Causes of structural failures of a building: Case study of a building at Oba-Ile, Akure

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ABSTRACT This article investigates the cause of the failure of some parts of a two-storey building under construction, in Oba-Ile, Akure, Ondo State, Nigeria. The article examines the effect of the quality of sand used for concrete production on the quality of concrete produced from them. The article also investigates whether the provided main and shear reinforcements in buildings complied with the provisions of the BS 8110. Site inspections were carried out, and concrete samples were taken. Many of the structural components were exposed, so as to determine the number of reinforcements in each structural element, the anchorage length of main reinforcement provided and the spacing of shear reinforcement. The field settling method was used to determine the percentage content of silt/clay impurity in the sand. The average silt/clay content of the sand was found to be 10.5 per cent, which is above the maximum 4 per cent value stipulated by the code. The results of both the destructive and non-destructive tests show that the average compressive strength of the concrete is 9.6 N/mm^2 , which is less than 20 N/mm^2 specified minimum concrete strength for structural use. The anchorage length provided is less than the value stipulated by the code. The low quality of the concrete is due to the high percentage content of silt/clay in the sand used. From the above investigation, the possible cause of the collapse of the building is the provision of anchorage length less than required, spacing of shear reinforcement is less than required and, the poor quality of the concrete used for the construction.

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INTRODUCTION

Collapse of buildings

In his report, Adeoye (1998) noted that between December 1976 and January 1995, there were over 30 cases of collapse of buildings reported across the country, with well over 250 persons losing their lives and several others being severely injured. In addition, Amanda-Ayafa (2000) noted that between May 1987 and April 2000 over 22 cases of

Figure 1: Collapsed part of the building.

Figure 2: The reconstructed combined footing with the column reinforcement of the collapsed part of the building.

building failure were reported in Lagos State. Between January 2005 and August 2006, over eight cases of building collapse were recorded in the country. Hence, as a matter of responsibility, the Federal Government, Ministry of Works and Housing, State and Local Governments, including private individuals and professional bodies should be concerned. Figure 1 shows the collapsed part of the building under investigation, whereas Figures 2 and 3 show the reconstructed combined footing with the column reinforcement of the collapsed part of the building.

Reinforced concrete structures

In the current construction industry in Nigeria, concrete has emerged as the most common building material. It is also worth noting that 100 per cent of the collapsed buildings in Nigeria were constructed from reinforced concrete. Hence, careful consideration must be given to factors that affect the strength of reinforced concrete.

Figure 3: The reconstructed combined footing with the column reinforcement of the collapsed part of the building.

The constituent materials for concrete are: cement, fine aggregate, coarse aggregate and water. Concrete is a very variable material, having a wide range of strengths. Concrete generally increases its strength with age. The precise relationship will depend on the type of cement used (Mosley *et al*, 2007). It is important that the aggregates for making concrete should be free of all sorts of impurities (BS 882, 1992).

The maximum percentage of silt/clay content of sand for which the compressive concrete strength will not be less than 21 N/mm² is 3.4 per cent for mixed ratio 1:2:4 (Olanitori and Olotuah, 2005). It is very important to control the quality of the aggregate to be used in concrete making. Most importantly, the effect of the silt/clay content of sand on the compressive strength of concrete must be controlled.

There are two basic methods by which the effect of silt/clay content of sand on the compressive strength of concrete can be controlled. These are by washing the sand free of silt/clay or by adding some extra percentage of cement to neutralize the effect of the silt/clay content (Olanitori, 2006).

Recognizing that one of the major failures of reinforced concrete is through shear failure, in 1962 Joint ACI-ASCE Committee 326 (1962a,b,c) published a report regarding the design and behavior of beams failing due to shear and diagonal tension. To develop safe design recommendations, a database of 194 beam tests without shear reinforcement was compiled. The database consisted of 130 laboratory specimens tested under single and double point loads and 64 beams subjected to uniformly distributed loads. On the basis of that data, the following design equation was developed and is included in ACI-05 or ACI 318M-05 for the SI equation as equation 11.5 (Brown *et al*, 2006). Equation 11.5 is rewritten as equation (1).

$$V_c = \left(\sqrt{f'_c} + 120 \rho_w \frac{V_u d}{M_u} \right) \frac{b_w d}{7} \leq 0.3 (\sqrt{f'_c}) b_w d \quad (1)$$

V_c is the nominal shear strength provided by concrete; f'_c is the specified compressive strength of concrete; ρ_w is $A_s/b_w d$; V_u is the factored shear force at section; M_u is the

factored moment at section; b_w is the web width; d is the effective depth of section; and A_s is the area of non-prestressed tension reinforcement.

By neglecting the term involving Vd/M , a simplified, conservative version of equation (1) could be derived (equation (2)). Using equation (2), 2.5 per cent of the test results in the 1962 database failed at shear values less than those computed (Brown *et al*, 2006).

$$V_c = \frac{1}{6}(\sqrt{f'_c})b_w d \quad (2)$$

However, the British Standard presented the value of the nominal shear strength of concrete in tabular form (Table 3.8, BS 8110-1, 1997), whereas equation 5 of the same code can be used to determine the area of shear reinforced concrete for a specific spacing, or the spacing of shear reinforcement for a specific area of shear reinforcement. Equation 5 of the BS 8110 is rewritten as

$$\frac{A_{sv}}{S_v} = \frac{b(v - v_c)}{0.9f_{yv}} \quad (3)$$

where A_{sv} is the cross-sectional area of the two legs of the stirrup; S_v is the stirrup spacing; b is the beam width; v is the average shear stress on the section; v_c is the nominal shear strength provided by concrete.

As reinforced concrete is a composite material, for it to work effectively there must be no slip between the concrete and reinforcing bars. In order to ensure this, adequate anchorage length must be provided. Anchorage values for bends and hooks are given in clause 3.12.9.4 of BS 8110-1.

MATERIALS AND METHODS

The materials used for this study are structural detailing, the PUNDIT 6 (Portable Ultrasonic Non-destructive Digital Indicating Tester), portable rotary drilling machine, 15 samples of 75 mm diameter cores of concrete, soil samples and a manually operated universal testing machine.

The clients of the collapsed building were not willing to provide the architectural plans and structural detailing. Consequentially, as-built architectural plans and the structural detailing were produced from site inspection and by exposing the structural components such as slab, beams and columns. From the as-built structural detailing in conjunction with the as-built architectural plan, enabled reassessment of the structural integrity of the building was carried out. Results of the reassessment of structural elements for tension reinforcement are given in Table 1, whereas the summary of the results of the reassessment of the structural elements for anchorage length is presented in Table 2 and the summary of the reassessment of the beam for shear reinforcement is presented in Table 3.

Fifteen samples of 75 mm diameter cylindrical cores of concrete were taken from slabs, beams and columns. Five samples each were taken from each structural element. The cores were vertically and horizontally drilled with a portable rotary drilling equipment using water as the drilling fluid and diamond impregnated bit. The retrieved cores were taken to the laboratory for examination and tested for strength using universal testing machine in accordance with BS 1881-120 (1983). The result of the test is given in Table 4.

Table 1: The summary of the results of the reassessment of the structural elements for area of tension reinforcement

Serial no.	Member checked for area of reinforcement	Remark
1	Slab (150 mm)	Area of reinforcement provided ok
2	Beams (250 mm×400 mm)	Area of reinforcement provided ok
3	Columns (250 mm×250 mm)	Area of reinforcement provided ok

Redesign information:

Use of building: Hotel.

Imposed load: 2.0 kN/m² (BS 63399-1).

Table 2: The summary of the results of the reassessment of the structural elements for anchorage length

Serial no.	Member	Diameter of reinforcement (mm)	Provided anchorage length (mm)	Required anchorage length (mm)	Remark
1	Slab	12	75	144	Not ok
2	Beams	16	75	192	Not ok
3	Columns	16	75	192	Not ok

Table 3: The summary of the results of the reassessment of beam for shear reinforcement

Serial no.	Spans	Provided shear reinforcement	Required shear reinforcement	Remark
1	Span 1	Y10@300	Y10@250	Not ok
2	Span 2	Y10@300	Y10@250	Not ok
3	Span 3	Y10@300	Y10@250	Not ok

Non-destructive test was carried out on the building using the PUNDIT 6 instrument. The PUNDIT 6 can be operated on the AC mains; however, for field use, an internal nickel cadmium battery, when fully charged, will supply power for about 12 hours continuous use. The instrument is used to measure the time of pulse transmission through the material tested. The distance that the pulses travel in the material must also be measured to enable the velocity to be determined from

$$\text{Pulse velocity} = \text{path length} / \text{transit time}$$

The instrument indicates the time taken for the earliest part of the pulse to reach the receiving transducer measured from the time it leaves the transmitting transducer when these transducers are placed at suitable points on the surface of the material. For this to work, the transducers are arranged on the surface of the selected specimen, with the transmission being direct. Selected specimens could be any part of the structural components from the collapsed buildings, which seem not to have been adversely affected by the collapse. The frequency of pulse vibration used for this work is 50 kHz. The test is carried out in accordance with BS 1881-201 (1986a) and BS 1881-203 (1986b). The result of the PUNDIT 6 test is also given in Table 4. The characteristic strength means that value of the cube strength of concrete f_{cu} , the yield or proof strength of reinforcement f_y or the ultimate strength of a prestressing tendon f_{pu} below which 5 per cent of all possible test results would be expected to fall (BS 8110-1, 1997). This condition is satisfied if

Table 4: Results from universal testing machine and the PUNDIT 6

<i>Structural member</i>	<i>PUNDIT 6 (N/mm²)</i>	<i>Universal testing machine (N/mm²)</i>
Slab	11.5	10.0
	10.2	9.8
	11.0	9.4
	9.8	9.0
	10.2	9.7
Beam	10.5	9.2
	9.3	10.5
	9.5	7.9
	10.2	8.8
	9.8	10.8
Column	10.4	9.4
	10.6	9.6
	9.1	10.2
	9.9	10.4
	8.5	8.2

Table 5: Characteristic strengths from universal testing machine and the PUNDIT 6

<i>Formulae</i>	<i>PUNDIT 6 (N/mm²)</i>	<i>Universal testing machine (N/mm²)</i>
$\bar{\varepsilon}$	10.03	9.53
$\Sigma(x - \bar{\varepsilon})^2$	8.01	9.47
$\sigma = \sqrt{\Sigma(x - \bar{\varepsilon})^2 / (n - 1)}$	0.76	0.82
$F_k = \bar{\varepsilon} - 1.64 \sigma$	8.8	8.2

$$F_k = \bar{\varepsilon} - 1.64 \sigma \quad (4)$$

where F_k is the characteristic strength; $\bar{\varepsilon}$ is the arithmetic mean of sample strengths; σ is the standard deviation and

$$\sigma = \sqrt{\Sigma \frac{(x - \bar{\varepsilon})^2}{(n - 1)}} \quad (5)$$

where x is the strength of a sample; n is the number of samples.

Using results in Table 4 and equations (4) and (5), the characteristic strength of the concrete was determined and given in Table 5.

Five samples of the sand being used on-site were collected. Sieve analysis and field settlement tests were carried out on the sand samples to determine the percentage silt/clay content of the sand. Results of the sieve analysis and field settlement tests are given in Table 6.

RESULTS AND DISCUSSION

The results of the structural reassessment of the collapsed building are presented in Tables 1–3. Table 1 shows that the design of the structural elements for tension reinforcements (for slab and beam) and compression reinforcements (for column) is adequate and could not have been the cause of the collapse. However, Table 2 shows that the anchorage length provided for tension reinforcements is not adequate. An anchorage length of 75 mm was provided for slab reinforcement, whereas the required anchorage

Table 6: Percentage content of silt/clay in sand

<i>Sample no.</i>	<i>Sieve analysis (%)</i>	<i>Field settlement test (%)</i>
I	10.0	10.7
2	9.7	10.8
3	10.7	10.5
4	10.4	10.6
5	10.4	10.5
Average	10.24	10.78
Net average	10.24 + 10.78 = 10.5	

Table 7: The variation of strength against percentage content of silt/clay

<i>Sample</i>	<i>Percentage content of clay</i>	<i>Average compressive strength (N/mm²)</i>
A	0.96	24.13
B	1.45	22.86
C	2.63	21.27
D	3.00	21.56
E	3.22	21.41
F	4.89	17.66
G	7.01	14.21
H	8.00	11.56
I	12.07	7.47
J	12.63	5.94

Source: Olanitori and Olotuah (2005).

length is 144 mm. An anchorage length of 75 mm was also provided for beam and column instead of 192 mm. Table 3 indicated that the stirrup spacing provided is inadequate. Spacing was provided at 300 mm instead of 250 mm. From Table 4, the cube strength ranges between 8.5 and 11.5 N/mm² for the PUNDIT 6, whereas for the universal testing machine the result of the cube strength ranges between 7.9 and 10.8 N/mm². From Table 5, the characteristic strength of the concrete from the PUNDIT 6 is 8.8 N/mm², whereas that of universal testing machine is 8.2 N/mm². Table 6 shows the results of the sieve analysis and field settlement test. The percentage content of silt/clay in the sand used for the construction of the collapsed building is 10.24 and 10.78 per cent for sieve analysis and field settlement test, respectively. The average value of the percentage content of silt/clay from the two tests is 10.5 per cent. Table 7 shows the variation of strength against percentage content of silt/clay.

CONCLUSION AND RECOMMENDATION

The structural reassessment of the collapsed building indicated that the anchorage length of tension reinforcement provided and the spacing of the shear reinforcement provided were compromised. The characteristic strength of concrete used for the construction of the collapsed building is 8.8 N/mm² for the PUNDIT 6 test, whereas that of the universal testing machine is 8.2 N/mm². The minimum specified concrete strength for structural use is 20 N/mm², and the consultant structural engineer could not have used a lesser value. This shows that the concrete used for the construction of the collapsed building is of lower grade and less than half of the specified minimum concrete strength for structural use. The percentage content of silt/clay of the sand used is 10.5 per cent, which is more than 4 per cent stipulated in Table 6 of BS 882. From Table 7, by interpolation, the maximum concrete strength that can be achieved with 10.5 per cent silt/clay content is

9.6 N/mm², which is even higher than the values of 8.2 and 8.8 N/mm² from both the destructive and non-destructive methods of strength determination, respectively.

From the above discussion, it can be seen that the structural integrity of the building is compromised, and this is due to construction errors of providing inadequate anchorage length and shear links spacing, and the low quality of the concrete used for the construction. In addition, the inability of the Nigerian construction industry to have their own local code of practice, which would have taken into consideration the effect of the quality of our local materials on concrete strength, is another major factor that affects the quality of buildings built in Nigeria.

In order to reduce the incidence of collapse of buildings in the country, it is hereby recommended that as a matter of urgency The Nigerian Society of Engineers and other relevant government agencies should make available The Nigerian Codes of Practice, which will take into consideration the peculiar nature and quality of our local building materials and make sure that the client employs the services of a qualified engineer to supervise building projects.

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