the shear capacity of the frame. Using equation below, the shear capacity can be estimated, assuming that the crack induced by shear failure is at 45°:

$$V_{45} = 0.18 \text{x } bw \text{ x } d\ (1-\frac{F_{CU}}{250})F_{CU}$$

Equating V_{45} to V: where

b_w = The width of beam
D = The effective depth
F_{CU} = The characteristics strength of concrete

Substituting bw = 75 mm, d = 91 mm and Fcu = 7N/mm^2 into the equation, we have:

$$V_{45} = 0.18\text{x } 75\text{x } 91(1-\frac{7}{250})\times 7\times 10^{-3} = 8.35KN$$

Estimation of theoretical collapse load using standard collapse mechanism: The work equation gives or collapse gives:

$$P = \frac{8M}{L}\left(1+\frac{2M_b}{ML}\right)$$

$$= \frac{8(1.1)}{1^2}\left(1+\frac{2(0.79)}{1.1(1)^2}\right)$$

$$= 21.44KN/m$$

Therefore, the theoretical collapse load using standard collapse mechanism is 21.44KN/m

CONSTRUCTION OF THE MODEL

Setting out: Set out the footings of the frame on the ground with the scale from the working drawing (Fig. 1)

Excavation: Before the frame was casted the column base was first of all excavated to a depth of 0.15 m or thereabout. Excavation was carried out so as not lay the frame on the ground surface where it can be easily washed away by erosion.

Formwork: The form work of square single panel space frame used were all of timber, temporarily constructed to support, keep and hold concrete in required shape and position until its set (Plate 1).

Plate 1: The construction of form work and reinforcement

Plate 2: Casted micro concrete frame

Plate 3: Assembly of box and loading of the frame

Plate 4: Dial gauge under the slab and the beam of the frame

Materials: The construction of the space frame model was made up of concrete, using micro concrete (that is, cement and sand in ratio 1:6) and reinforcements.

Concrete of grade $6\frac{N}{mm^2}$ and steel reinforcement of characteristics strength of 250 N/mm^2 were used. The cement and sand with adequate water were thoroughly mixed and gently poured into the formwork provided for the model starting from foundation to columns, then later to beams and slab. The slab thickness was dimensioned to be 50mm with the edge size of beam 100 mm by 75 mm which was supported by column at the corners of the slab with the column size 75 mm by 75 mm at 1 m height (Fig.1 and Plate 1 for details) and model type of the frame (Plate 2). Reinforced Concrete (RC) model was allowed to set, harden and cure for 28days after which it was ready for loading.

Cube crushing strength of concrete: Samples were casted and cured in water tank for adequate strength for 28 days before testing period. Cubes were crushed and the result of the universal testing machine was also taken to give the value of characteristics strength of the concrete (Table 5 and 6).

Testing for practical collapsed load of the model: After 28 days when the concrete had gained enough strength, RC model was loaded. Loading of the model was done by putting a loading box of 1m×1m×2.4m on top of the slab of the frame (Plate 3). Two dial gauges were used, one was set at the centre of the bottom of the slab while the other one was set below the edge beams to monitor, measure centre and edge deflections. The dial gauges were adjusted to zero (Plate 4). Sand was poured into the box using head pans of known weight 18.3kg (Plate 3). Reading of the dial gauges were taken at every 10 head pans into the loading box.

That is:

$$\frac{18.3 \times 10 \times 10}{1000} KN$$
$$= 1.83\, KN \;/\; Reading$$

Table 5: Results from universal testing machine

Structural member	Universal testing machine N/mm^2
	8.0
	7.8
	7.4
	7.0
Space framed cube model 1	7.7
	7.2
	8.5
	5.9
	6.8
	8.8
	7.4
	7.6
	8.2
	8.4
Space framed cube model 3	6.2
	7.0
	8.6
	7.5
	6.6
Space framed cube model 4	6.4

Table 6: Characteristic strengths from universal testing machine

Formulae	Universal testing machine N/mm^2
E	7.45
$\sum(x-\varepsilon)^2$	12.91
$(n-1)$	0.19
$_k = \varepsilon - 1.64\,\sigma$	7.1

Result from experiment (2010)

(Table 7)
Note: 1kg = 9.8N ≈10N

RESULTS AND DISCUSSION

The result of the universal testing machine Table 5 and 6 gave the value of characteristics strength of our concrete which is 7N/mm^2. which was still within average characteristic compressive strength of micro concrete.

Yield line pattern and cracks: The RC model was subjected to increasing load (Plate 3), cracking and

Table 7: Reading of the loading of the space framed model

LOAD (kN) column 1	Beam centre deflection (MM) column 2	Slab centre deflection (MM) column 3	Remarks
1.83	0	0.86	
3.66	0.01	1.16	
5.49	0.17	1.55	
7.32	0.33	2.04	
9.15	0.5	2.6	
10.98	0.67	3.22	
12.81	0.9	4.02	
14.64	1.15	4.92	Cracks on slab
16.47	1.5	5.6	
18.3	1.91	8.1	Cracks on beam
20.13	2.81	15.11	Cracks on joints
21.96	5.85	22.33	Total collapse

Result from experiment (2010)

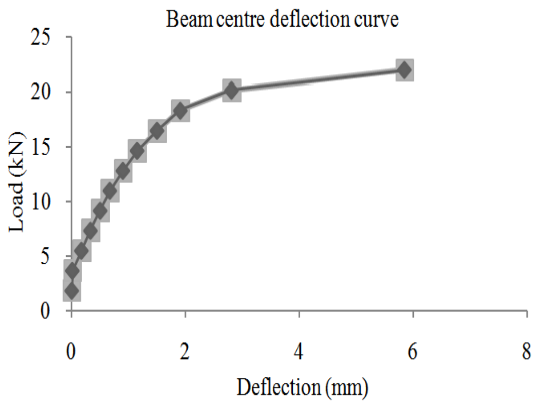


Fig. 4: Beam centre deflection curve

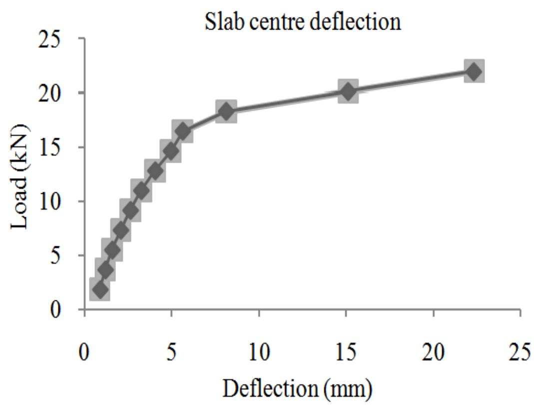


Fig. 5: Beam centre deflection

reinforcement yield first occur in the most highly stressed zone. This act as plastic hinge as subsequent load are distributed to other region of the slab. Crack developed to form a pattern of 'yield lines' until a mechanism is formed and collapse was indicated by increasing deflections under load (Table 7 and Fig. 4 and 5). There are many cracks, especially near the centre of the slab. This web of cracks formed at a relative low load, but as the load increases only a few of the cracks become large. In this particular case, the cracks roughly on the diagonals have opened out. The combination of large cracks and concrete crushing occurred as if an under- reinforced beam reaches its moment of resistance after plastic rotation. At the last loading that is, the twelfth time. The practical collapse load was estimated to be as follows:

$$P = 1.83 \times 12 = 21.96.4\text{kN}$$

where P is the practical collapse load in kN (Table 7).

Result of the loading and corresponding deflection of the space frame model (Table 7) are shown in Fig. 4 plotted using the readings in column 1 and column 2 while that of Fig. 5 was plotted using column 1 and 3.

Under the loads of 18.3 kN, cracks were noticed on the beam/column joint across the span of the beams but more pronounced at the mid- span of the beam and across like shape under the slab. When the applied load reached 21.96kN, deflections continued to increase without further increase in load. The frame collapse at a load of 21.96 kN. Reading was taking for 40 min at this constant load of 21.96 kN that is at 10 min interval. The frame finally collapse by breaking at joint of beam/column after 45 min. The estimated collapse loads for beam and slab were 6.32 kN/m and 20 kN/m, respectively.

CONCLUSION AND RECOMMENDATIONS

It was confirmed from the theoretical calculation of moment of resistance of beams and the slab concrete section from which their collapse load were determine to be 6.32 kN and 20 kN respectively, the estimated collapse load using standard collapse mechanism is 21.44 kN and the experimental collapse load or actual load is 21.96 kN. Therefore, it can be deduced in comparing the estimated collapse load. That is, theoretical collapse load is less than the actual collapse load in which the theoretical and experimental collapse load ought to be the same but conditions and factors were not constant.

In conclusion it was observed that the collapse load took place at the joint between the beam and column, confirming that the slabs strength was more than that of the beam thereby, transferring the load directly to the columns. Hence there was no failure at the slab and the beam joint, instead it was due to shear at the beam and column joints.

From the foregoing, it is recommended that slab should be designed in such a way that the load will produce the moment of resistance of slab. The shear capacity at the beams and column's joint should correspond. The beams' depth can also be increased at the various beams and column joint and reinforced accordingly so as to give more shear support.

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