Engineering Innovations
ISSN: 2813-1002, Vol. 5, pp 1-13
doi:10.4028/p-2b38z4

Submitted: 2022-04-28
Revised: 2023-02-01
Accepted: 2023-02-01
Online: 2023-04-19

Strengthening of a Damaged Concrete Structure - Case Study of an Eleven Stories Building in Dar es Salaam

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Keywords: Columns, crushing, non-destructive tests, concrete quality, deflection, plumb, jacketing, strengthening

Abstract: Concrete structures may become obsolete and be unfit for use to the extent that they need special attendance of repair or strengthening so as to revive them. The weakness in the buildings may be caused by natural disasters like earthquake, floods, changes of use of the buildings in which higher loads more than the design loads, e.g. vertical extension loads, are applied. When the structures are defective they need to be strengthened in order to restore their original structural integrity. Sometimes, the defect or deterioration needs to be scientifically analysed first in order to know the root cause of the problem and apply the right corrective measures. A case study on an eleven stories damaged building in Dar es Salaam is presented, starting with an investigation on causes of sudden crushing of one column and a strengthening method which embraced a number of techniques such as Land Surveying and non-destructive tests in assessing the building structural integrity. The crushed column and other columns is the ground floor were all strengthened using jacketing method and provision of additional columns at the crushed column.

1.0 Introduction

Structural defects in concrete structures may be caused by earthquake[**1**], overloading, structural damages, materials deterioration, apart from design and construction faults. However, if a structure is defective it needs repair and or strengthening. There exist various methods of strengthening defective concrete structures which include; use of bolted steel plates for strengthening columns and beams[**2**], jacketing of columns using a membrane of reinforced concrete[**1, 3**], using composites such as Glass Fibre and Polypropylene Fibre Based Engineered Cementitious Composites (GFPPECC)[**4**] and Post-Tensioned Metal Strapping (PTMS) or Side-Near Surface Mounted (NSM) techniques[**5**]. A number of strengthening techniques mentioned above from the authors were done in models in laboratories. This paper presents a method of strengthening a defective reinforced concrete column through a case study of a crushed column of an eleven stories building in Dar es Salaam Tanzania shown in Figure 1.


Figure 1: Crushed column

The strengthening technique included first a structural integrity investigation on the building in order to establish if all structural elements; beams, slabs, columns and foundation pads were still strong or not, land surveying work to check the verticality and displacement of the building, carbonation test to check if the concrete has been destroyed by carbonation effect. Also, the quality and amount of steel reinforcement were determined and structural analysis and design were carried out to verify the adequacy of steel reinforcement in the building. Finally, after getting the results, which showed that most of the building elements were still in good condition, the strengthening work was carried out for all columns from footing level to the first floor level by applying concrete jacketing technique, and additional of new columns.

1.1 The Problem

An eleven stories building located within the city of Dar es Salaam had one of its columns abruptly crushed at the head below 1st floor slab beams with a loud noise like a small bomb in the year 2018. The concrete column head failed by crushing and the main steel reinforcement bend by bowing outwardly as depicted in Figure 1. It was not clear on the reason of the failure knowing that the building has been in service for more than 10 years. Due to this problem, the government of Tanzania ordered the residents of the building plus those in the adjacent neighborhood to be evacuated as a safety measure in case of any progressive failure. Following this concern, the Office of the District Commissioner of Ilala requested the University of Dar es Salaam, to carry out a thorough investigation on the structural strength of the building, and provide recommendations on the strength status and appropriate corrective measures[**6**].

1.2 Objectives

The objective of the assignment was to carry out structural investigation on the building in order to determine the existing structural strength, and recommend on the proper corrective measures to be applied**.** The specific objectives were therefore;

- ☞ To determine the quality of concrete materials of the existing structural system;
- ☞ To determine the load carrying capacity of the existing structural system
- ☞ To determine the appropriate method of strengthening the crushed column
- ☞ To ensure that the building at ground up to 1st floor level is properly strengthened so that it is safe to the occupants. Under this retrofitting objective, the sub-objectives were
    - To supervise the excavation of bases and connections of the specified columns
    - To ensure good construction practices starting from reinforcement fixing, formwork, casting and curing of the concrete.

2.0 Materials and Methods

The building was investigated in four main steps which included the following:

(a) Visual assessment
(b) Assessment of verticality of the building using Land Surveying techniques
(c) Structural investigation for the superstructure
(d) Assessment of the foundations

2.1 Visual Assessment

The eleven stories building was observed to be a framed structure with three rows of columns longitudinally by four rows transversally as seen in Figure 2. The floors were of solid concrete slabs of an average thickness of 160 mm spanning two way. The ground floor was used for parking and had no infill walls except at the concrete staircase and lift shaft. From an interview of one person who was there when the crushing of the column took place, it was noted that it suddenly and abruptly crushed emitting a loud noise. However, from an observation on the beams, slabs, walls in upper floors, and columns feet, nothing detrimental could be seen. There were neither cracks nor settlement observed at all, except at the crushed point as depicted in Figure 1.

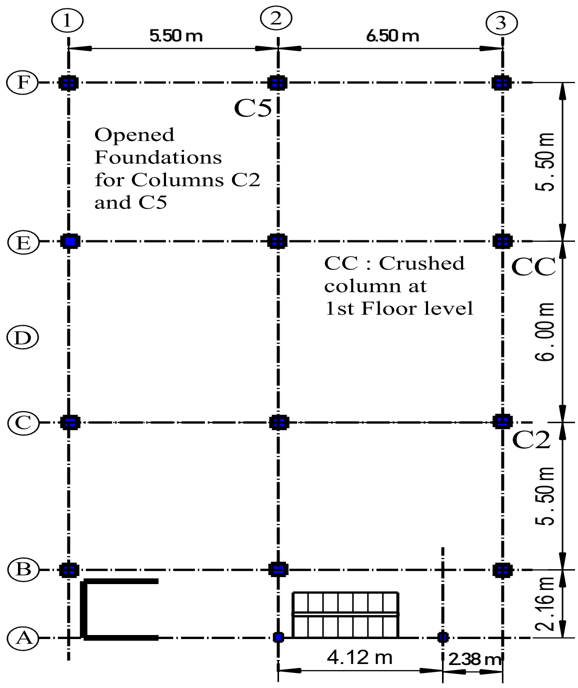

Figure 2: Layout of columns and slab of the building

2.2 Assessment of Verticality of the Building

Verticality of a building structure was measured in order to check if the structure was vertically plumb and exhibit safety behaviour or otherwise. The measurements were carried out using Land Surveying Equipment as detailed below:

2.2.1 Observation of Deviation Angles and Analysis for Verticality

Three points (P1, P2 and P3 ref. Figure 3) were established within the area along the front road opposite the building, and the instruments were centred and levelled at each point. Angles were observed for column CC at point E3 when the instrument was at P1, at point F3 with the instrument at P2 and lastly, at point F1 with instrument at P3. The columns E3, F3 and F1 are as shown in Figure 2. Angular measurements were taken using a Total Station TS 01 on which the telescope pointed at first floor and zero degrees was set. Then, the angles were read along the column height at each Floor level, (ref. Figure 3)

The observed angles were recorded and the deviation angles were computed in order to assess if the building exhibit a safe behaviour or if there is any significant tilt. From the data analysis, observations made from Column (CC) at point E3 showed that the highest deviation angle was 5' 23" while the lowest deviation angle was 20". Also, for the Column at point F3, observation made showed that the highest deviation angle was 7' 07" and the lowest deviation angle was 26". And, for the Column at point F8, observation made yielded the highest deviation angle of 6' 20" and the lowest deviation angle was 01". The control limit in tilting is normally H*1/500 to H*1/1000[**7**]. Taking H*1/500 = 33000/500 = 66 mm. The obtained tilting of 0°6’20” is equivalent to 60 mm for a 33.00 m height. Therefore, the tilting is within the allowable value. There is no any danger of toppling of the building.

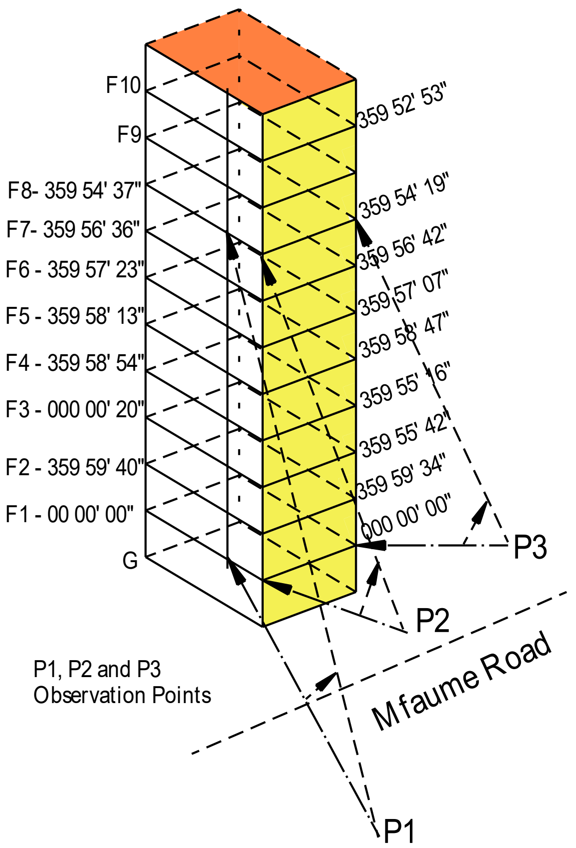

Figure 3: Measurement of building verticality

2.2.2 Levelling of Beams to Determine Downward Displacement

Levelling was done for the beams meeting at column E3 (ref. Figure 4) in order to check the settlement of the building. Beams levels were taken in reference to an established Temporary Benchmark at site with the help of an inverted staff. Referring to Figure 4 which shows the arrangement of beams at first floor, levels were taken for the beams along line numbers L1 and L3, L9 and L7 to L24. The results obtained indicate that the differences of the connected nodes of L1-L3 has a value of 0.012m, L9-L24 has a value of 0.024m and L7-L9 has a value of 0.042m. In this regard, the beam along grid 3 at the crushed column (E3) was shortened by 42 mm. This displacement is within the deflection limits of 11500/250 = 46 mm.

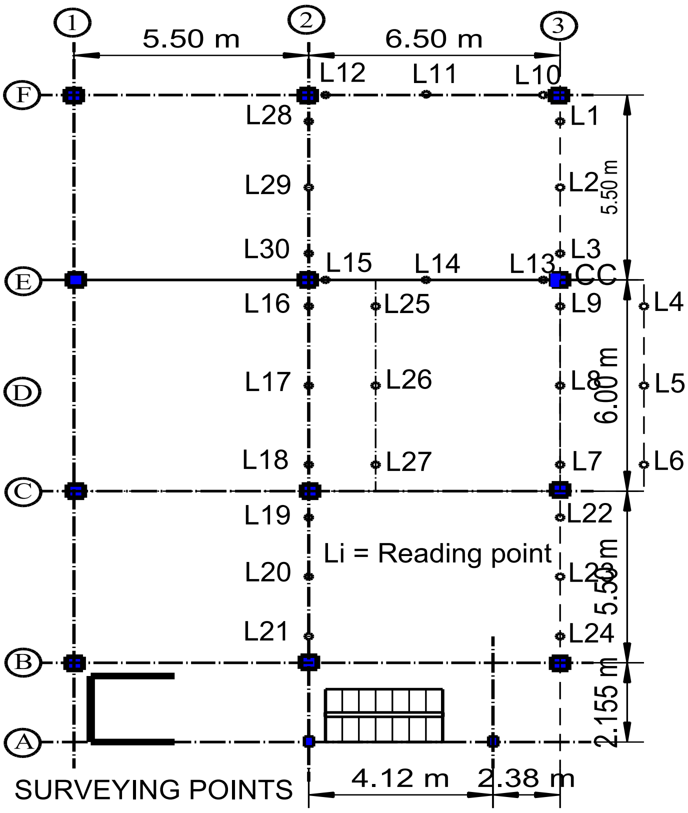

Figure 4: Surveying work layout

2.2.3 Measurement of Column (E3) Displacement Due to Crushing of Concrete

Measurement of buckled bars was carried out along the bend bars and also the actual vertical height between the end points as depicted in Figure 5. The results obtained were as given in Table 1, where it can be seen that the bend covered a depth of 40 mm, while from surveying measurement, the total downward movement was observed to be 42 mm. These results together, show that there was a settlement of 42 – 40 = 2 mm for column E3.

Table 1: Measurements for establishing the shortening of the column due to crushing

No.	L (mm)	h (mm)	Displacement Δ (mm)
1	650	610	40
2	660	620	40
3	540	510	30
4	780	750	30
5	650	610	40

2.2.4 Remarks on the Measurements

Based on the survey tests done to determine the tilting of the building, and downward displacement at the crushed column, the analysed data shows that the plumb of the building is within the allowable values, and the levelling data shows that the beams deflected down by 42 mm, while measurements along the bent bars gave an average of 40 mm downward displacement. This implies that the foundation moved downward by 2 mm only. In general, the downward displacement is still within the allowable values of not more than 20 mm.

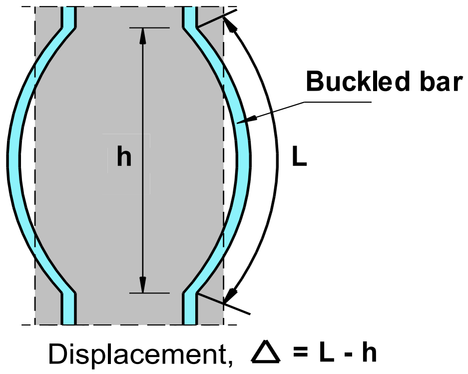

Figure 5: Configuration of measurement of depth due to crushing

2.3 Structural Investigation; Tests and Sampling for Laboratory Works

2.3.1 Drilling and Testing of Concrete Cores

For the purpose of assessing the compressive strength of concrete, twelve concrete core samples were drilled from the building at various locations; two from exposed foundations at C2 and C5 shown in Figure 2; two from 1st floor, one from each of 3rd, 4th, 5th, 6th, 7th and 8th floor slabs, and finally, two cores were sampled from the 10th floor. The concrete cores were visually inspected and their structural features recorded as given in Table 2. The concrete core samples were resized in the laboratory before testing.

The concrete core samples were subsequently tested for compressive strength in accordance with BS 1881: Part 120: 1983[**8**]. In addition, strength tests were conducted by using the Rebound Hammer method to supplement values obtained from the tests of concrete cores. Reinforcement bars were detected by a Profometer equipment without exposing them. For the exposed steel in the crushed column head, reinforcement bars were viewed and found to be 12 ribbed bars of 25 mm diameter as a confirmation of the results from detecting meter.

Table 2: Summary of Inspection of drilled Core samples

Core No.	**Extent of voids**			**Degree of compaction**	**Other comments**
	Small	***Medium***	***Large***		
1	Few	Few	none	Fair	Core cut on 1st Floor
2	Few	Few	none	Fair	Core cut on 1st Floor
3	Few	Few	none	Fair	Core cut on 3rd Floor
4	Few	Few	none	Fair	Core cut on 4th Floor
5	Few	Few	none	Fair	Core cut on 5th Floor
6	Few	Few	none	Fair	Core cut on 6th Floor
7	Few	Few	none	Fair	Core cut on 7th Floor
8	Few	Few	none	Fair	Core cut on 8th Floor
9	Few	Few	none	Fair	Core cut on 10th Floor
10	Few	Few	none	Fair	Core cut on 10th Floor
11	Few	Few	none	Fair	Core cut on base C2
12	Few	Few	none	Fair	Core cut on base C5

The effectiveness of the method used to compact the concrete on site was judged based on the size and quantity of visible voids or pores on the surface of the concrete cores. The obtained strength of concrete cores in the bases was found to have an average value of **27.7 N/mm^2**, while for superstructure it varied from **24.8 N/mm^2** to **31.5 N/mm^2.** This implies that the grade of concrete for all the floors and footings was **25 N/mm^2.**

2.3.2 Rebound Hammer Test

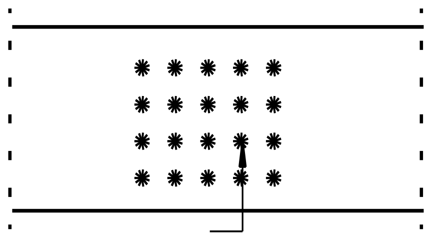

Figure 6: Rebound Hammer Test on Columns and Beams

The Rebound Hammer test is a non- destructive test, and it was undertaken in order to assess the strength of the existing concrete in the building. This test was performed on selected columns, beams and slabs at locations as shown in Figure 6. The Rebound Hammer test was done at positions in structural elements as shown in Figure 6. The average rebounds numbers were 15 per location or point. For the columns, from ground floor level to the eleventh floor, the obtained average concrete compressive strength was as summarized in Table 3.

Table 3: Compressive strength of Columns from Rebound Hammer Test

Column location	**Estimated compressive strength (N/mm^2)**						**Remarks**
	GF	**1st FL**	**4th FL**	**6th FL**	**8th FL**	**BGL**	
Grid E3	19	27	31	32	29		Crushed column
Grid E2	27					34	At foot of exposed foundation
Grid C3	28					34	At foot of exposed foundation

Key: GF = Ground floor storey, BGL = Below ground level

At ground floor storey, it can be seen that the concrete compressive strength for the defective column was **19 N/mm^2** being lower than concrete grade **C20** which is the minimum grade for structural concrete. The other columns had strengths of not less than **25 N/mm^2**. It is most probable that column **CC** at point **E3** (ref. Figure 2) crushed because it had less compressive strength of concrete up to bottom of 1st floor beams. The compressive strength obtained from Rebound Hammer Test is in agreement with the results obtained from concrete cores.

2.3.3 Steel Detection

Steel detection was done using a Profometer steel detector equipment. The test was performed in order to find out the sizes and quantity of reinforcement in various structural elements. For beams, slabs and columns, the observed amount of steel was found to be sufficient even from analysis as shown in Figure 7.

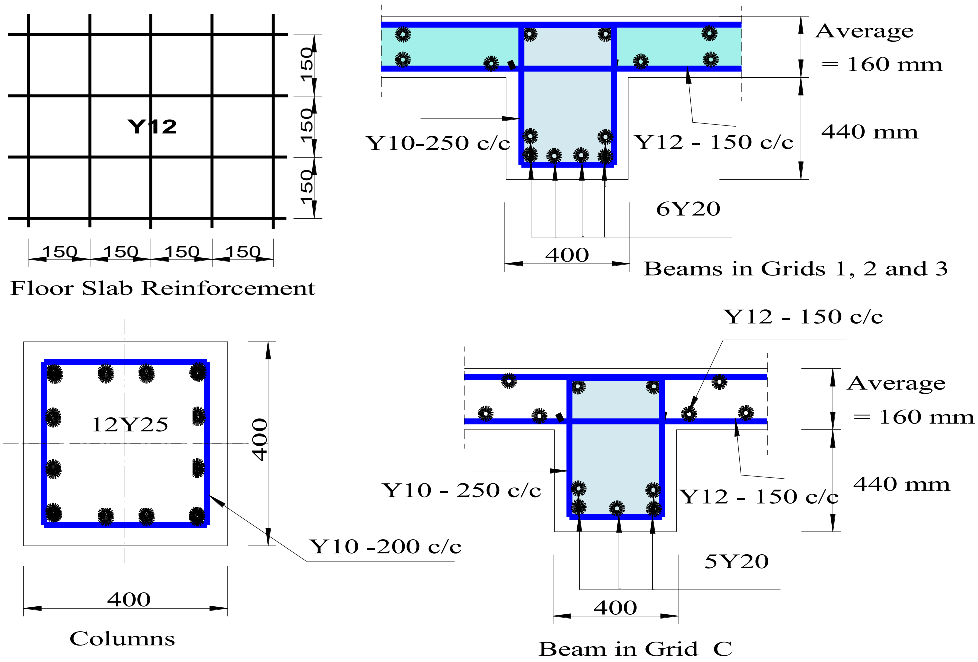

Figure 7: Steel detection in slabs, beams and columns

2.3.4 Assessment of Chemical Attack in the Concrete

Phenolphthalein chemical solution was applied to the concrete in columns in order to assess as to whether the concrete has been affected by carbonation attack. As seen in **Figure 8**, the test results showed that the concrete wasn't attacked by chemicals and therefore the reinforcement in it can't corrode easily, and that the concrete is still safe without any agent of diminishing the strength thereof.

Figure 8: Carbonation test results
- No carbonation attack

2.4 Concluding Remarks with Regard to Structural Investigation

With regard to the tests done on the strength of concrete, it was found that all concrete elements of the structure had a strength of not less than 25 N/mm² except the crushed column where it was 19.0 N/mm² which is very low. It is therefore established that the column crushed because of concrete weakness at the top of the column at 1st floor level. The concrete at the point was observed to be rich in fines in comparison to others. Also the surveying measurements have shown that the building has not significantly tilted and that its vertical downward displacement is within the allowable values.

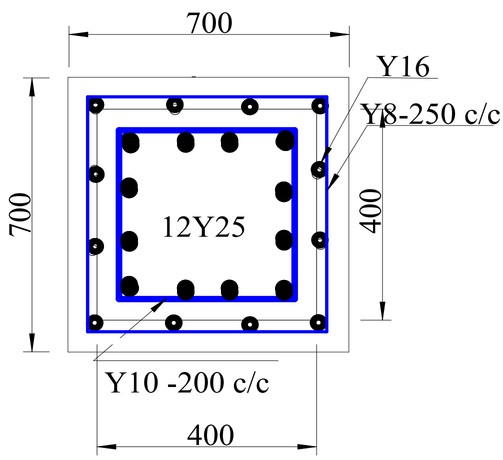

Figure 9: Columns strengthening

Due to the above results and concluding remarks, it was recommended that the columns be strengthened from foundation level to the first floor level by jacketing with 150 mm thick concrete of grade C30 (ratio 1:1.5:2 by volume) all around for those in grids C, E and F. Those in Grid A and B may remain without any treatment because of the masonry walls and Lift-shaft which helps the column system to be more stable. Reinforcement of 16 mm diameter 12 in number and links of 8 mm diameter spaced at 250 mm c/c were to be provided as shown in Figure 9.

2.5 The Retrofitting Works

The retrofitting and strengthening work involved: i) Site inspection, ii) Preparation of Method Statement and iii) Retrofitting work[**9**] as detailed below:

2.5.1 Site Inspection

A total of nine (9) columns at ground floor level including the crushed one were inspected visually to see if there was any more or new defects after being supported by steel H sections and steel props with threads for tightening or loosening. It was observed that there was no any new defect in the building after 1 year, implying that secure permanent support was needed to reinstate the building to its original functional purposes.

2.5.2 Preparation of Method Statement

The Method Statement was prepared by the contractor based on the report on the **Structural Investigation** prepared by BICO[**6**] after a thorough technical investigation on the building. The Method Statement was prepared in such a way that it showed sufficient details on the process of strengthening the 9 columns in grids (C) to (F) given in Figure 2. Structural drawings were prepared on how to anchor the columns reinforcement starter bars in the existing footings because during the structural investigation, the foundation was observed to be in good condition. For this reason, the jacketing of the columns had to start at the existing footings.

2.5.3 Instructions to the Contractor

For the purpose of ensuring that each stage of jacketing work of the columns is properly done, the consultant had to give instructions for excavation to expose each column footing, cleaning and anchoring the starter bars in the footing, ground beams, fixing shear keys and reinforcement with the links for the columns jacketing and formwork. The concrete materials and the grade of concrete were also specified as Grade C30 for all concrete works, and aggregates size not exceeding 20 mm, but preference to 12 mm aggregate size for enhancing better concrete matrix as the new concrete had a thickness of 150 mm all round the old columns. In each case, 12 anchor bars of 16 mm diameter were fixed in the footing in drilled holes of 200 mm deep and 16 mm diameter, cleaned and filled with epoxy material and then the starter bars were inserted in the holes and when the epoxy had hardened, 16 mmϕ high yield steel bars extending from the footing to the bottom of the 1st floor slab were fixed including links of 10 mm diameter spaced at 200 c/c as shown in Figure 9 (improved from the recommended values). An overlap of at least 800 mm for the steel bars was to be observed.

(a) Excavation to expose the footing

Each column footing was excavated from ground floor level by removing the paving bricks and breaking the oversite concrete of varying thickness from 100 to 150 mm. The excavated soil materials was heaped around the trench, then the top of the footing was cleaned and scarified to form key for bonding with the new concrete. Locations for the holes were marked, then holes of 16 mm diameter and 200 mm deep were drilled and cleaned again.

Figure 10: Excavation to expose the footing and fixing of starter bars

(b) Fixing of Reinforcement Bars

From calculations in BICO report[**9**], the required amount of steel was 10Y16, but 12Y16 bars were provided to increase the safety margin. The starter bars of around 1000 mm long and 16 mm diameter were fixed in the epoxy filled holes as shown in Figure 10 above. The defective column as shown in Figure 11(a) was replaced by 3 columns bundled and attached to the old column in the directions of the three beams meeting at the said column. The concrete was tested to see that it conformed to grade C30.

Figure 11: (a) Column E3 (b) Columns along grid D reinforcement

In Figure 11(b), shown are the main reinforcement bars and links for jacketing of columns along grid D. Thereafter, the formwork from marine wood was fixed and then concrete was cast and properly vibrated.

With respect to Figure 12(a), after casting the jacketing concrete, after 7 days, the formwork was removed, then the columns were clothed with sacks sheets and continuously cured for 21 days. On finishing the curing, plastering was done to each of the columns as illustrated in Figure 12(b), and then cured for 7 days.

Figure 12: (a) Column in curing state (b) Plastering of the cured column

2.5.4 Analysis of Column E3 (Reviving from crushing)

The observed original size of columns was 400 x 400 mm, with 12Y25 bars. However, after jacketing with 150 mm thick all round, the size changed to 700 x 700 mm. Column CC at point E3, (ref. Figure 13) the crushed one, but now replaced by 3 columns and itself jacketed as well, was analyzed and redesigned to ascertain its adequacy. Reduction of live loads in each floor was done as per Table 2 of BS 6399 Part 1 (1996)[**10**]. From calculations[**6**], the imposed load constituted 33% of the total design load. Hence, the total axial design load was calculated in kN/floor. Bending moment in column E3 was also established in kNm. The slenderness ratio was found to be 4.5, implying that it is a short column, and so no presence of an additional moment. Thus, the load acting at the bottom of column CC (the crushed one) was analyzed and established in kilo Newton.

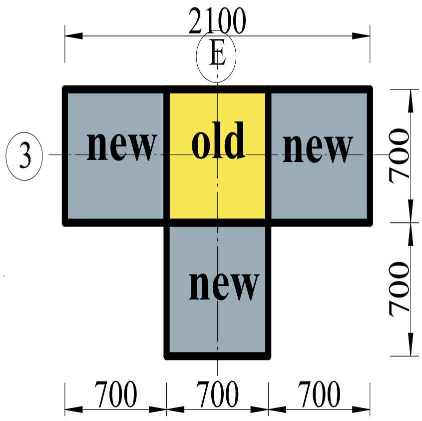

Figure 13: Column E3 layout

Since the compressive strength of concrete in the crushed column was 19.0 N/mm^2, and the compressive strength for the new jacketing[**11**] concrete was not less than 25 N/mm², an average of 20.0 N/mm² was taken into account, specific for the defective column. The design results, revealed that, for the new column size, the required amount of steel would be 10Y16. The added steel during jacketing was 12Y16, being higher than the required amount of steel.

The strength capacity of the strengthened columns was determined using the expression:

$$N_{sc} = N_c + N_{cm} \qquad \text{................(1)}$$

Where N_{sc} = Strength of strengthened column
N_c = Strength of column before strengthening
N_{cm} = Strength of concrete jacket membrane

Amplifying equation (1), get:

$$N_{sc} = 0.35 f_{cu1}bh + 0.35 f_{cu2}ut + 0.67 f_y(A_{sc1} + A_{sc2}) \qquad \text{..............(2)}$$

Where f_{cu1} = Characteristic strength of old concrete in N/mm²
f_{cu2} = Characteristic strength of membrane concrete in N/mm²
b = width of old column

h = height of old column
u = centerline perimeter of the concrete jacket membrane
t = thickness of concrete jacket membrane
f_y = Characteristic strength of reinforcement steel in N/mm²
A_{sc1} = Area of reinforcement steel in the old column
A_{sc2} = Area of reinforcement steel in the concrete jacket membrane

2.5.5 Completion of the Works

After all concrete works have reached 28 days age, the supports to the structural system, namely steel H-sections and other steel props were taken carefully as was indicated in Instructions No. 9 quoted as follows

"*When removing the supports, start with the steel H-Sections and at the end remove the steel props by unthreading slowly. This action will ensure smooth transfer of loads from the supports to the concrete columns safely*"[9]. Figure 14 portrays the ground floor columns after removing all the temporary supports which were instituted when Column E3 crushed in March 2018.

Figure 14: Revived column E3 (in skimming process)

3.0 Results and Discussion

From the investigation results, it was observed that:

(1) The structural members such as columns, walls, beams and slabs didn't show any form of deterioration, exception is for column **CC** at point **E3** (Figure 2) which crushed and the beams meeting at the column moved downward by **42 mm**. The crushing of the column at bottom of 1st floor beams caused 40 mm downward movement, while settlement was 2 mm which is negligible.

(2) The strength of concrete in the columns is at least **25.0 N/mm²**, with the exception of the crushed column **CC** which has a strength of **19.0 N/mm²,** being below the minimum structural strength of 20 N/mm², hence it contributed to the crushing problem.

(3) The crushed column had **12Y25,** while due to its low strength of **19.0 N/mm²,** it needed **14Y25** steel bars[**6**]. In addition, the verticality of the building was observed to be still good, posing no any danger of toppling or overturning.

With regard to the retrofitting work that has been carried out to the nine (9) concrete columns from footing level to the 1st floor level, it was established that;

(1) The eight (8) columns in grids C, E and F, their sizes have been increased from 400 x 400 mm to 700 x 700 mm, i.e they have been jacketed with 150 mm thick reinforced concrete with new 12Y16 in each one of them.

(2) The compressive strength of concrete in the jacketed columns is not less than C25, i.e **30.0 N/mm^2**. The **crushed column average** strength has been taken as **20.0 N/mm^2 to cater for the weakness of the old column of 19.0 N/mm^2 at top although** the new jacket concrete compressive strength is **30.0 N/mm^2.**

(3) Due to the strengthening of the columns from foundation level to the bottom of 1st floor, the load carrying capacity of the columns has been increased to almost double of the previous capacity.

(4) The formerly crushed column has been strengthened by jacketing, and by adding three (3) columns, one in each of the three beams directions meeting at the point E3. The column is now more than 4 times stronger than before retrofitting.

4.0 Concluding Remarks

From the investigation results and discussions made above, the following concluding remarks are deduced,

- The concrete jacketing method is suitable if the columns are not completely crushed
- The building is now sufficiently strong and all the tenants are back in the buildings and they will stay there safely without any structural problem on the structure. Further, it is suggested that frequent monitoring of the building be done for a period of five years to check and ascertain its performance.
- During construction, it is important to make sure that professional practices are adhered.
- It is recommended that use of self compacting concrete in jacketing be studied as it may be easier to work with and more effective.

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