Effects of Load Ratio Variation on the Safety of Timber Concrete Composite Floor

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Abstract- This paper presents the structural reliability appraisal of timber concrete composite floor designed in line with Eurocode 5 (2004) and Eurocode 2, (2004). Limit state expressions for timber concrete composite floor subdued to tension, bending, tension and bending, shear and compression were generated and their entailed reliability degrees were assessed. The basic variables associated with the design are considered to be random variables with their properties espoused from the previous studies. Reliability analysis was performed using reliability mothed i.e. first order reliability method (FORM) owing to assess the safety levels of the composite floor structural elements by considering six different modes of failure. The analysis comprised of different selected species of softwood, hard wood and glue laminated timber whose strength class were obtained from BS EN 338, 2008 and concrete of strength class C30 from Eurocode 2. The results obtained disclosed that safety indices decrease as the load ratio steps up that led to cut down of the strength. It was detected that timber with strength classes D70, D50 and C50 are safe against all different failure modes looked at except C50 and D50 against shear failure at load ratio of 1, 1.5 and 2. It was conclude timber of strength classes D70, D50 and C50 would reliable for the construction of composite floor i.e. timber-concrete floor.

Keywords- Composite floor, concrete, failure modes, FORM, safety index, Timber.

1 INTRODUCTION

Convetionally, timber was mainly used for building constructions and domestic purposes. However, in previous years researchers have been looking for a ways of developing or forming a composite material made with a timber and concrete that will allow large buildings to be constructed. Timber-concrete composite floors are defined as structural arrangements in which top concrete flange is linked up to a bottom timber web, allowing the characteristics of both materials to be used by blending concrete's compression resistance with the timber capacity to withhold tension and bending (Lukaszewska, 2010). In building construction, softwoods are the most used timber, while in some structures that needed the use of high strength and durability timber, hardwoods are usually used specially in railway sleepers and bridges (Karlsen and Slitskouhov, 1989).

According Ceccotti, (1995) composite floor experienced less deflection when imposed loads are applied because of its high stiffness and density, and at same time it has a high thermal and fire resistance, and less susceptible to vibration when equate to floors produced with a timber. He concluded that composite beams was immensely used in many western countries to improve the existing timber floors. Bathon *et al.*, (2006) reported that different kinds of timber-concrete deck floors with appealing characteristics have been built up for offices, residential, commercial buildings and industrial uses.

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Aguwa and Sadiku (2011) claimed the use locally available raw materials such as timber in buildings constructions and other civil engineering activities in most of growing countries is major measures towards industrialization and economic independence. Uche and Afolayan (2008) defined reliability as the chances of the structure to execute its intended function adequately for a span of duration under the operating conditions it may undergo. According to Richard and Digby (2005) a timber-concrete composite beam is two times strong and thrice stiffer than a timber beam acting on its own. A reinforced concrete is not as economical when equate with timber-concrete composite this is due to the fact that the cracking zone that allows the water to percolate leading to corrosion of steel, spalling and other kinds of impairment (Gutkowski *et al.*, 2008).

A study on reliability analysis performed by Ogork and Nakore (2017) disclosed that their findings depicted that the design is acceptable as deflection as well as stresses were not exceeded the bounding limits. A report by Abdulwahab and Uche, (2017) disclosed that the safety index decreases as the load ratio increases. It was also highlighted that the bending stress and longitudinal stress were safe at load ratio of 0.1 to a load ratio of 0.6 with safety indices runs from 3.20 to 4.26 with the chance of failure between 10 to 5, however, it becomes critical at load ratio of 0.8 to a load ratio of 1.0 that marches to safety indices of 2.51 to 2.84. According to Ogork and Nakore (2017) the safety indices of floor joist in shear and bending of 1.2 to 2.8 with decrease in dead to live load ratio respectively were less than the stipulated safety index of 3.8. They concluded that the timber floor are more dependable in bearing, shear and deflection and critical in bending mode of failure. Benu and Samuel (2019) reported that as the load ratio and slenderness ratio increased the reliability index decreased, and concluded that load ratio and slenderness ratio have influences on the results of reliability of a solid timber column.

Nigeria uses reinforced concrete floor in over ninety percent of its multi-story buildings, most of these floor systems are solid slabs with very few constructions made up of other floor systems like hollow core and flat slabs. With many researches done on TCC flooring systems, it's pertinent for the Nigerian construction industry to adopt this method due to its cost and environmental advantages over the normal reinforced concrete (RC) floors. However, the need to determine the efficient ways of improving the structural performance of concrete slabs or floors cannot be over-emphasised. So, combining timber and concrete with the view of producing a composite floors is the one of the efficient methods of improving the performance of concrete slabs. Timber-concrete composite floor gives higher load-bearing capacity and stiffness than timber only or concrete only slabs. It also gives high fire resistant and shows good insulation properties, and reduces the dead load which allows larger spans with the same thickness to be constructed.
The study aims at evaluating the effects load ratio variation on the safety of timber-concrete composite floor.

2 Materials and Methods

2.1 Materials

Glued laminated timber with different classes was used. Grade 30 concrete was used for this study. While the MATLAB software was used for reliability based analysis and design. Eurocode 5 and Eurocode 2 were used for timber and concrete design.

2.2 Methods

2.2.1 Design of Timber Concrete Composite Floor

Timber-concrete composite floor was designed in order to fulfil the ultimate limit states (ULS) and serviceability (SLS) in the short and long term. The ULS was ascertain by equating the maximum shear force and the maximum stress in connection and concrete respectively, and at same time the combined axial force and bending moment in timber with the respect to resisting design value. The elastic formulas for solving Timber Concrete Composite floors are shown below;

$$(EI)_{eff} = E_1I_1 + E_2I_2 + \gamma_1E_1A_1a_1^2 + \gamma_2E_2A_2a_2^2, \quad (1)$$

where,

$$\gamma_1 = \frac{1}{1 + \pi^2E_1A_1S_{eff}/Kl^2}, \quad (2)$$

$$\gamma_2 = 1, \quad (3)$$

$$A_i = b_ih_i \; with \; i = 1,2 \quad (4)$$

$$I_i = \frac{b_ih_i^3}{12} \; with \; i = 1,2 \quad (5)$$

$$a_1 = \frac{\gamma_2E_2A_2H}{\gamma_1E_1A_1 + \gamma_2E_2A_2}, \quad (6)$$

$$a_2 = \frac{\gamma_1E_1A_1H}{\gamma_1E_1A_1 + \gamma_2E_2A_2} \quad (7)$$

$$H = \frac{h_1}{2} + a + \frac{h_2}{2}, \quad (8)$$

$$S_{eff} = 0.75s_{min} + 0.25s_{max} \quad (9)$$

$$\sigma_{m,i}(x) = \frac{1}{2}\frac{E_ih_iM^*(x)}{(EI)_{eff}}, \quad (10)$$

$$\sigma_1(x) = \frac{\gamma_1E_1a_1M^*(x)}{(EI)_{eff}}, \quad (11)$$

$$\sigma_2(x) = \frac{\gamma_2E_2a_2M^*(x)}{(EI)_{eff}}, \quad (12)$$

Where $(EI)_{eff}$,E, K and Z are flexural stiffness, Young's modulus of material, slip modulus of connection and section modulus respectively. However, σ_1, σ_2 , $\sigma_{m,1}$ and $\sigma_{m,2}$ are stress due to the axial force in concrete, stress due to the axial force in timber, maximum stress due to the bending moment in concrete and timber respectively. Lastly, s_{min}, s_{max}, and s_{eff}, G, A, and I represent minimum, maximum spacing of connectors, centroid, area and the second moment of area of the cross-section. The subscripts 1 and 2 represent concrete and timber respectively.

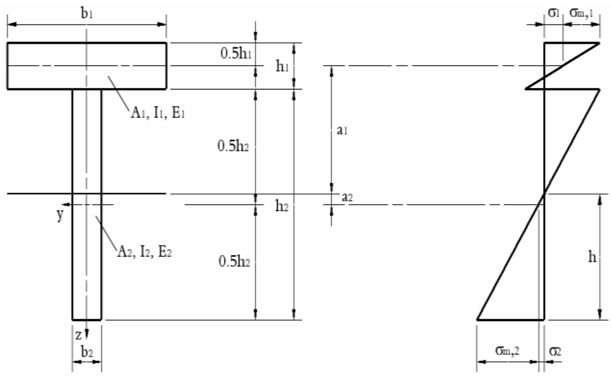

Fig. 1: Timber-concrete composite T-beam

2.2.2 Reliability Index

The reliability index is the representation of the shortest distance from the origin (reduced variable space) to the limit state line. The reduced form of a random variable, X is given by

$$Z_x = \frac{X - \mu_X}{\sigma_X} \quad (13)$$

So, the reliability index β, is associated with the probability of failure, P_f, by

$$\beta = -\Phi^{-1}(P_f) \quad (14)$$

2.2.3 Development of the Reliability Function

The limit state function $G(x)$ is defined by equation (15) where R is the strength and S is the load.

$$G(x) = R - S \quad (15)$$

If the value of $G(x)$ is negative the structure will fail, but if it turns to be positive $G(x)$ the structure is safe, while a zero value indicates a point on the failure surface. The failure modes of a timber-concrete composite floor are presented in Equations (19) to (37) (Yeoh and Fragiacomo, 2012).

At Ultimate Limit State,

$$Mx = M_D \quad (16)$$

$$M_D = \frac{Q(\alpha\gamma_g + \gamma_q)l^2}{8} \quad (17)$$

2.2.3.1 Failure Mode 1

For failure to occur in the timber due to axial stress caused by axial force derived from loading,

$$\sigma_2(x) > f_{t,0,d}, \quad (18)$$

$$\frac{E_2a_2M_D}{(EI)_{eff}} > K_{mod} \times {}^{f_{t,0,k}}/_{\gamma_m}, \quad (19)$$

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Hence the limit state function is

$$G(x)_1 = \theta_R \left[\frac{K_{mod} \cdot f_{t,0,k}}{\gamma_m}\right] - \left[\frac{E_2 a_2 M_D}{(EI)_{eff}}\right] \theta_S \quad (20)$$

Where θ_R is the resistance model uncertainties and θ_S is the load action model uncertainties.

2.2.3.2 Failure Mode 2

For failure to occur in the timber due to axial stress caused by bending moment obtained from loading,

$$\sigma_{m,2}(x) > f_{m,d} \quad (21)$$

$$\frac{1}{2}\frac{E_2 h_2 M_D}{(EI)_{eff}} > K_{mod} \times {f_{m,k}}/{\gamma_m} \quad (22)$$

Hence the limit state function is

$$G(x)_2 = \theta_R \left[\frac{K_{mod} \cdot f_{m,k}}{\gamma_m}\right] - \left[\frac{1}{2}\frac{E_2 h_2 M_D}{(EI)_{eff}}\right] \theta_S \quad (23)$$

2.2.3.3 Failure Mode 3

For failure to occur due to combined bending and tension to occur, then the ratio;

$$\frac{\sigma_2(x)}{f_{t,0,d}} + \frac{\sigma_{m,2}(x)}{f_{m,d}} > 1 \quad (24)$$

$$\frac{\gamma_m \sigma_2(x)}{K_{mod} \cdot f_{t,0,k}} + \frac{\gamma_m \sigma_{m,2}(x)}{K_{mod} \cdot f_{m,k}} > 1 \quad (25)$$

Hence the limit state function is

$$G(x)_3 = 1 - \left[\frac{\gamma_m \sigma_2(x)}{K_{mod} \cdot f_{t,0,k}} + \frac{\gamma_m \sigma_{m,2}(x)}{K_{mod} \cdot f_{m,k}}\right] \quad (26)$$

2.2.3 Shear Stress

For the timber section to fail due to shear stress from the loading

$$\tau_{d,max} > f_{v,d} \quad (27)$$

$$1.5\frac{V_D}{A_2} > K_{mod} \times {f_{v,k}}/{\gamma_m} \quad (28)$$

Hence the limit state function is

$$G(x)_4 = \theta_R \left[\frac{K_{mod} \cdot f_{v,k}}{\gamma_m}\right] - \left[1.5\frac{V_D}{A_2}\right] \theta_S \quad (29)$$

Where

$$V_D = \frac{Q(\alpha\gamma_g + \gamma_q)l}{2} \quad (30)$$

The reliability of the designed Timber Concrete Composite floor is verified using probabilistic methods.

3 Results and Discussions

3.1 Influence of Variation of Load Ratio for Tension Failure on Safety Index

Figure 2 showed a safety indices of different strength classes of timber i.e. softwood, hardwood and glue laminated timber. It showed that the safety indices for all the strength classes of timber decreased as the load ratio increased. The safety indices also decreased as strength class of timber increased. On the other hand, the safety indices decreased as the strength class increased for glue laminated (GL) timber. It was observed that the timber with strength class D70 has the highest safety indices while the timber with strength class C14 has the least safety indices when compared with other timbers with different strength classes. The decrease in the safety indices may be ascribed to the cutting down in the flexural values (EI) of the timber especially timber with strength classes C14, C20 and even GL24. However, the values of the safety indices of timber with strength class D70, D50, GL36, C50, D30 and GL24 fell within the range except D30 and GL24 at load ratio of 1.5. So, C50 would be reliable and economical against tension failure.

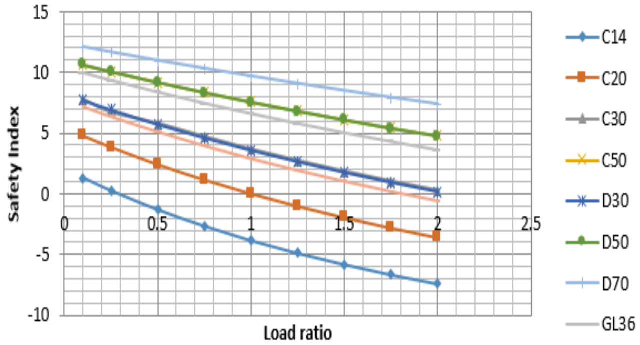

Fig. 2: Safety index against load ratio for tension failure

3.2 Influence of Variation of Load Ratio for Bending Failure on Safety Index

The safety indices of different strength classes of timber is presented in Figure 3. It was observed that the safety indices for all the strength classes of timber decreased as the load ratio increased. And also, the safety indices decreased as strength class of timber increased. On the other hand, it was also observed that the timber with strength class D70 has the highest safety indices when compared with other classes of timber while C14 has the least safety indices when compared with other timbers with different strength classes. The decrease in the safety indices may be due to the stepping down in the flexural rigidity values (EI) of the timber especially timber with strength classes C14 and C20. Though, the values of the safety indices of all the timber with strength classes had fallen within the range except C14 and C20 at load ratio of 1. So, C30 would be reliable and economical against bending failure.

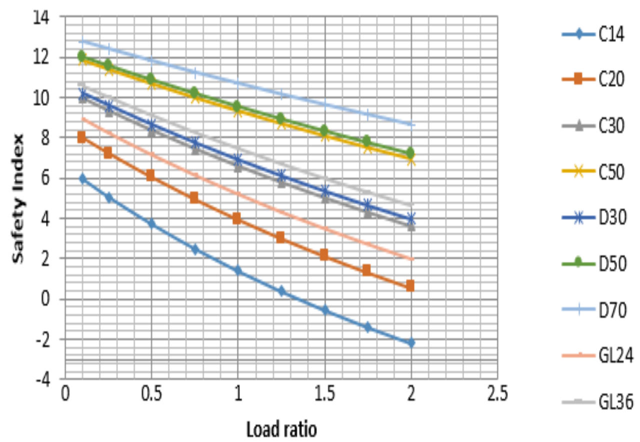

Fig. 3: Safety index against load ratio for bending failure

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3.3 Effect of Variation of Load Ratio for Combined Tension and Bending Failure and Shear Failure on Safety Index

The safety indices of combined tension and bending failure and shear failure against load ratio are presented in Figure 4 and figure 5 respectively. It was discovered from Figure 4 and Figure 5 that as the load ration increased, the safety indices for all the strength classes of timber decreased. On the other hand, the safety indices decreased as strength class of timber increased for both cases. The decrease in the safety indices may be associated with the stepping down in the flexural rigidity values (EI) of the timber. It was also observed that the timber with strength classes C14 and C24 are greatly affected as shown in Figure 4 since both have a negative safety indices with negative value at load ratio of 2, while C14 in figure has a safety indices below 0. However, D70 has the highest safety indices and the values of safety indices fell within the range in both cases. This showed that timber with strength class D70 is reliable in both cases when compared with other strength classes of timber.

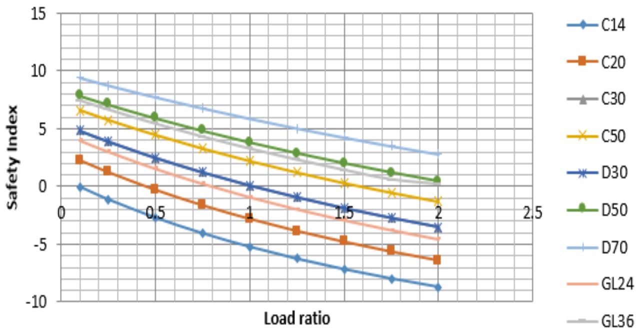

Fig. 4: Safety index against load ratio for combined tension and bending failure

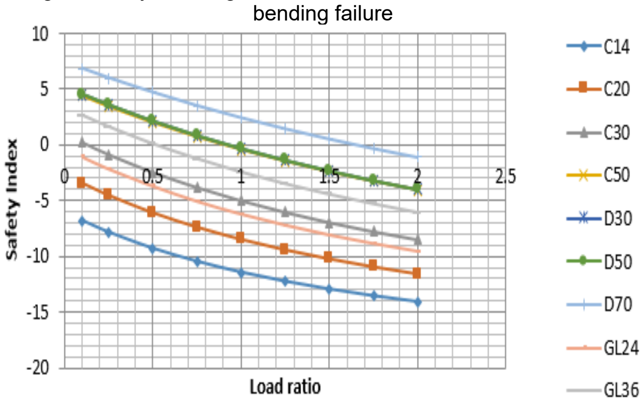

Fig. 5: Safety index against load ratio for shear failure

3.4 Effect of Variation of Load Ratio for Concrete Total Upper and Lower Fibre Compression

The results of safety indices of concrete with total fibre compression failure are presented in Figure 6, while Figure 7 showed the safety indices of concrete with lower fibre compression failure. It was observed from figure 6 that the safety indices increased as the load ratio increased. A timber with strength class C14 in this case has highest safety indices when compared with other timber strength classes of timber. It was noted that the safety indices of all strength classes of timber were above 20, this indicated that all strength classes of timber are reliable against concrete total upper fibre failure. While the safety indices of all the strength classes of timber except for timber with strength class C14 increased as the load ratio increased. The decrease of safety indices for C14 as load ratio increased may be due to stepping down in the flexural rigidity values (EI) of the timber. It can be seen from Figure 7 that all the safety indices were positive and could be reliable against concrete total lower fibre compression failure.

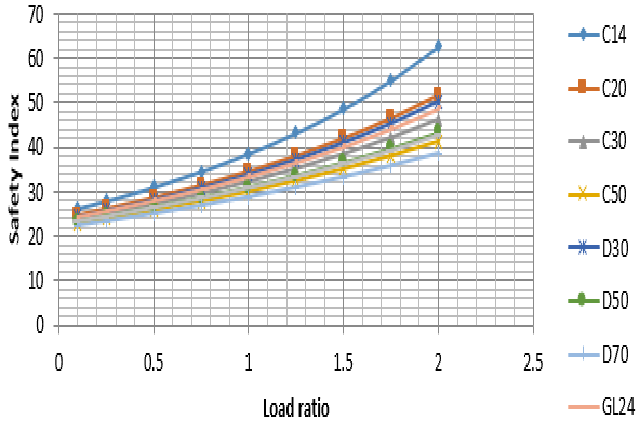

Fig. 6: Safety index against load ratio for concrete with total upper fibre compression failure

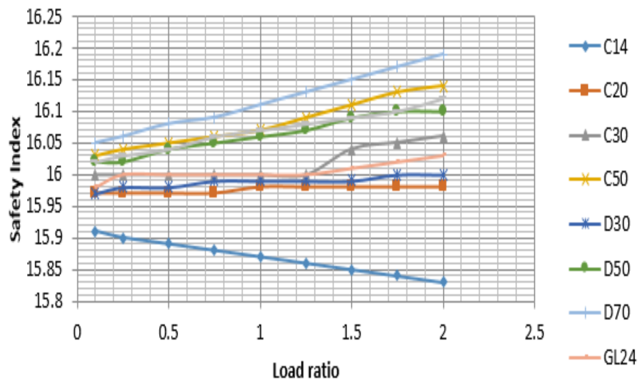

Fig. 7: Safety index against load ratio for concrete with total lower fibre compression failure

4 Conclusions

Based on the results presented the following decisions were drawn.; the Limit state equation for tension, bending, combined tension and bending, shear and compression mode of failures for timber and concrete were formulated. Reliability analysis on the design of timber and concrete disclosed that safety indices decreased as load ratio steps up. It was observed that timber with strength classes D70, D50 and C50 are safe against all modes of failure considered except C50 and D50 against shear failure at load ratio of 1, 1.5 and 2. It was conclude timber of strength classes D70, D50 and C50 would reliable for the construction of timber concrete composite floor.

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