STRUCTURAL PERFORMANCE USING CORRECTED CHARACTERISTIC STRENGTH OF STEEL: CASE STUDY OF A BUILDING IN ABUJA

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Abstract
There has been a considerable body of literature of late about issues that contribute to overall poor building structural design practices in Nigeria. Steel reinforcement is the primary load resisting element of reinforced concrete buildings and has received attention in research. However, a common theme with these studies is that none of them derived characteristic strengths of their steel samples, instead typically determining the average yield strength of steel from different samples of steel. The characteristic yield strength of steel is a value that is lower than 95% of the yield strength of steel samples. In this study, one of these studies in Abuja is examined in more depth and the characteristic strength of its steel samples is derived. This characteristic strength of steel is then used to redesign a building that has already been built in Abuja. It was found that the characteristic strength was inadequate structurally.

Keywords: Characteristic strength, Average strength, Steel, Reinforced concrete, Structural design

Introduction
There has been a considerable body of literature of late about issues that contribute to overall poor building structural design practices in Nigeria (Agwu, 2014; Ayedun, Durodola, & Akinjare, 2011; Ayininuola & Olalusi, 2005; Ede, 2014; Hamma-Adama & Kouider, 2017; Olajumoke, Oke, Fajobi & Ogedengbe, 2008). Several have posited that there is a menace of "incessant building collapse" in Nigeria. Such studies as (Agwu, 2014; Ayedun et al., 2011; Ayodeji, 2011; Dimuna, 2010) have concluded that substandard building materials are the primary causes of building failure and collapse in Nigeria. Studies on materials are therefore important for understanding the problem. Structurally, reinforced concrete frames are made of concrete and steel acting as a composite, but with steel primarily carrying the load. Fortunately, one of the most common areas of research has been on the mechanical properties of steel reinforcement (Abioye & Billihaminu, 2016; Alabi & Onyeji, 2010; Alabi, Odusote & Akannid, 2010 Arum, 2008; Baba 2020; Kulmedov, Dayyabu, Abdulganiyu & Hassan, 2021; Osarenmwinda & Amuchi, 2013). However, a common theme with these studies is that none of them derived characteristic strengths of their steel samples, instead determining the average yield strength of steel. The characteristic yield strength of steel is a value that is lower than 95% of the yield strength of steel samples. (Hartsuijker & Welleman, 2006). Using the characteristic strength allows for a more conservative and certain design for the overall structural integrity of a building. The difference between the characteristic and mean yield strength is shown in Figure 1.

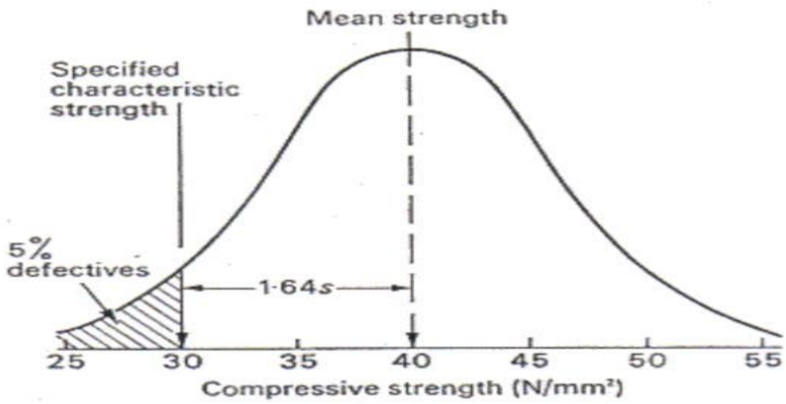

Figure 1: Difference between mean and characteristic strengths (Sarat, 2013)

From Ahmed and Sturges (2011), the equation which follows from Figure 1 is

$f_{yk} = f_{ym} - 1.64s$ (eq.1)

Where:
f_{yk} is the characteristic yield strength
f_{ym} is the mean yield strength
s is the standard deviation.

Following this observation, in this study, investigation from a different perspective was done, by examining the characteristic yield strength of steel instead of the widely researched average yield strength. A case study has already been conducted of steel samples in Abuja, Nigeria's capital city (Kulmedov et al., 2021). The purpose of this paper is to derive the characteristic strength for the samples in Kulmedov et al. (2021) using equation 1 and to use that strength to examine the structural design performance of a building's structural design already built in Abuja. This building's final structural calculations and drawings were obtained from its developers, and the aim is to see how much the building's design performance changes based on the changed steel characteristic yield strength. No similar study has been found studying structural design practices in Nigeria, and the findings will shed light on the adequacy of current practice.

Methodology

The building is a 3-storey residential building, symmetrical at the centre and located in Abuja, Nigeria. The floor and roof plans of the building are shown in Figure 2 and Figure 3. Varying reinforcement bar diameters were used in the structural members. Slab members have depths of 150mm and 175mm. Beams on the 1st and 2nd floors are 230 x 450mm while the roof beams are 230x300mm. Columns are all 230 x 230mm members, with floor to floor heights being 3m. 12mm bars were adopted in slab structural members; 16 and 20mm bars were used in beam structural members; 16mm bars were adopted all through the column and foundation structural members of the building. The building was designed according to BS8110 with an assumed f_{yk} of 460 MPa and a concrete grade of C16/20.

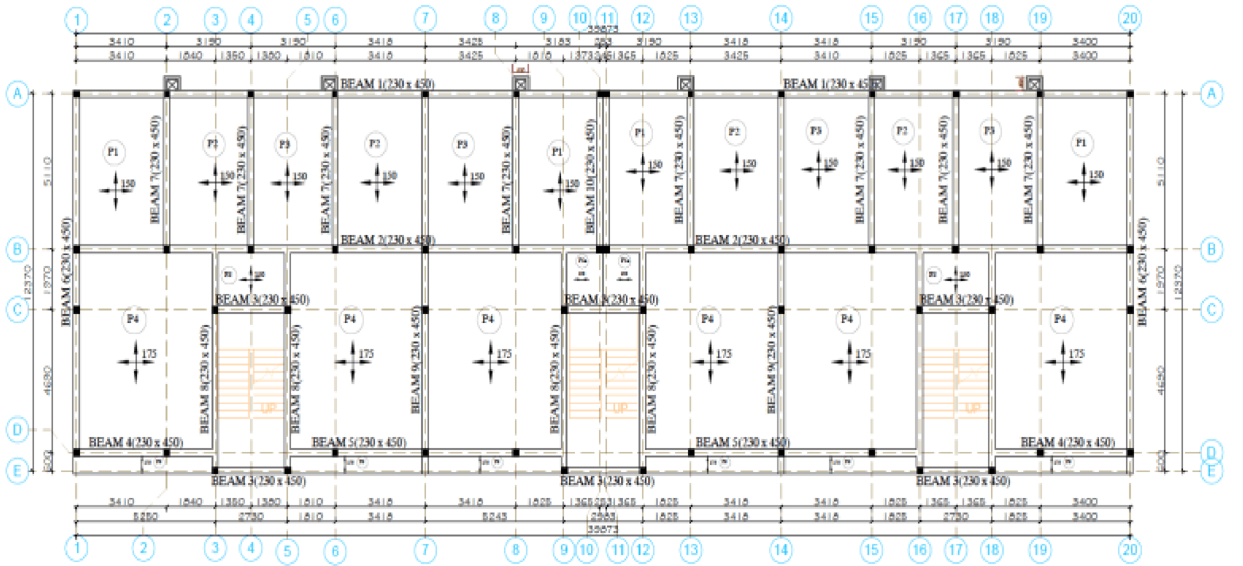

Figure 2: First and second-floor plans of building as-built

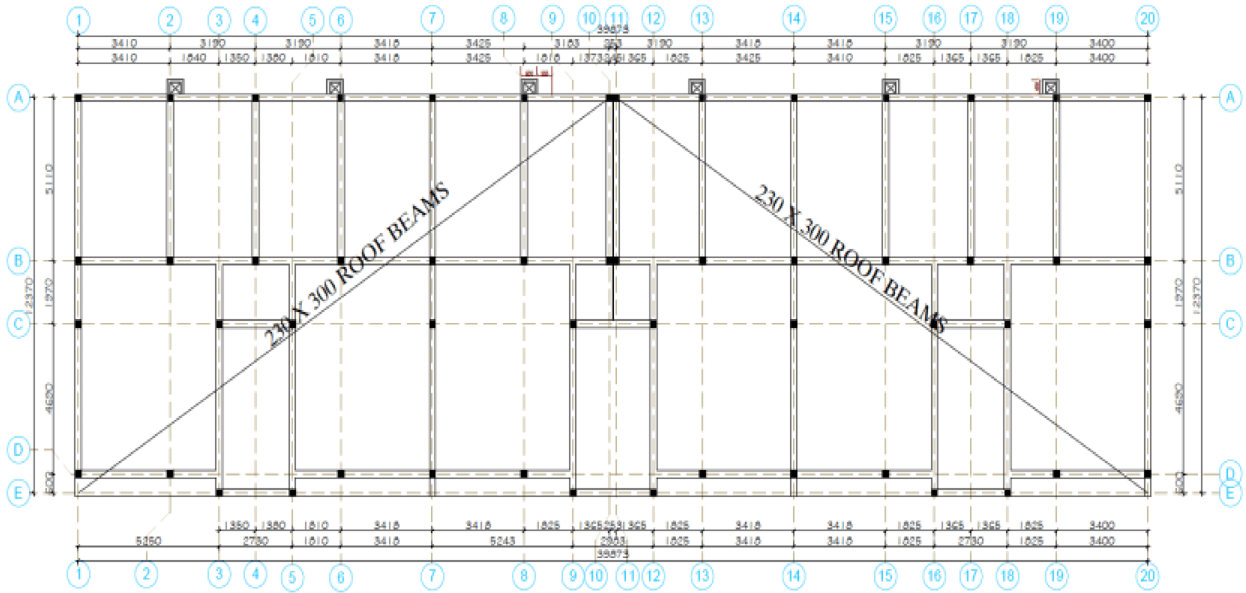

Figure 3: Roof plan of building as-built

Key assumptions made in the structural design from the design sheets obtained were:

- Dead load on slab = 2 kN/m^2
- Imposed load on slab = 1.5 kN/m^2
- All beam wall loading = 9.37 kN/m
- Slab Cover = 20mm
- Beam Cover = 25mm
- Column Cover = 25mm

As stated earlier, the building being studied has already been built. Its structural calculations sheets and design drawings were obtained for this study. It should be noted that there are slight discrepancies between the calculations and the drawings, with the drawings being generally more conservative than the calculations. From these documents, it was seen that the structure was designed using BS 8110-1:97 and BS 6399-1, which are the British Standards titled Structural Use of Concrete and Loading for Buildings respectively. Orion 18, a popular structural design software package in Nigeria, was used to design the building originally. In this study, a model of the building was made in ProtaStructure 2018 with all relevant dimensions and parameters as shown in Figure 4. ProtaStructure 2018 is a software with a similar interface to Orion 18.

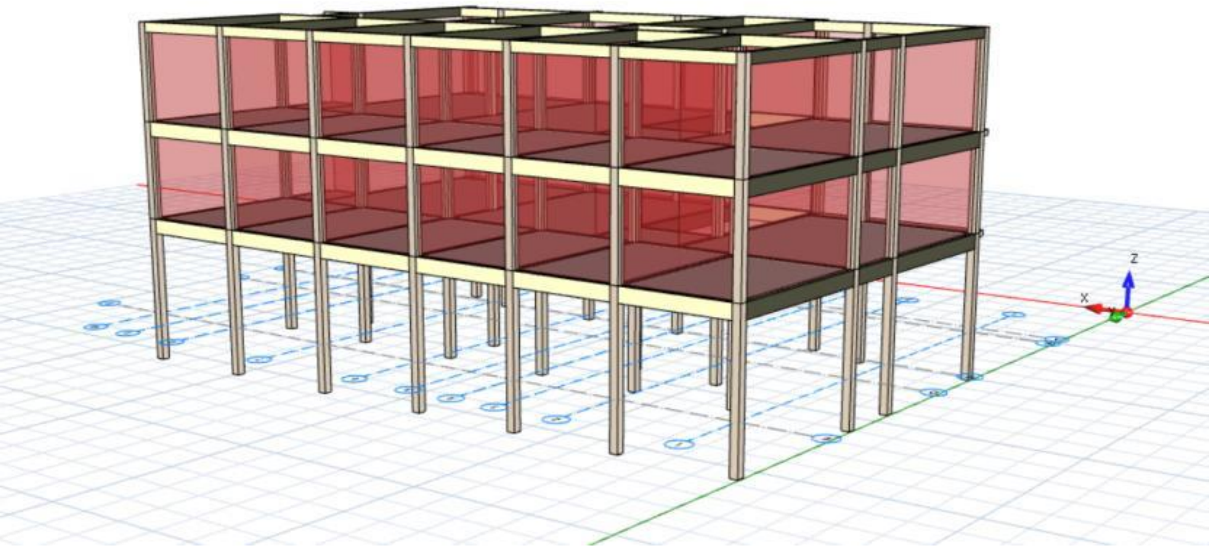

Figure 4: 3D model of building in Protastructure 2018

Results from the structural analysis were obtained and compared with those of the original design. For all slabs, beams, and columns, the results were found to be identical. This was taken as a cue that the model reproduction had been successful.
On the other hand, 8 sets of 3 steel samples - making a total of 24 - were tested in a study of the yield strength of steel in Abuja (Kulmedov et al., 2021). The results of the yield strength tests are shown in Table 1.

Table 1: Yield strength results of reinforcement rods in Abuja obtained in (Kulmedov et al., 2021).

Sample	Yield Strength (MPa)
1	408.96
2	477.36
3	418.01
4	374.13
5	377.79
6	379.32
7	344.14
8	407.97
9	412.1
10	416.24
11	453.73
12	443.86
13	427.29
14	428.62
15	427.48
16	476.4
17	469.98
18	506.09
19	479.96
20	465.89
21	365.04
22	337.76
23	331.96
24	352.59

The characteristic yield strength of the samples was derived using equation 1. Afterwards, the characteristic yield strength of the computer model was modified from the original 460 MPa to that obtained from equation 1. Another building analysis was carried out to see the building performance with the new characteristic strength. The results for all structural members were then compared to the original building calculations and working drawings. The primary difference between this and the original design was an increase in the required area of steel reinforcement, due to the reduction of the characteristic strength. Naturally, the provided reinforcement of the old design will be found wanting in some instances of the new design. The list of failed members was then collated, and patterns were observed and discussed. Do recall that only half of the structure is analysed because it is symmetrical about the middle. Foundation designs were not included in the structural design of the building obtained, so foundations were not compared.

Results and Discussion:

The characteristic strength of the samples tested in Kulmedov et al. (2021) was found to be 335.8 MPa using equation 1. This was then used for re-analysing slabs, beams, and columns. The results for each analysis will be discussed in turn.

Slabs

There are 14 slabs in the half of the structure analysed. All existing slab reinforcement were found to be sufficient, except in two instances; the top support reinforcements at Slabs S4A and S4B. Their locations are shown in Figure 5.

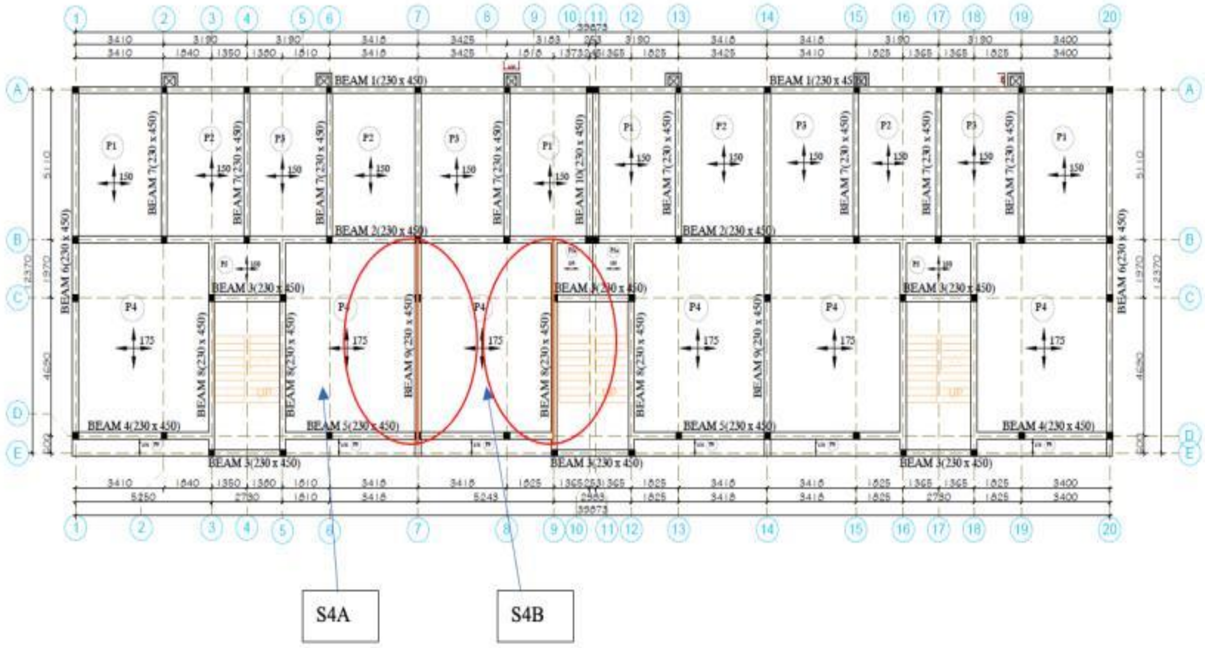

Figure 5: Locations of failed slab reinforcement

The modified and original design calculations are shown in Table 2 and Table 3, with the problematic support reinforcement being highlighted in yellow. It is evident that the area of reinforcement specified in Table 3 is insufficient for meeting the requirements in Table 2. The working drawings were then checked and it was found that the reinforcement of 12mm bars at 250mm spacing was used for both supports as shown in Figure 6. The areas supplied are still insufficient. Therefore, it is concluded that the structural design of these two supports as-built is insufficient.

Table 2: Analysis and design of slabs with fyk = 335.8 MPa

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Slab Strip: X2 -- Storey: 1
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Materials: C16/20 / Grade 335 (Type 2)


            Type        g        L1     C-sup    C-span        As
 Slab        d/h        q        L2     M-sup    M-span   Req/Sup   S T E E L   B A R S
            (mm)   (kN/m2)     (mm)    (kN.m)    (kN.m)     (mm2)

                         Support Mc = 2.8Support As = 353.93/452.39     SupTop: Y12-250(T1)

 1S4           7     6.200   5250.00    0.0000    0.0622  477.2/502.65
         144/175     1.500   6660.00       4.7      19.0                      StrBot: Y12-225(B1)
                            Deflection Check:   L/d = 36.46 < 45.86 *** Sufficient ***

                         Support Mc = 3.9Support As = 303.37/452.39     SupTop: Y12-250(T1)

 1S5           2     5.600   2730.00    0.0370    0.0280 303.37/452.39
         107/150     1.500   1855.00       1.3       1.0                      StrBot: Y12-250(B2)

                        Support Mc = 14.1Support As = 431.97/452.39     SupTop: Y12-250(T1)

 1S4A          2     6.200   5228.10    0.0604    0.0457 353.93/452.39
         144/175     1.500   6660.00      18.3      13.8                      StrBot: Y12-250(B1)
                            Deflection Check:   L/d = 36.31 < 52.0 *** Sufficient ***

                        Support Mc = 18.3Support As = 460.02/565.49     SupTop: Y12-200(T1)

 1S4B          2     6.200   5243.00    0.0602    0.0455 353.93/452.39
         144/175     1.500   6660.00      18.3      13.9                      StrBot: Y12-250(B1)
                            Deflection Check:   L/d = 36.41 < 52.0 *** Sufficient ***

                        Support Mc = 16.0Support As = 492.75/565.49     SupTop: Y12-200(T1)
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Table 3: Analysis and design of slabs with fyk = 460 MPa

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 1S4A          2     6.200   5227.50    0.0604    0.0457  258.3/452.39
         149/175     1.500   6660.00      18.3      13.8                      Bottom: T12-250(B1)
                            Deflection Check:   L/d = 35.08 < 52.0 *** Sufficient ***

                        Support Mc = 18.3Support As = 323.90/452.39     Top:T12-250(T1)

 1S4B          2     6.200   5242.50    0.0602    0.0455  258.3/452.39
         149/175     1.500   6660.00      18.3      13.9                      Bottom: T12-250(B1)
                            Deflection Check:   L/d = 35.18 < 52.0 *** Sufficient ***

                         Support Mc = 2.1Support As = 258.30/251.33     Top:T8-200(T1)
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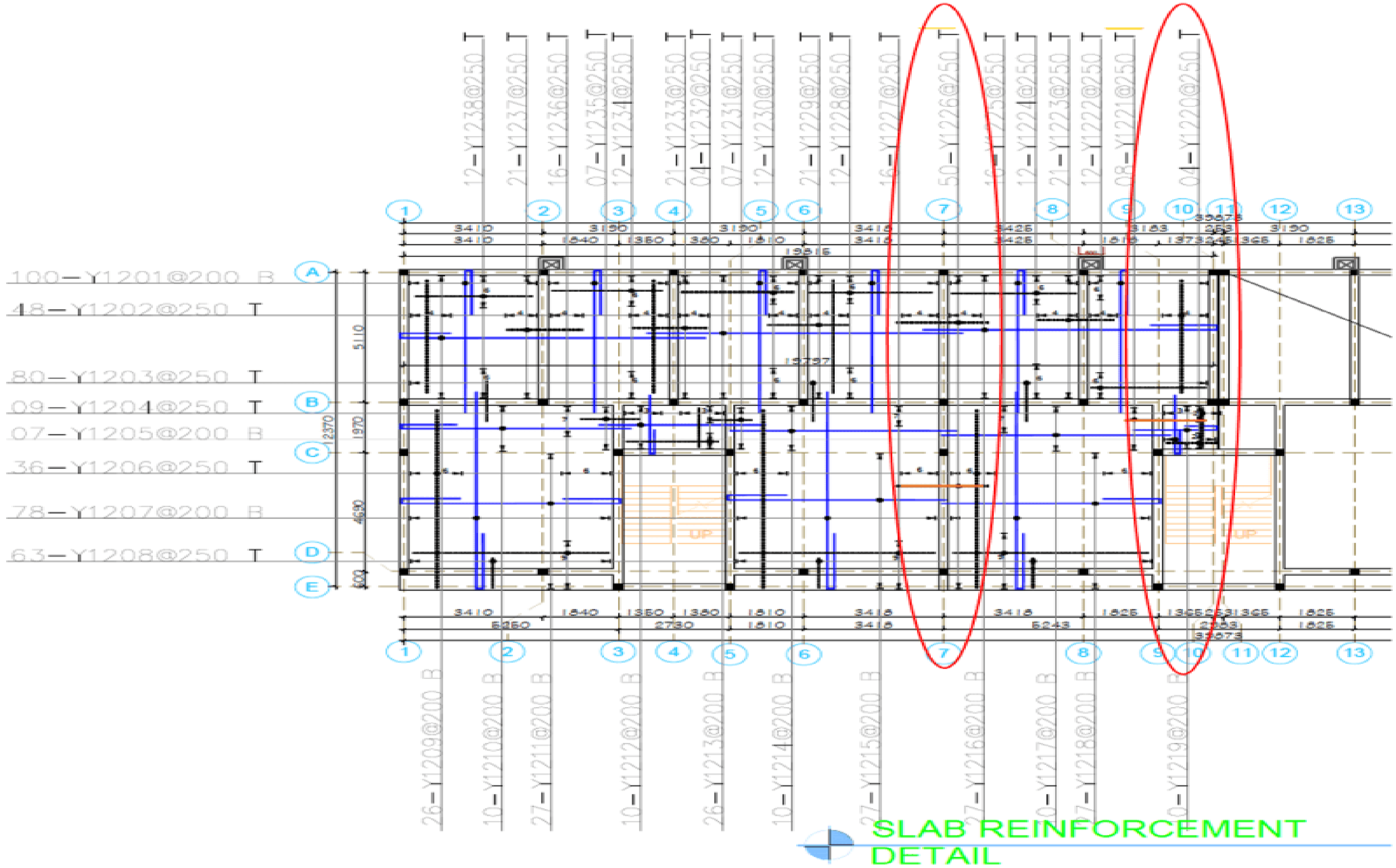

Figure 6: R.C. Detail of First floor slab from the original design

Beams

The list of failed beams and their locations is shown in Table 4. Figure 5 can be used to locate the beams on the plan. The total makes up to 11 failures in beams.

Table 4: List of Failed Beams

Axis	Beam Name	Reinforcement Location	Reinforcement from Design Report		Reinforcement in Drawing		Modified Design (fyk= 335.8 MPa)
			Number	Area (mm2)	Number	Area (mm2)	As,req (mm2)
Axis 2	Beam 7	Midspan of Beam	4 H16	804.25	4 T16	804.25	1029.57
Axis 3	Beam 8	Midspan of 1st Span	3 H16	603.19	3 T16	603.19	607.54
Axis 3	Beam 8	1st Interior Support	4 H16	804.25	4 T16	804.25	920.28
Axis 4	Beam 7	Midspan of Beam	4 H20	1256.64	4 T16	804.25	1008.33
Axis 5	Beam 8	Midspan of 1st Span	2 H20	628.32	3 T16	603.19	612.86
Axis 5	Beam 8	1st Interior Support	2 H20	628.32	4 T16	804.25	916.26
Axis 6	Beam 7	Midspan of Beam	4 H16	804.25	4 T16	804.25	1030.39
Axis 7	Beam 9	Mispan of 1st Interior Span	4 H16	804.25	3 T20	942.47	986.8
Axis 8	Beam 7	Midspan of Beam	4 H16	804.25	4 T16	804.25	1030.27
Axis 9	Beam 8	Midspan of 1st Span	2 H20	628.32	3 T16	603.19	612.81
Axis 9	Beam 8	1st Interior Support	2 H20	628.32	4 T16	804.25	932.85

Columns

There were no labels provided in drawings for the column structural members in the original design, hence only failed structural members on the new design were tabulated and no direct comparison was made. However, as all originally designed columns were 230mm x 230mm with reinforcement of 4Y16 bars and floor to floor heights of 3m, this turned out to not be a problem. A simple check of whether every column worked according to the aforementioned specifications was sufficient. The list of failed columns in the analysis is shown in Table 5, ranked in descending order of their utilisation ratios - where the utilisation ratio here is the ratio of required reinforcement to the area of the 4Y16 bars provided for each column. It should be noted that even though column 1C3 is marked in green, it is still deemed to have failed because a utilisation ratio of 1 is unacceptable. A total of 21 columns were found to have failed.

Table 5: List of failed columns

Column	Storey	b1	b2	Design	U.Ratio	Print	Qty	Steel Bars	Links
2C2	2	230	230	✘	4.41	☑	1	4x1Y16	Y10-175
2C5	2	230	230	✘	4.4	☑	1	4x1Y16	Y10-175
2C3	2	230	230	✘	4.39	☑	1	4x1Y16	Y10-175
2C29	2	230	230	✘	4.17	☑	1	4x1Y16	Y10-175
2C8	2	230	230	✘	4.09	☑	1	4x1Y16	Y10-175
2C12	2	230	230	✘	3.95	☑	1	4x1Y16	Y10-175
2C10	2	230	230	✘	3.94	☑	1	4x1Y16	Y10-175
2C9	2	230	230	✘	3.83	☑	1	4x1Y16	Y10-175
1C2	1	230	230	✘	2.42	☑	1	4x1Y16	Y10-175
1C5	1	230	230	✘	2.4	☑	1	4x1Y16	Y10-175
1C8	1	230	230	✘	2.33	☑	1	4x1Y16	Y10-175
1C12	1	230	230	✘	2.32	☑	1	4x1Y16	Y10-175
1C10	1	230	230	✘	2.3	☑	1	4x1Y16	Y10-175
3C2	3	230	230	✘	1.79	☑	1	4x1Y16	Y10-175
3C4	3	230	230	✘	1.78	☑	1	4x1Y16	Y10-175
3C6	3	230	230	✘	1.78	☑	1	4x1Y16	Y10-175
3C12	3	230	230	✘	1.78	☑	1	4x1Y16	Y10-175
3C87	3	230	230	✘	1.77	☑	1	4x1Y16	Y10-175
3C3	3	230	230	✘	1.76	☑	1	4x1Y16	Y10-175
1C3	1	230	230	✔	1	☑	1	4x1Y16	Y10-175
3C10	3	230	230	✘	1	☑	1	4x1Y16	Y10-175

Conclusions

Using the characteristic strength derived from the 24 samples of steel in Abuja tested and reported by Kulmedov et al. (2021), a total of 2 slab supports, 11 beams, and 21 columns were found to have failed in the building studied. These are alarming results, given that the building has already been built. It can be concluded that for reinforcement bought at random from markets in Abuja, current structural design practices are insufficient. To the authors' knowledge, some structural designers have begun to be proactive, making sure to test samples of steel before using them on site. However, it is important that the difference between the characteristic and mean strength is noted, and the former is the strength assumed by both the British Standards, and the Eurocode; the two standards used in structural design in Nigeria.

A call must also be made on regulators in Nigeria to ensure steel used in construction sites at has characteristic yield strength equal to at least 410 MPa or 460 MPa often assumed by structural designers in the country.

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