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RELIABILITY ASSESSMENT OF REINFORCED CONCRETE PANELLED-BEAMS

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Abstract: This study presents reliability assessment of a large span reinforced concrete panelled-beams floor system designed in accordance with BS 8110 (1997). Deterministic designs against flexure, shear and deflections of the panelled-beams were carried out in consistent with the provisions of the code and also submissions in the literature. The performance functions of the respective failure modes of flexure, shear and deflections were then developed. The reliability assessment of the floor system using the performance functions derived were implemented based on stochastic approach where basic design variables were treated as random variables with their statistical characteristics obtained from JCSS code (2000) and executed using First Order Reliability Method (FORM). The results obtained showed that safety index decreases with increase in load ratio in all the modes of failure considered. In deflection, the safety indices indicated that the design is only safe with a load ratio of 0.8 to 1.0 and a failure at load ratios 0.9 to 1.0 having beta (β) values of 3.02 and 2.87 with corresponding approximate probability of failure of 1.28E-03 and 2.04E-03, respectively. Sensitivity assessments showed that the reliability index (β) values for design of reinforced concrete panelled-beams are mostly influenced by the characteristic compressive strength of concrete, span and depth of the beams. It was also noted that safety index increases with increase in variables such as characteristics compressive strength, and depth, while it decreases with increase in span of the beams and applied load.

Keywords: Reinforced concrete, Panelled beams, reliability analysis, uncertainties, sensitivity analysis

Introduction

A Panelled-beam floor system is a reinforced concrete floor supported by series of beams with equal depth spanning in two perpendicular or skewed directions. This floor system is normally employed in structures requiring floors with very large clear span to provide column-free internal spaces with consequent reduction in cost when compared with traditional methods (El-Leathy, 2016).

These beams divide the large floor with spacing ranging from 2 to 4 meters into a number of small panels that can be easily designed as solid slabs as shown in Fig. 1.

Although other approaches like composite beams, tapered girders, composite trusses and prestressed concrete beams floor support systems equally provide similar solution but the panelled-beam system is more economical and requires less sophisticated method of erection (Ghoneim and Almihilmy, 2008).

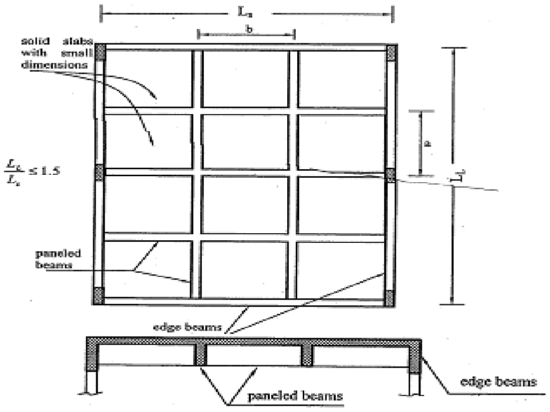

Fig. 1: Layout of panelled-beams floor (Ghoneim and Almihilmy, 2008)

The Panelled-beams system can be simply supported or continuous. The simply-supported-beam system supports the floor and transfers load to adjacent end-beams with the whole floor acting like a slab panel discontinuous on all edges. For a continuous panelled-beam system, a girder (a beam with greater stiffness than the panelled-beams) is introduced to break the floor system into spans, providing supports along the longer direction of the floor (El-Leathy, 2016).

The modes of arrangement of the beams provide options for higher stiffness and a variety for aesthetics on the soffit of the floor as shown in Fig. 2, as they can be arranged in different patterns of grid system ranging from rectangular grid, skew grid, triangular grid and quadruple grid system (Ghoneim and Almihilmy, 2008).

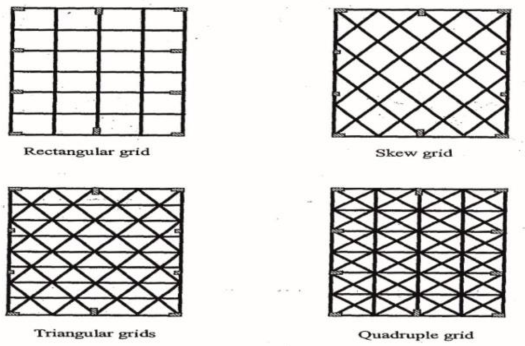

Fig. 2: Types of panelled-beams systems (Ghoneim and Almihilmy, 2008)

The rectangular grid system has two series of beams spanning in two perpendicular directions which divide the large floor into a number of small panels that can be easily designed as solid slabs. Skew grid system also has series of beams intersecting perpendicular to each other but making an angle of 45° with the edge beams. Triangular grid system is an improvement on the skew grid obtained by adding a series of horizontal beams across the skew grid while the quadruple is as a result of imposing the rectangular grid on the skew grid system.

Current design provisions for panelled-beam are based on deterministic approach largely in accordance with National or International Standards such as BS8110, Egyptian Code of Practice (ECP 203-2007), etc. Due to inherent uncertainties in materials and loadings, the codes/standards provide for safety factors to account for them. This however, could lead to a conservative design (Abdulwahab and Uche, 2016) as observed in their research working on folded plates structures. Hence the most rational approach to analysis of safety is bythe probabilistic models where the effects of the uncertainties can be accounted for and treated in a way that would result in having structures with high level of reliability.

Structural reliability is commonly described as the probability or likelihood of structure performing its purpose adequately for a period of time intended under the operating conditions encountered (Uche and Afolayan, 2008).

The parameters of loading and load-carrying capacities of structural members are not deterministic quantities which are perfectly known. They are random variables and the presence of uncertainty in the analysis and design of engineering structures has always been recognized, thus, absolute safety (or zero probability of failure) cannot be achieved (Abubakar and Ma'aruf, 2014). As such, there is a clear recognition that uncertainty and variability are associated with many variables describing a structure's performance and that this can be accounted for explicitly by the use of probability distributions and structural reliability theory (Hao and Li, 2012).

Materials and Methods

Materials

FORM5 computer package which uses an algorithm linked to FORTRAN was used in this study to compute the implied safety levels for the different limit state functions, outlining the design criteria for reliability assessment of reinforced concrete paneled beam in accordance with BS 8110 (1997). It handles up to 60 uncertain variables (x-variables) and can perform up to 40 iterations to achieve convergence.

Methods

A typical reinforced concrete rectangular paneled-beams floor to cover a particular roof of 13m by 17m as represented in Fig. 3 was designed using deterministic method based on BS 8110 (1997) and considering the failure modes identified, bending, deflection and shear, limit state equations were derived for the reliability analysis.

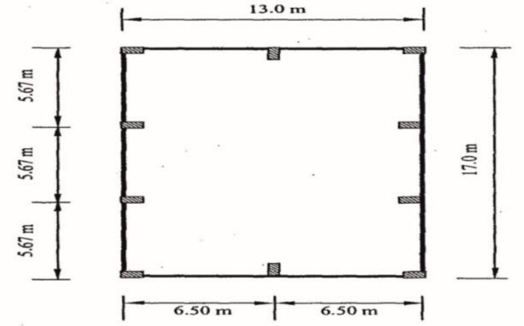

Fig. 3: Plan view of the roof slab

The floor is divided into small slabs spanning between (3 – 4 m in each direction) assuming three (3) beams spanning in the longitudinal direction (four spacing) and four (4) beams spanning in the shorter direction (five spacing).

First order reliability method (FORM) was used to determine and ascertain the safety levels (JCSS, 2000), (β values) of the panelled-beam through a subroutine program in FORTRAN 77 in order to access the FORM5 program. Sensitivity analysis was also carried out to know the effect of variation of each of the design variables.

Derivation of safe design parameters

In order to resist the loads, the resistance properties were carefully chosen so as to aid in deriving the limit state expression of the various failure modes considered in its loading. However, the limits state equation considered for this design are bending, shear and deflection failure and are as given in Equations 1 to 4.

Bending Failure Mode:

The limit state equation for the performance function for bending at the span and support respectively are given by Equations 1 and 2.

$$g(x) = 0.156 f_{cu} b d^2 - 0.125(1.4\alpha + 1.6) Q_k L^2 \qquad (1)$$

and

$$g(x) = 0.156 f_{cu} b d^2 - 0.083(1.4\alpha + 1.6) Q_k L^2 \qquad (2)$$

Where:

f_{cu} is the characteristic compressive strength of concrete at 28 days

b is the width of the beam (mm)

d is the depth of the beam (mm)

L is the span of beam (mm)

G_k is the characteristic permanent action

Q_k is the characteristic variable action

α is the dead – live load ratio

Shear Failure Mode:

$$g(x) = 0.8\sqrt{f_{cu}} - \frac{(1.4\alpha+1.6)Q_k L}{2b \times d} \qquad (3)$$

Deflection Failure Mode:

$$g(x) = \frac{L}{250} - \frac{5(1.4\alpha+1.6)Q_k L^4}{384EI} \qquad (4)$$

Where:

$E$is the Young modulus(N/mm^2)

ISecond moment of inertia(mm^4)

FORTRAN subroutine

The FORTRAN subroutine was written to accommodate different modes of failure of reinforced concrete paneled beams in FORTRAN language and linked with FORM5 to solve the limit state for bending, shear and deflection modes of failure. The flow chart for the subroutine is shown in Fig. 4. The FORM 5 was then launched via the command prompt of the computer.

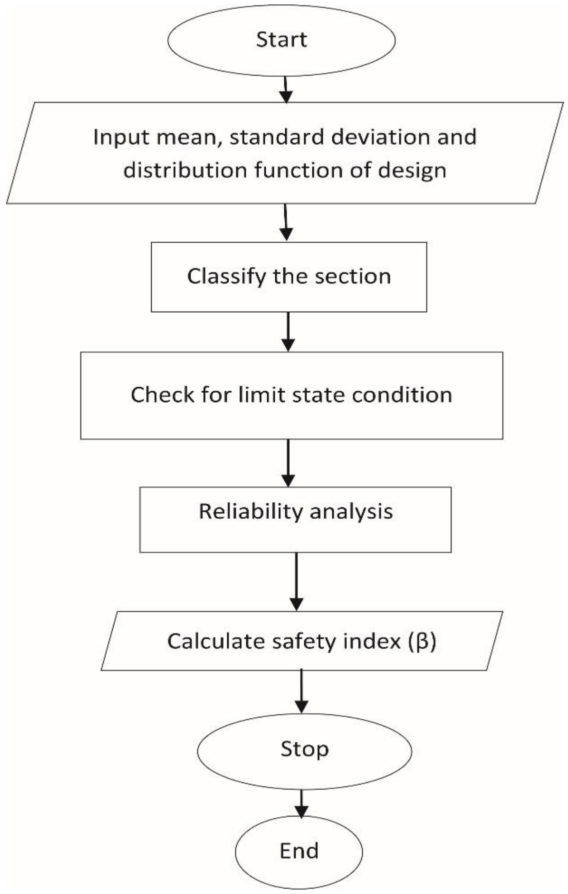

Fig. 4: Flow diagramfor reliability analysis using FORM 5

Results and Discussion

The safety indices for bending, shear and deflection mode failures for the reinforced concrete panelled-beam at corresponding load ratios were recordedand the results obtained from the evaluation of the reliability indices by FORTRAN-77 program are presented in Fig. 5.

Reliability analysis

Considering the recommendation made by JCSS (2000) of safety index range of 3.1 to 4.2 for minor consequences of failure, the reliability indices obtained showed that the design is safe in bending and shear for all load ratios. In bending and shear, the increase of load ratio considerably increases the safety indices while in shear the change is gradual.

However, in deflection, the safety indices indicated that the design is only safe with a load ratio of 0.8 to 0.1 and a failure at load ratios 0.9 to 1.0 having beta values of 3.02 and 2.87 with corresponding approximate probability of failure of 0.128E-02 and 0.204E-02, respectively.

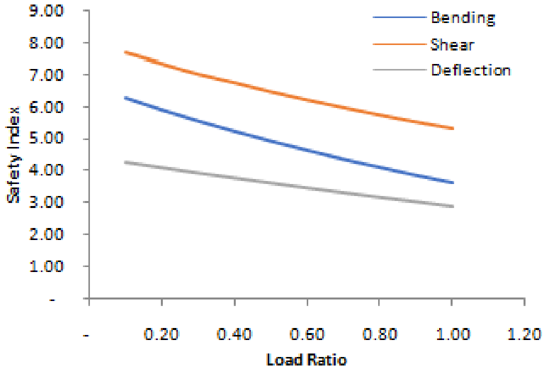

Fig. 5: Safety indices versus load ratio for paneled-beam

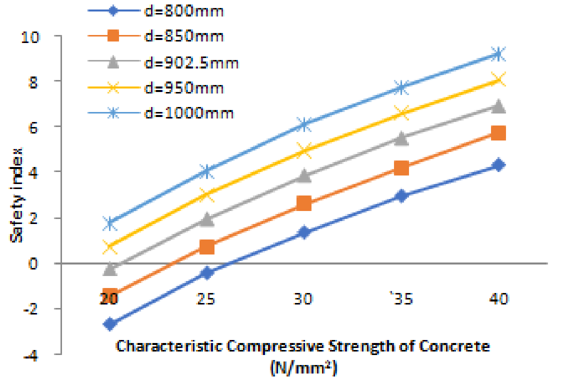

Fig. 6: Safety Indices (β) against characteristic compressive strength (f_{cu}) at varying effective depth of beam for bending mode failure

Sensitivity analysis

Safety indices were computed by varying each basic parameter and holding the remaining constant. It was observed that the compressive strength of concrete and the effective depth were the most sensitive parameters in bending, shear and the deflection failure modes.

From Fig. 6, it was observed that the safety indices increase with increase in the characteristic compressive strength of concrete for a given effective depth of the panel beam. While the safety index, 3.92, obtained at fcu of 30 N/mm^2 was within the safety range for a depth of 902.5 mm with a probability of failure of 0.447E-04, lower values of fcu yielded beta values that were below the lower limits for minor consequences of failure. For smaller values of d, 850 and 800 mm the minimum fcu for a safe design were 35 and 40 N/mm^2, respectively.

Figure 7 shows the variation of the Safety Indices (β) against Breadth (b) at varying effective depth of beamfor bending mode failure and it was observed that the safety indices increase with increase in the breadth of the beam for a given effective depth. For an effective depth of 902.5 mm, the minimum breadth of the beam for a safe design considering minor consequences of failure was found to be 300 mm. However, a beam with breadth value as low as 260 mm could be safe for a beam with an effective depth of 950 mm and above. From Fig. 8, the Safety indices decrease with increase in the applied load on the beam for a given effective depth. The effect of the load increment was linear and a beam of 1000 mm depth under the same configuration could carry up to 45 N/mm of load safely.

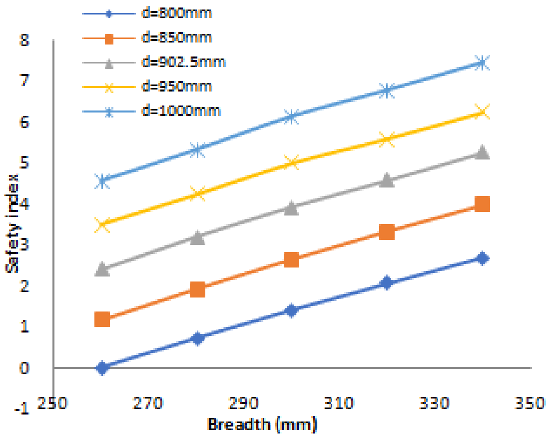

Fig. 7: Safety Indices (β) against Breadth (b) at varying effective depth of beam for bending mode failure

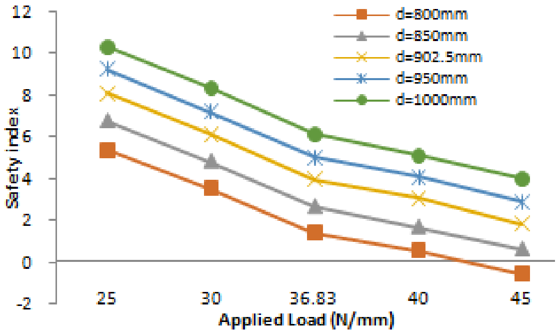

Fig. 8: Safety Indices (β) against applied load (w) at varying effective depth of beamfor bending mode failure

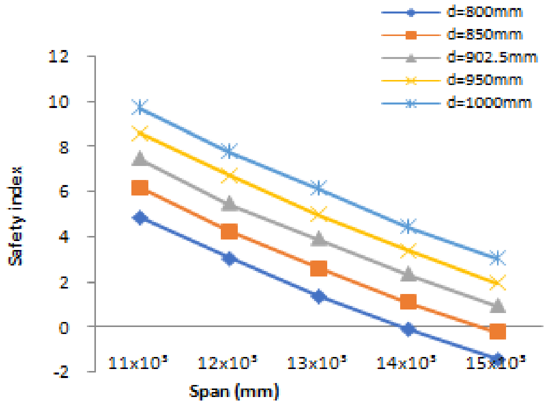

Fig. 9: Safety Indices (β) against span (L) at varying effective depth of beamfor bending mode failure

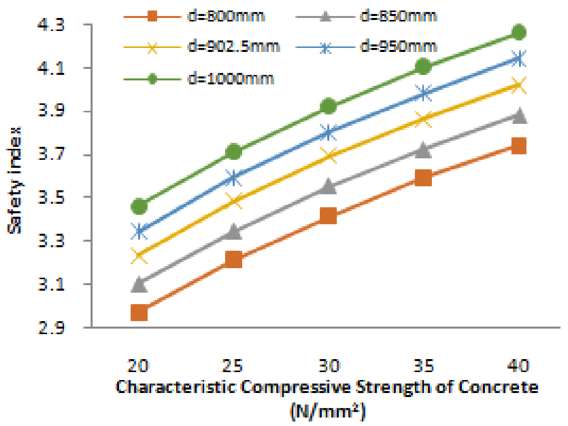

Fig. 10: Safety Indices (β) against characteristic compressive strength (f_{cu}) at varying effective depth of beam for shear mode failure

Figure 9 shows that the safety indices decrease with increase in the span of the beam for a given effective depth. For an effective depth of 902.5 mm, the maximum span of the beam for a safe design considering minor consequences of failure was 13000 mm with a safety index of 3.92 representing a probability of failure of 0.447E-04which fall within the JCSS (2000) recommended range. The span can be increased up to 14000 mm for this particular situation but with a depth of 950 mm and above. For spans of 11000 mm and above, design become conservative having a beta value of 4.87 (P_f=0.472E-06) at 800 mm depth and 9.74 (P_f=0.976E-22) for a depth of 1000 mm. From Fig. 10, it was observed that the safety indices increase with increase in the characteristic compressive strength of concrete for a given effective depth of the panel beam. While the safety index of 3.69 obtained at fcu of 30 N/mm^2 with an associated probability of failure 0.114E-06, was within the safety range for a depth of 902,5 mm, lower values of fcu with a depth lower than 902.5 mm yielded beta values that were within the limits for minor consequences of failure.

From Fig. 11, the safety indices decrease with increase in the applied shear force on the beam for a given effective depth. The effect of the sudden drop of the safety indices was clearer as the applied shear force was increased to 200,000N from 100,000N. The values of the safety indices also revealed that a depth of 800 mm could be sufficient for this design if only the effect of shear force was considered.

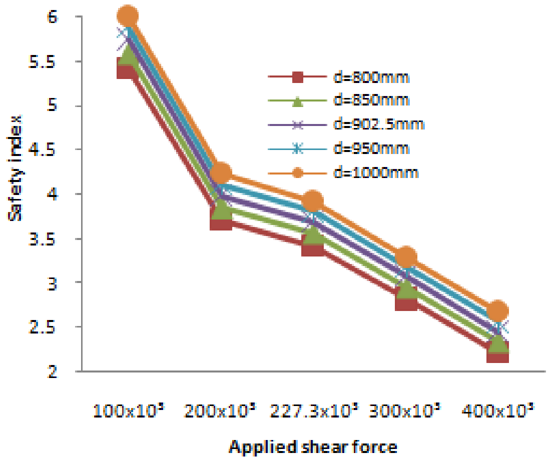

Fig. 11: Safety Indices (β) against applied shear force (N) at varying effective depth of beam for shear mode failure

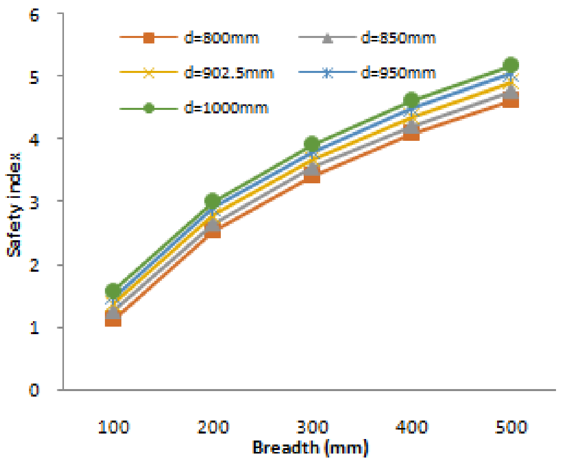

Fig. 12: Safety Indices (β) against Breadth (b) at varying effective depth of beam for shear mode failure

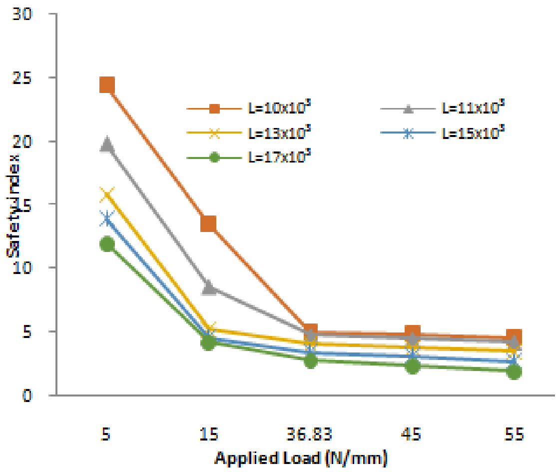

Fig. 13: Safety Indices (β) against Applied Load (w) at varying effective depth of beam for shear mode failure

Figure 12 presents the sensitivity analysis of shear which shows that the safety indices increase with increase in the breadth of the beam at a given depth. To ensure safe design, breadth of 300 mm at a depth of 800 to 1000 mm with safety indices of 3.41 to 3.90 and corresponding probability of failure of 0.322E-03 and 0.473E-04 are preferable considering minor consequences of failure. A beam breadth of 200 mm and below at any depth have safety indices that fall below the lower safety limit hence will result to a critical design. However, conservative design was experienced when the breadth increased above 300 mm at a depth of 800 mm and above. Fig. 13 shows that the safety indices decrease with increase in the applied load at a given span of the beam. The span of 13000 mm used in this design could take as high a load as 55 N/mm with a safety index of 3.47 having a probability of failure of 0.256E-03 which fall within the recommended indices of safety for minor consequences of failure by JCSS (2000).

The results also indicated that the maximum load a span of 15000 mm could be designed to carry with this configuration was 45N/mm with a safety index of 3.1 and a probability of failure of 0.963E-03.

Conclusion

Reliability based design of a reinforced concrete panelled-beams floor system in accordance with BS 8110 (1997) was carried out using FORM5 and the following conclusions were reached;

i. The limit state equation established for bending,deflection and shear modes of failure are $g(x) = 0.156f_{ck}bh^2 - 0.125(1.4\alpha + 1.6)Q_kL^2$,$g(x) = \frac{L}{250} - \frac{5(1.4\alpha+1.6)Q_kL^4}{384EI}$,$g(x) = 0.8\sqrt{f_{cu}} - \frac{(1.4\alpha+1.6)Q_kL}{2b\times d}$.

ii. The reliability analysis showed that safety indices decrease with increase in load ratios for bending, shear and deflection mode failure.

iii. The sensitivity analysis carried out showed that the safety indices increase with increase in the depth, breadth, and the concrete compressive strength of the panel beams and decrease with the increase in applied load and span of the beams.

iv. It was further observed that the compressive strength of concrete and the effective depth were the most sensitive parameters in bending, shear and the deflection failure modes.

v. All the design results are consistent when compared with the safety indices recommended by the Joint Committee of Structural Safety Code (JCSS, 2000) for minor consequences of failure.

Conflict of Interest

The authors declare that there is no conflict of interest related to this work.

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