RELIABILITY ANALYSIS OF GRID FLOOR SLABS

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Abstract - *Reliability Analysis as per IS456-2000 in Limit State of Flexure, Shear & Deflection for Square and Rectangular grid slabs have been evaluated with varying rib width and for different grades of concrete and characteristic strength of the steel. Monte Carlo simulation technique and Advanced First Order Second Moment (AFOSM) also known as Fisseler's Algorithm method was employed in the evaluation procedure for both square and rectangular grid slabs. The variables relating to geometry, material properties and loading are considered as random. The study investigates the reliability index and probability of failure of the grid slabs and plotting of the Histogram and probability distribution curve. Timoshenko plate theory was used for deterministic approach. Grid slab was modelled using ETABS software and the values of moment, shear & deflection at various points of the grid are taken for probabilistic evaluation. The entire reliability analysis was implemented through developing a program in MATLAB software.*

Key Words: Reliability Analysis, Monte Carlo simulation, Fisseler's Algorithm, ETABS, MATLAB.

1. INTRODUCTION

Grid floor slabs consisting of beams which are spaced at regular intervals in perpendicular directions and monolithic with slab. Grid slabs are used for large rooms such as theatre hall, show room shops and large auditoriums. Rectangular, square, diagonal and continuous are the different patterns of the grid slab. Grids are found to be very efficient in load transferring. It is generally adopted when large column free space is required and reduces the span to depth ratio of rectangular grids. Grid slab leads to reduction in dead load due to voids and they are suitable for longer spans with heavy loads. Grid slab offers reduction in cost and gives good resistance to vibration.

In this work an attempt is made to evaluate safety of grid slabs for a square and rectangular floor area with varying rib width under different design situations by establishing reliability index in limit state of flexure, shear and deflection using Monte Carlo simulation technique and Advanced first order second moment (AFSOM).

1.1 Reliability Analysis

Consistent evaluation of design risk using the probability theory is called Reliability analysis. The reliability is the probability of an item performing its intended function over a given period of time under the operating conditions encountered. Probability theory and reliability-based design provide a formal framework for developing criteria for design, which safeguard that the probability of unfavorable performance is acceptably minor. The overall goal of structural reliability analysis is to quantify the reliability of structures under consideration of the uncertainties associated with the resistances and loads. The reliability of the grid slab is controlled by the methods used in selecting maximum resistance and minimum load effects. The resistance of the materials and the loads acting upon it do not have single known values; rather they are random variables whose variability must be somehow considered in the design processes. The parameters of strength of structure and load applied are non-deterministic, they nevertheless exhibit statistical regularity.

The fundamental goal in designing a structure is to provide an economical structure that will, with the desired level of reliability, remain functional throughout its design life. The goal can be expressed as,

Resistance ≥ load effect

Table -1: Statistics of the basic variable

Sl. No.	**Variables**	**Type**	**Bias**	**C.O.V**	**Reference**
1	f_{ck}	Normal	1.02	0.15	O. S. Abejide(2014)
2	f_y	Normal	1.02	0.15	O. S. Abejide(2014)
3	A_{st}, A_{sv} & s_v	Normal	1.01	0.04	O. S. Abejide(2014)
4	Load	Normal	1.25	0.35	Ranganathan
5	Dimensions (b_w, d, b_f, x_u & Z)	Normal	1.03	0.05	Z. Sakka et al.(2014)

The variables included in the study are dimensions, material properties, loads. The current study assumes a normal distribution for all variables.

2. GENERATION OF ACTION STATISTICS

Reliability analysis for grid slab is carried out in limit state of flexure, shear and deflection. It is very much essential that the randomness in the action part is characterized by means of appropriate probability distributions. This needs generation of action part like bending moments, shear forces and torsion forces in large numbers so as to find the statistical parameters leading to probability modeling. To achieve the above purpose, a typical model of grid slab is developed for square and rectangular shape with varying rib spacing and rib width in ETABS software. Due to the applied load the central rib is subjected to maximum moment and larger deflection. The random values of basic variables are generated by using the relevant probability density functions, the details are extracted from the literature.

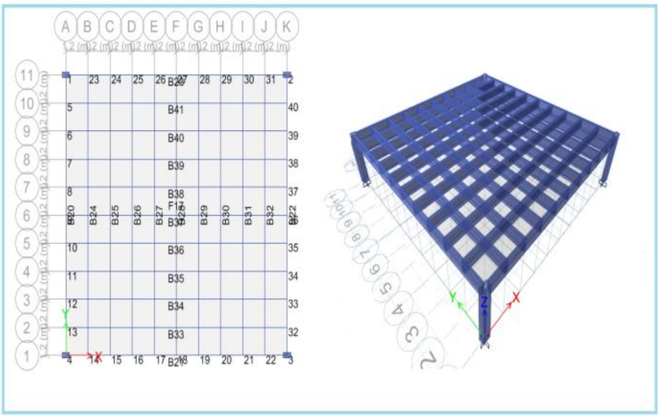

Fig -1: 3D view of grid slab

Live load is applied to the grid slab and the dead load is calculated by the software. Live load is applied as 4 KN/m^2 and floor finish as 0.5 KN/m^2. The grid slab model is made to run for number of times for random values of characteristic strength of concrete and characteristic strength of steel. By this process basic parameters namely dimensions, grade of concrete, characteristic strength of steel, spacing of ribs are given as random input for square gird and rectangular grid and the analysis is repeatedly carried out. This process will help to generate random values of action.

3. GENERATION OF RESISTANCE STATISTICS

Modelling of the resistance variable of a structural element and a structure is a difficult task. The basic variables namely geometric dimensions and physical properties are involved in resistance function. Obtaining field data for the resistance of a reinforced grid slab is extremely expensive or impossible so for such situations simulation is the only tool that may be used to obtain relevant results. The probability distribution and statistics of the strength of the grid slab are to be known. By defining probability distribution of basic variables in terms of mean values and standard deviation values etc., Statistics of the strength of the slab are established using Monte Carlo technique. Due to the fact that loads and resistances are subject to uncertainties, to ensure that the design is associated with an adequate level of reliability the design values for resistances and load effects are introduced in the design equations. When there is a reinforced concrete slab over a reinforced beam, the slab and beam can be designed and constructed in such a way that they act together. The combination of beam and slab units is called flanged beams.

3.1 Moment of Resistance

With respect to the position of the neutral axis the resistance equation for the T - beam can be visualized in three different cases. They are,

a) Neutral Axis within the Flange

$$M.O.R = 0.36 \times f_{ck} \times b_f \times x_u \times (d - 0.42 \times x_u) \quad .....(1)$$

When, $x_u < x_{u,\,max}$ (Under Reinforced s/c)

b) Neutral Axis below the Flange and $D_f/d < 0.2$ (Flange Uniformly Stressed)

$$M.O.R = 0.36 \times f_{ck} \times b_w \times x_u \times (d - 0.416 \times x_u) + 0.446 \times f_{ck} \times (b_f - b_w) \times D_f \times (d - \frac{Df}{2}) \quad .....(2)$$

c) Neutral Axis below the Flange and $D_f/d > 0.2$ (Flange not Uniformly Stressed)

$$M.O.R = 0.36 \times f_{ck} \times b_w \times x_u \times (d - 0.416 \times x_u) + 0.446 \times f_{ck} \times (b_f - b_w) \times y_f \times (d - \frac{Df}{2}) \quad .....(3)$$

If $x_u > x_{u.max}$, it is over reinforced section. Design it as balanced section by replacing x_u by $x_{u,max}$ in above moment of resistance equation.

3.2 Ultimate Shear Resistance

If V_{uc} and V_{us} denote respectively the ultimate shear resistance of the concrete and shear reinforcement, then the total ultimate shear resistance V_{uR} at any section of the beams is given by,

$$V_{uR} = V_{uc} + V_{us} \quad .....(4)$$

$$V_{uc} = \tau_c \times b_w \times d \quad .....(5)$$

$$V_{us} = \frac{0.87 \times f_y \times Asv \times d}{Sv} \quad .....(6)$$

3.3 Control of Deflection

The final deflection due to all loads including the effects of temperature, creep and shrinkage and measured from the as cast level of the supports of floors, roofs and all other horizontal members, should not normally exceed,

$$\text{Permissible Deflection} = \frac{\text{Span}}{250} \quad .....(7)$$

4. DETERMINISTIC DESIGN DETAILS

If the structural properties of the plate differ in two mutually perpendicular directions, the plate is described as orthogonally anisotropic or orthotropic. Such structural anisotropy can be introduced by ribs or beam stiffeners. For an orthotropic plate under a given load distribution and for a known boundary conditions, the deflections, moments, shears are determined by integrating the differential equation for orthotropic plates.

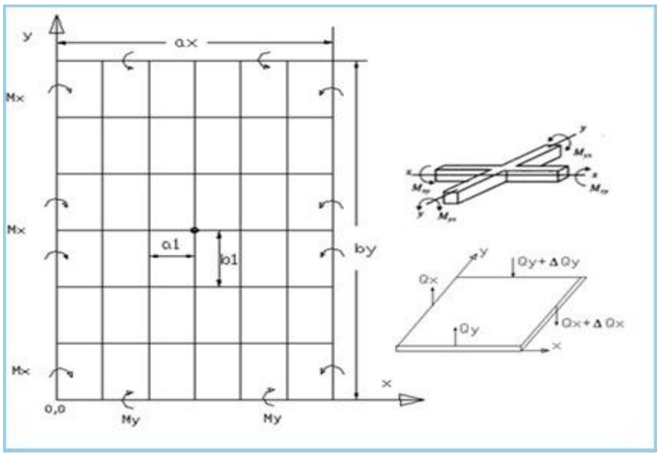

Fig-2: All-round Simply Supported Grid Slab

a_x and b_y = length of plate in x and y directions, respectively.
a_1, b_1 are spacing of ribs in x and y directions.

$$M_x = -D_x\left(\frac{\partial^2\delta}{\partial x^2}\right) = -D_x\frac{16q}{\Pi^6}\left[\frac{\left(\sin\frac{\Pi x}{a_x}\right)\left(\sin\frac{\Pi y}{b_y}\right)}{\left(\frac{D_x}{a_x^4}\right)+\left(\frac{2H}{a_x^2 b_y^2}\right)+\left(\frac{D_y}{b_y^4}\right)}\right] \quad \text{..... (8)}$$

$$M_y = -D_y\left(\frac{\partial^2\delta}{\partial y^2}\right) = -D_y\frac{16q}{\Pi^6}\left[\frac{\left(\sin\frac{\Pi x}{a_x}\right)\left(\sin\frac{\Pi y}{b_y}\right)}{\left(\frac{D_x}{a_x^4}\right)+\left(\frac{2H}{a_x^2 b_y^2}\right)+\left(\frac{D_y}{b_y^4}\right)}\right] \quad \text{..... (9)}$$

$$Q_x = \frac{\partial}{\partial x}D_x\left(\frac{\partial^2\delta}{\partial x^2}\right)+C_y\left(\frac{\partial^2\delta}{\partial y^2}\right) = \frac{16q}{\Pi^6}\left[\frac{\left(\sin\frac{\Pi x}{a_x}\right)\left(\sin\frac{\Pi y}{b_y}\right)}{\left(\frac{D_x}{a_x^4}\right)+\left(\frac{2H}{a_x^2 b_y^2}\right)+\left(\frac{D_y}{b_y^4}\right)}\right]\left[\left(\frac{D_x\Pi^3}{a_x^3}\right)+\left(\frac{C_y}{a_1}\right)\left(\frac{\Pi^3}{a_x b_y^2}\right)\right] \quad \text{..... (10)}$$

$$Q_y = \frac{\partial}{\partial y}D_y\left(\frac{\partial^2\delta}{\partial y^2}\right)+C_x\left(\frac{\partial^2\delta}{\partial x^2}\right) = \frac{16q}{\Pi^6}\left[\frac{\left(\sin\frac{\Pi x}{a_x}\right)\left(\sin\frac{\Pi y}{b_y}\right)}{\left(\frac{D_x}{a_x^4}\right)+\left(\frac{2H}{a_x^2 b_y^2}\right)+\left(\frac{D_y}{b_y^4}\right)}\right]\left[\left(\frac{D_y\Pi^3}{b_y^3}\right)+\left(\frac{C_x}{b_1}\right)\left(\frac{\Pi^3}{a_x^2 b_y}\right)\right] \quad \text{..... (11)}$$

4.1 Square grid (12x12) m, 1.2m spacing

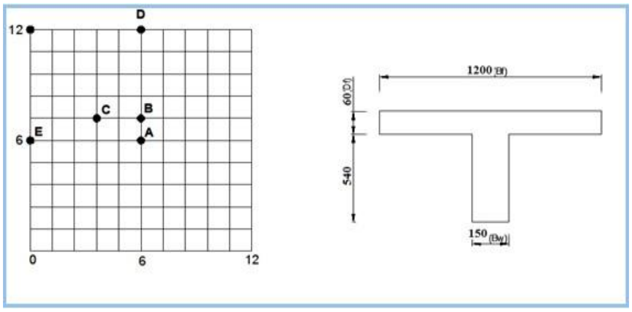

Fig-3: Plan of grid floor and section of ribs in x & y direction

Table-2: Moment and Shear values at various salient points

Points	M_x (KN-m)	M_y (KN-m)	Q_x (KN)	Q_y (KN)
A	102.81	102.81	0	0
B	97.81	97.81	0	8.620
C	79.10	79.10	15.65	6.97
D	0	0	0	27.97
E	0	0	27.97	0

4.2 Rectangular grid (12x16) m, 2.0m spacing

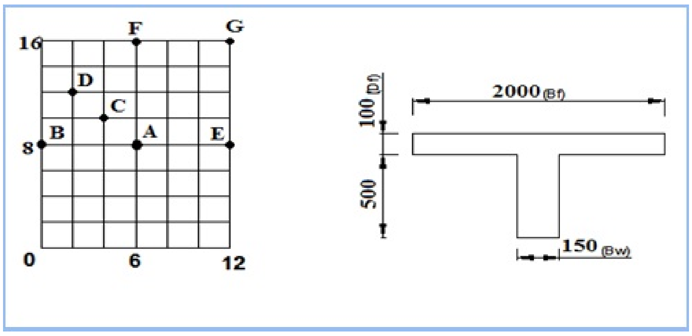

Fig-4: Plan of grid floor and section of ribs in x & y direction

Table-3: Moment and Shear values at various salient points

Points	M_x (KN-m)	M_y (KN-m)	Q_x (KN)	Q_y (KN)
A	149.51	84.10	0	0
B	0	0	40.01	0
C	119.63	67.29	18.50	0
D	52.89	29.75	24.52	0
E	0	0	40.01	0
F	0	0	0	17.67
G	0	0	0	0

5. COMPUTATION OF PROBABILITY OF FAILURE

Histogram provides an immediate impression of the range of the data, its most frequently occurring values and the degree to which it is scattered. It is the presentation of data in useful form. The collected data will be in an unorganized form, it is arranged properly. The values are plotted in an increasing order. These ordered values are then divided into intervals and the number of observations in each interval is plotted as a bar. The suitability of a probabilistic model to fit the data is arrived after applying any one of the following goodness-of-fit test in MATLAB.

a) Chi-square Test.
b) Kolmogorov-Smirnov (K S) Test.

500 data sets were randomly generated for each section, and each data set varied randomly as a function of statistical models for the variables involved mean, standard deviation, coefficient of variation and distribution type.

5.1 Methodology of finding the probability of failure of grid slab

a) For random variations in different grades of concrete, characteristic strength of steel, dimensions and live load, corresponding Moment, Shear & Deflection values are obtained from ETABS software and is denoted as action (S).

b) Using MATLAB software simulate moment of resistance, shear resistance and deflection using above said equation (1 to 7) and denote it as resistance (R).

c) Compute safety margin i.e., M = R – S

d) Compute Reliability Index (β)= $\frac{\mu}{\sigma}$ of safety margin

e) Compute probability of failure by equation P.F = $\varphi(\beta)$

Table-4: Reliability Index and Probability of failure for square grid in flexure by Monte Carlo simulation

Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Spacing mm	Rib width mm	Reliability index	Probability of failure
1	20	415	1200	150	3.7380	0.0927 x10^{-3}
2	25	415	1200	170	3.4780	0.2526 x10^{-3}
3	30	415	1200	190	3.2330	0.6125 x10^{-3}
4	20	500	1200	210	4.4667	0.0039 x10^{-3}
5	25	500	1200	230	3.6432	0.1346 x10^{-3}
6	30	500	1200	250	3.8758	0.0531 x10^{-3}

Table-5: Reliability Index and Probability of failure for square grid in shear by Monte Carlo simulation

Sl. No	f_{ck} N/mm^2	f_y N/mm^2	Spacing mm	Rib width mm	Reliability index	Probability of failure
1	20	415	1200	150	4.8957	0.4904 x10^{-6}
2	25	415	1200	170	5.1278	0.1468 x10^{-6}
3	30	415	1200	190	4.9842	0.3115 x10^{-6}
4	20	500	1200	210	5.0084	0.2748 x10^{-6}
5	25	500	1200	230	5.1714	0.1163 x10^{-6}
6	30	500	1200	250	5.1518	0.1292 x10^{-6}

Table-6: Reliability Index and Probability of failure for square grid in deflection by Monte Carlo simulation

Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Spacing mm	Rib width mm	Reliability index	Probability of failure
1	20	415	1200	150	8.5125	8.617 x10^{-18}
2	25	415	1200	170	8.4104	20.67 x10^{-18}
3	30	415	1200	190	8.0030	613.3 x10^{-18}
4	20	500	1200	210	7.7113	6283 x10^{-18}
5	25	500	1200	230	8.3216	43.89 x10^{-18}
6	30	500	1200	250	8.2321	93.01 x10^{-18}

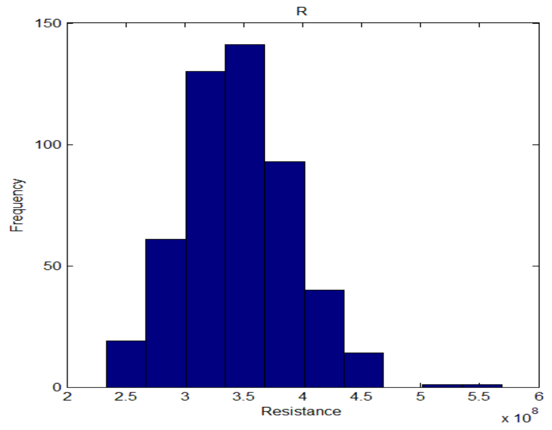

Fig-5: Histogram for Square grid against Resistance in Flexure (M20, Fe 415)

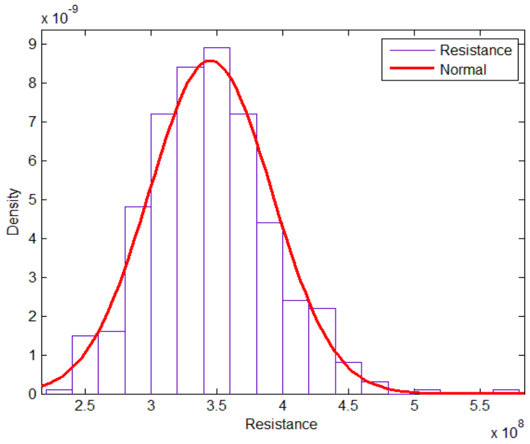

Fig-6: Probability distribution curve for Square grid against Resistance in Flexure (M20, Fe 415)

Reliability Index and Probability of failure for rectangular grid is evaluated for constant rib spacing of 2m.

Table-7: Reliability Index and Probability of failure for rectangular grid in flexure by Monte Carlo simulation

				M_x		M_y	
Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Rib width mm	Reliability index	Probability of failure	Reliability index	Probability of failure
1	20	415	150	3.763	0.083 x10^{-3}	4.051	0.025 x10^{-3}
2	25	415	170	3.686	0.113 x10^{-3}	4.132	0.017 x10^{-3}
3	30	415	190	3.947	0.039 x10^{-3}	4.077	0.022 x10^{-3}
4	20	500	210	4.040	0.026 x10^{-3}	4.260	0.010 x10^{-3}
5	25	500	230	4.514	0.003 x10^{-3}	4.573	0.002 x10^{-3}
6	30	500	250	4.379	0.005 x10^{-3}	4.509	0.003 x10^{-3}

Table-8: Reliability Index and Probability of failure for rectangular grid in shear by Monte Carlo simulation

				Q_x		Q_y	
Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Rib width mm	Reliability index	Probability of failure	Reliability index	Probability of failure
1	20	415	150	4.0812	0.022 x10^{-3}	5.1725	0.115 x10^{-6}
2	25	415	170	5.4974	0.019 x10^{-6}	5.1477	0.132 x10^{-6}
3	30	415	190	5.2436	0.078 x10^{-6}	5.4347	0.027 x10^{-6}
4	20	500	210	5.8935	0.001 x10^{-6}	5.5829	0.011 x10^{-6}
5	25	500	230	5.0529	0.217 x10^{-6}	5.5769	0.012 x10^{-6}
6	30	500	250	5.3151	0.053 x10^{-6}	5.4842	0.020 x10^{-6}

Table-9: Reliability Index and Probability of failure for rectangular grid in deflection by Monte Carlo simulation

Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Rib width mm	Reliability index	Probability of failure
1	20	415	150	8.1665	0.160 x10^{-15}
2	25	415	170	7.4303	0.054 x10^{-12}
3	30	415	190	7.6368	0.011 x10^{-12}
4	20	500	210	6.8807	0.002 x10^{-9}
5	25	500	230	7.0056	1.237 x10^{-12}
6	30	500	250	7.5846	0.016 x10^{-12}

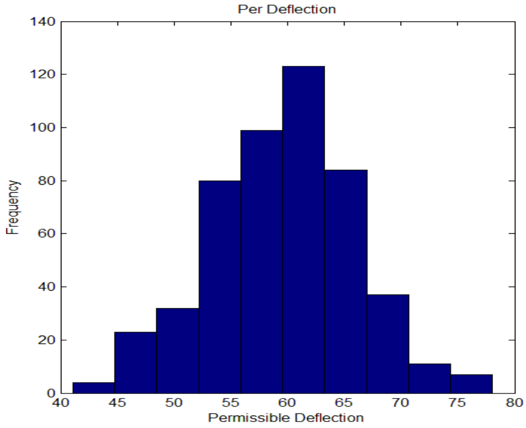

Fig-7: Histogram for rectangular grid against Resistance in Deflection (M25, Fe 415)

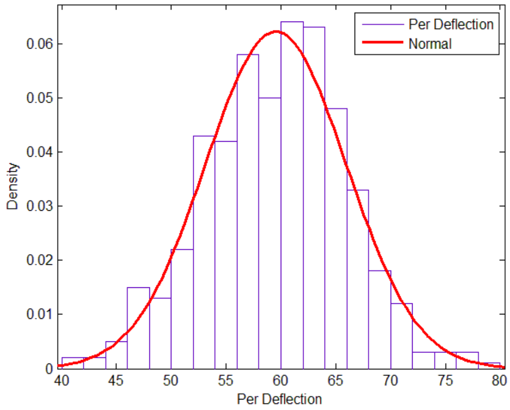

Fig-8: Probability distribution curve for rectangular grid against Resistance in Deflection (M25, Fe 415)

5.2 Advanced First Order Second Moment Method

Table-10: Reliability Index and Probability of failure for square grid in flexure

Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Spacing mm	Rib width mm	Reliability index	Probability of failure
1	20	415	1200	150	4.8610	0.5847 x10^{-6}
2	25	415	1200	170	4.7302	1.1228 x10^{-6}
3	30	415	1200	190	4.8607	0.5856 x10^{-6}
4	20	500	1200	210	5.1621	0.2942 x10^{-6}
5	25	500	1200	230	4.8614	0.1223 x10^{-6}
6	30	500	1200	250	4.8613	0.5838 x10^{-6}

Table-11: Reliability Index and Probability of failure for square grid in shear

Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Spacing mm	Rib width mm	Reliability index	Probability of failure
1	20	415	1200	150	5.11440	0.1576 x10^{-6}
2	25	415	1200	170	5.28180	0.0640 x10^{-6}
3	30	415	1200	190	5.39414	0.0599 x10^{-6}
4	20	500	1200	210	5.60570	0.0103 x10^{-6}
5	25	500	1200	230	5.93260	0.0014 x10^{-6}
6	30	500	1200	250	5.83015	0.0027 x10^{-6}

Table-11: Reliability Index and Probability of failure for square grid in deflection

Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Spacing mm	Rib width mm	Reliability index	Probability of failure
1	20	415	1200	150	6.664849	0.013 x10^{-9}
2	25	415	1200	170	6.248615	0.207 x10^{-9}
3	30	415	1200	190	6.450407	0.056 x10^{-9}
4	20	500	1200	210	6.408887	0.073 x10^{-9}
5	25	500	1200	230	6.368286	0.096 x10^{-9}
6	30	500	1200	250	6.328138	0.124 x10^{-9}

Reliability Index and Probability of failure for rectangular grid is evaluated for constant rib spacing of 2m.

Table-12: Reliability Index and Probability of failure for rectangular grid in flexure

				M_x		M_y	
Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Rib width mm	Reliability index	Probability of failure	Reliability index	Probability of failure
1	20	415	150	4.86349	0.577 x10^{-6}	4.86381	2.514 x10^{-6}
2	25	415	170	4.30120	8.499 x10^{-6}	4.82726	0.693 x10^{-6}
3	30	415	190	4.75825	0.977 x10^{-6}	4.86177	0.582 x10^{-6}
4	20	500	210	4.86198	0.581 x10^{-6}	4.85920	0.590 x10^{-6}
5	25	500	230	4.86192	0.582 x10^{-6}	4.86240	0.580 x10^{-6}
6	30	500	250	4.86163	0.582 x10^{-6}	4.85212	0.611 x10^{-6}

Table-13: Reliability Index and Probability of failure for rectangular grid in shear

				Q_x		Q_y	
Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Rib width mm	Reliability index	Probability of failure	Reliability index	Probability of failure
1	20	415	150	4.834979	0.666 x10^{-6}	5.174228	0.114 x10^{-6}
2	25	415	170	5.674825	0.006 x10^{-6}	5.155839	0.126 x10^{-6}
3	30	415	190	5.399973	0.033 x10^{-6}	5.176218	0.113 x10^{-6}
4	20	500	210	5.562835	0.013 x10^{-6}	5.085160	0.183 x10^{-6}
5	25	500	230	5.841613	0.015 x10^{-6}	5.115455	0.156 x10^{-6}
6	30	500	250	5.629280	0.009 x10^{-6}	5.145150	0.133 x10^{-6}

Table-14: Reliability Index and Probability of failure for rectangular grid in deflection

Sl. No.	f_{ck} N/mm^2	f_y N/mm^2	Rib width mm	Reliability index	Probability of failure
1	20	415	150	7.138149	0.476 x10^{-12}
2	25	415	170	6.663145	0.013 x10^{-9}
3	30	415	190	7.139733	0.470 x10^{-12}
4	20	500	210	6.893158	0.002 x10^{-9}
5	25	500	230	6.846525	0.003 x10^{-9}
6	30	500	250	6.754421	0.007 x10^{-9}

6. CONCLUSION

a) Explicit evaluation of safety in terms of probability of failure of a Grid slab when the design variables are random in nature and do follow given probability distributions is done using digital simulation, by Monte Carlo technique and AFOSM.

b) It is observed that the reliability index varies from 3.233 to 5.162 for square grid slab in flexure, in shear the reliability index varies from 4.895 to 5.830 and in deflection the reliability index varies from 6.248 to 7.711.

c) The reliability index varies from 3.686 to 4.861 for rectangular grid slab in flexure, in shear the reliability index varies from 4.834 to 5.841 and in deflection the reliability index varies from 6.663 to 8.166.

d) Thus there is almost a consistent level of reliability in the design methodology adopted by IS 456-2000. However the present limit state method of design does not consider the importance of a structure, exposure conditions, effect of quality control etc.

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