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An intelligent system for the design of RC slabs

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Abstract. The accurate finite element (FE) simulation of reinforced concrete (RC) slabs, having different boundary conditions and subjected to uniformly distributed loading, has led to the use of the developed FE models for generating results of ultimate loads from predictions of 'computer-model' RC slabs having different material and geometric properties. Equations derived from these results constitute the primary database of an intelligent computer-aided-design (CAD) system developed for accurate and fast information retrieval on arbitrary slabs. The system is capable of generating a secondary database through systems of interpolation and can be used for design assistance purposes.

Key words: knowledge-based system; finite element method; RC slabs; material modeling; codes-of-practice; numerical predictions.

1. Introduction

Most analytical and computer-assisted design tools used for reinforced concrete slabs are based on either the yield line theory for plates (Johansen 1962, Sobotka 1997) where rigidly plastic behavior is assumed, or on design codes of practice (BS8110 1985) which, for limit state design approach adopt partial factors of safety for the materials and loading without giving an indication of the global safety factor. In both cases the predicted ultimate loads are found to be significantly lower than actual experimental value and although they achieve a safe design little or no information on the economy of the design is given. The finite element method of analysis on the other hand incorporates suitable nonlinear material models which are capable of predicting with reasonable accuracy not only the ultimate load but also the loading path to failure. Design-assistance tools based on such FE predictions, when used alongside traditional design methods, give a fairly accurate indication of the global safety factor. Material models for reinforced concrete depend on parameters some of which are identified through simple laboratory experiments while values for the rest are established through sensitivity studies.

Recent research (Famiyesin and Hossain 1998, Hossain and Famiyesin 1997, 1998) has focused on the FE analysis of different classes of reinforced concrete slabs, classified on the basis of their

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boundary conditions. These range from all edges fully clamped (Famiyesin and Hossain 1998, Hossain and Famiyesin 1997) to all edges simply supported (Hossain and Famiyesin 1997). In between these two extreme situations other cases of partial restraints were considered (Famiyesin and Hossain 1998, Hossain and Famiyesin 1998). In each class of slabs, some previous test results were used as a basis for identifying parameter values and computational conditions which would guarantee reliable prediction of the ultimate load of arbitrary slabs within the class. This prediction capability has been verified by the use of the identified parameters for the direct simulation of other slabs tested by previous researchers.

Subsequent to this, the numerical prediction of hundreds of numerical model slabs, resulting from various combinations of geometric and material properties has been carried out for each class of slabs, giving rise to a large amount of data from which design charts and equations have been developed (Famiyesin and Hossain 1998, Hossain and Famiyesin 1997, 1998). These tools could be used for a quick and accurate determination of peak load and corresponding displacement for arbitrary slabs. The performance of the charts and equations have been compared with that of traditional methods of analysis and design, e.g., the yield line theory (Famiyesin and Hossain 1998). Traditional methods are noted to significantly under predict the strength of slabs as they do not account for membrane action which is present in slabs with edge restraints, and which the finite element method is capable of simulating with relative ease and accuracy, as it incorporates features of geometric and material nonlinearities.

This paper demonstrates the creation of a database from the equations developed and data generated by finite element predictions, and the retrieval of design information from this database via a knowledge based system. The developed system is capable of producing design options for arbitrary slabs when only part of their details are supplied. Relevant information on the slab details include aspect ratio, breath/depth ratio, steel yield strength, concrete compressive strength, amount of reinforcement in the slab, design (peak) load and corresponding displacement. The expert system will use the supplied data as criteria to produce design options, giving information on the unknown details associated with each option. The engineer could then refine his search and choose a preferred design. When a supplied parameter value is not identical to those in the database a secondary database is generated through series of interpolation. The intelligent system has successfully been used to predict the ultimate load of some previous test slabs.

2. Numerical study

The program of study leading to the development of the knowledge based system for reinforced concrete slabs was carried out in four phases. These are: (a) Preliminary finite element simulation where previous experiments are used as basis for calibrating the finite element model and identifying relevant parameter values and computational conditions through sensitivity studies; (b) Direct finite element simulation, where the calibrated finite element model is used for predicting the behavior of other previously tested slabs. The purpose is to ascertain the reliability of the calibrated model; (c) Development of design charts and equations from data generated by the FE simulation of hundreds of ‘numerical model’ slabs, varying the geometric and material strength parameters, and; (d) Incorporating the generated data into an intelligent system which utilizes the user-supplied information as constraints to construct possible design options from which the engineer could choose his preferred design.

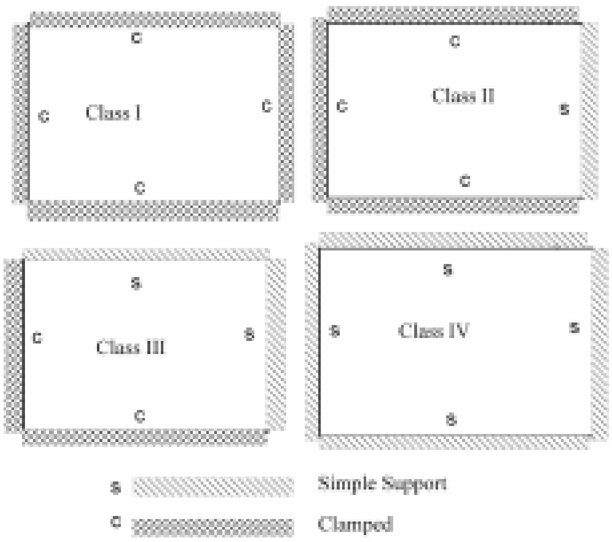


Fig. 1 Different class of slabs

The result of previous tests on concrete slabs having different support conditions (Powell 1956, Park 1964, Taylor *et al*. 1966, Owen and Figueiras 1984) have been used in a series of finite element studies (Famiyesin and Hossain 1998, Hossain and Famiyesin 1997, 1998). The test slabs are classified into the four groups on the basis of their boundary conditions and are shown in Fig. 1; Class I slabs are fully clamped on all four sides, Class II slabs have three sides fully clamped and the fourth side simply supported, Class III slabs have two adjacent sides fixed and the other two simply supported and Class IV slabs are simply supported on all four sides. The class II slabs have two sub-types: one having three sides fixed and one long side simply supported, and the other with three side fixed and one short side simply supported. Altogether therefore five broad classification of slabs were considered.

The finite element formulation used for the spatial discretisation of the slabs considered in steps (a)-(c) of the numerical study is a 3D degenerated, layered shell element having five degrees of freedom at each node, (3 translational and 2 rotational degrees of freedom), as outlined by Owen and Figueiras (1984). The reinforcing steel is represented as a smeared layer of equivalent thickness, with non-linear uniaxial strength and rigidity properties. Geometric nonlinearity is taken into account using the Total Lagrangian approach. The compressive behavior of concrete is modelled by the perfectly plastic and strain hardening plasticity approach. The criteria for yielding (in terms of stresses), and crushing (in terms of strains), are considered respectively. The yield function is assumed to be a modified Drucker-Prager surface with a curved meridian having its parameters values determined from Kupfer's (1969) test results. The model, which is fully described in Owen and Figueiras (1984), also incorporates smeared crack representation.

2.1 Basic finite element simulation

Of the parameters involved in a typical finite element model, some are identified from simple laboratory experiments while the rest are determined on the basis of their ability to predict expected behavior. A comprehensive study has been done (Famiyesin and Hossain 1998, Hossain and Famiyesin 1997, 1998) to establish the sensitivity of various parameters and computational conditions involved in the finite element model for each class of slabs. The computational conditions considered are the convergence criteria, integration rules and non-linear solution techniques; while the model parameters considered include the ultimate compressive strain of concrete (ε_{cu}), tension stiffening parameters, α (which accounts for the sudden stress drop following the initiation of cracks) and ε_m (the strain at which the crack is assumed to be fully opened), modulus of elasticity of concrete (E_c), and the elastic (E_s) and elasto-plastic (E_s') moduli of steel.

As noted in Famiyesin and Hossain (1998), the ultimate compressive (crushing) strain ε_{cu} should not be confused with the strain value at peak load which in most tests is located around a value of 0.002, a value that could be adopted as a material property. The ultimate compressive strain ε_{cu} on the other hand has been given different values ranging from 0.002 to 0.00384 in various international codes of practice (Johansen 1962, ACI 1989, Eurocode 1992, NS 3473 1989), and should therefore not be treated as a concrete material property. Of all the parameters listed above, the slab simulation shows the highest sensitivity to the ultimate concrete crushing strain (ε_{cu}), which, within the range acceptable in practice, can be used to control the numerical process and achieve accurate simulation while the other parameters are held unchanged. Study (Famiyesin and Hossain 1998) has shown that the value of ε_{cu} required for reliable simulation is dependent on the slab support conditions, which also delineates the class of problem.

In order to identify optimal values of ε_{cu} for each class of slabs, the simulation of representative test slabs from each class was carried out using the following fixed conditions and parameter values; The selective integration scheme, the initial stiffness solution method, and convergence criterion based on displacement norm. Actual test values were chosen for material properties such as the Young's moduli for steel and concrete, (E_s and E_c), and the compressive and yield strengths respectively for concrete and steel, (f_c' and f_y). Values chosen for other parameters are; for tension stiffening, factor for stress drop at tensile strength $\alpha = 0.5$, and strain at which crack is assumed to be fully opened $\varepsilon_m = 0.002$, and the elasto-plastic modulus for steel ($E_s' = E_s/15$). The Poisson ratios for concrete and steel are chosen as 0.18 and 0.25 respectively.

A total of 25 representative slabs belonging to the four classes of slabs, tested under uniformly distributed loading conditions by various researchers (Powell 1956, Park 1964, Taylor *et al.* 1966, Hung and Nawy 1971), were selected for the basic finite element simulation process (Famiyesin and Hossain 1998). The simulations were carried out based on both the displacement control (DC) and load control (LC) strategies. In the DC strategy, prescribed displacements reflecting the deflected shape of the slabs under uniformly distributed loading conditions, were applied incrementally to

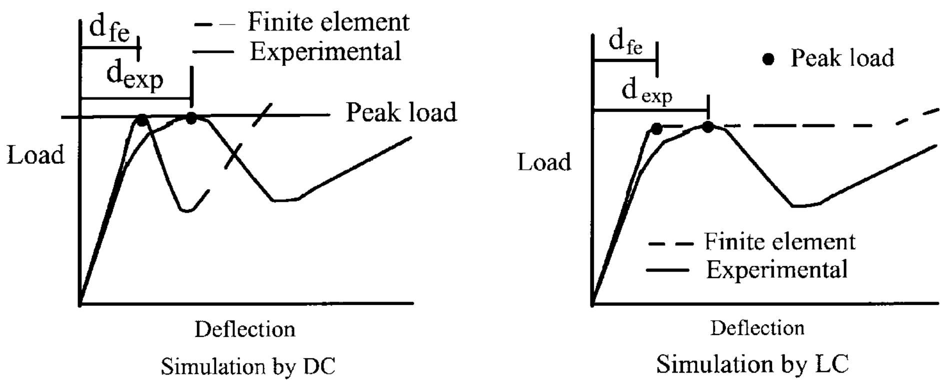
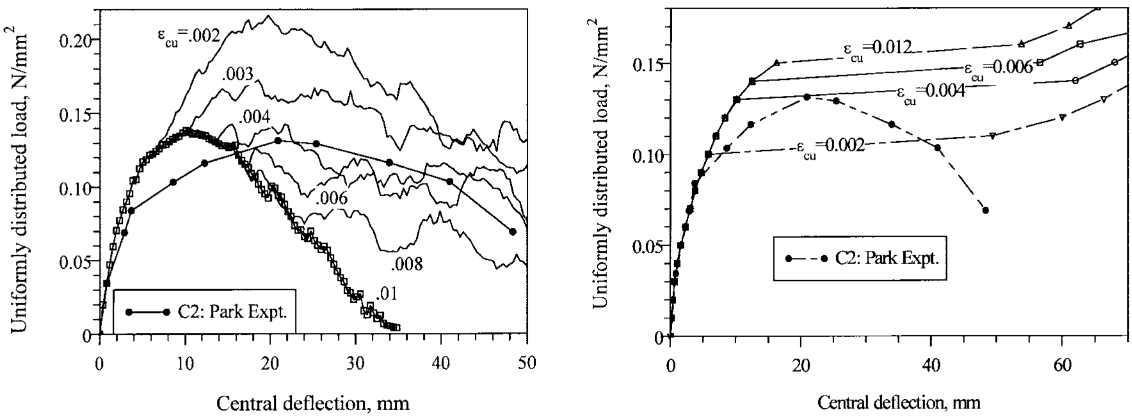


Fig. 2 Simulation of load-deflection response



(a) DC simulation of Park's slab C2 (b) LC simulation of Park's slab C2

Fig. 3 Load-deflection simulation of typical Class II slabs (Park 1964)

Table 1 Details of series *C* slabs tested by Park (1964) (Dimensions $L_y \times L_x \times h$: 1524×1016×50.8 mm)[(a)]

Slab No.	% of Steel				f_y N/mm²	f_c'
	Short span		Long span			
	Top	Bottom	Top	Bottom		
Three edges fixed and one long edge simply supported; L_y/L_x =1.50; L_x/h =20						
C1	0.38	0.19	0.41	0.20	327.6	34.5
C2	0.84	0.42	0.43	0.21	327.6	30.2
C3	1.44	0.72	0.45	0.22	327.6	28.0
C4	2.42	1.21	0.47	0.23	327.6	35.1

Note [(a)] L_y: length of slab; L_x: width of slab; h: overall depth of slab; f_y: steel yield strength; f_c': concrete cylinder strength

Table 2 Basic FE simulation of Park's Series C slabs (1964)

Slab No.	Experiments N/mm²	FE **Displ. Control (DC)**		FE **Load Control (LC)**	
		Peak load	Exp./DC	Peak load	Exp./LC
C1	0.115	0.120	0.94	0.110	1.05
C2	0.130	0.140	0.93	0.130	1.00
C3	0.125	0.165	0.78	0.150	0.83
C4	0.183	0.210	0.87	0.200	0.92
	Average		**0.88**		**0.95**
		ε_{cu} = **0.010**		ε_{cu} = **0.004**	

simulate the complete load-deflection responses. In the LC strategy, uniformly distributed loads were directly applied on the slabs incrementally, and the peak load is identified as that which is associated with a very large deflection (which is out of step with deflections at previous load increments). Typical load-deflection responses from DC and LC strategies superimposed on the experiment, is shown schematically in Fig. 2. The effect of ε_{cu} on the finite element load-deflection response of a typical class II (partially restrained) slab tested by Park (1964) is illustrated in Fig. 3 (Famiyesin and

Hossain 1998). For this and other representative slabs within the class (whose details are summarized in Table 1), the optimal values of ε_{cu} are identified by comparing the numerical response to that from experiment and the results for both DC and LC simulations are summarized in Table 2.

Following the basic FE simulation and parametric studies involving the 25 test slabs (Famiyesin and Hossain 1998, Hossain and Famiyesin 1997, 1998), the following conclusions and prediction strategies were arrived at:

- the optimized value of ε_{cu} for reliable prediction depends on the boundary condition of the slabs and was found to vary from 0.0025 (for Class I slab) to 0.005 (for Class IV slab) in the load control (LC) simulations.
- the ratio of experimental to finite element predicted load ranged from 0.95 to 1.05 for all classes of slabs showing a good level of agreement and confirming that reliable predictions can be carried out for slabs within each class, using the relevant value of ε_{cu}.
- The LC procedure is much simpler than the DC simulations and operates with values of ε_{cu} which are acceptable in practice. It was therefore decided to adopt the LC simulation strategy for the subsequent prediction purposes.

2.2 Direct finite element simulation

The reliability of the parameter values and computational conditions identified from the basic finite element simulation was assessed by the direct simulation of more experimental slabs within each class (Famiyesin and Hossain 1998, Hossain and Famiyesin 1997, 1998). A total of 67 slabs consisting of 42 slabs from Class I, 9 slabs from class II, 5 slabs from class III and 11 slabs from class IV were included in this study. The ratios of experimental to predicted loads were noted to fall within the range of 0.92 to 1.07 with a mean value of 0.9698 for class I slabs, 0.92 for class II slabs, 1.07 for class III slabs and 0.92 for class IV slabs. The accuracy of the direct finite element prediction was found to be of the same order as that of the basic simulation, thus confirming the suitability of the adopted parameter values and numerical conditions, for carrying out predictions for different classes of slabs to generate design charts and equations for the ultimate load and corresponding deflection.

2.3 Development of design tools

Establishing a finite element system that generates reliable solutions for different classes of slab problems has many advantages. A possible practical application of such a system is the development of peak-load prediction charts, from the finite element analysis of numerous ‘computer model slabs’, varying geometric and strength properties. Such charts would facilitate a quick and accurate strength determination of arbitrary slabs for design purposes.

Table 2 shows a summary of the geometric and material parameters utilized in the prediction process, involving different aspect ratios, breadth to depth ratios, concrete compressive strengths, reinforcement ratios (in %) and steel yield strengths to generate the database from which the charts and equations were developed (Famiyesin and Hossain 1998, Hossain and Famiyesin 1997, 1998). This involved a total of 1944 ‘computer model’ slabs consisting of 864 predictions for class I, 540 for class II, 270 for class III and 270 for class IV. From the results of the finite element predictions, design charts and equations (with a polynomial of 3rd degree) have been developed. A typical chart for class II slab is shown in Fig. 4 while another one for class I slabs showing design equations, is shown in Fig. 5.

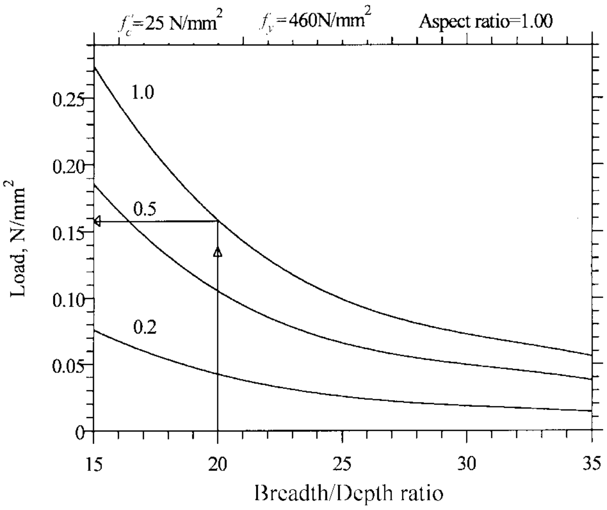


Fig. 4 Typical design chart

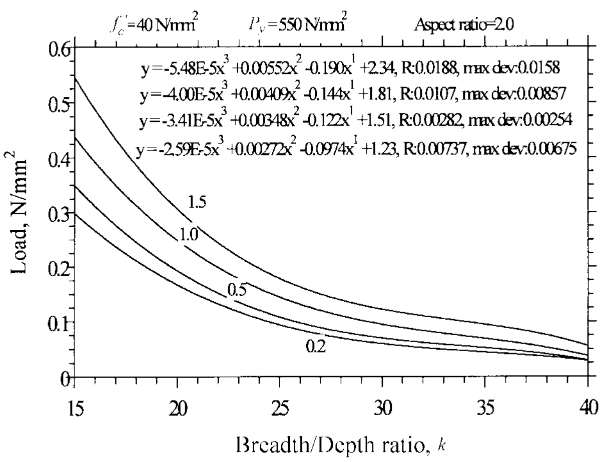


Fig. 5 Typical design chart showing design equations

A total of 108 design charts with 360 design equations have been generated, each chart being established for a particular concrete cylinder strength (f_c'), steel yield strength (f_y) and aspect ratio of the slab, with percentage reinforcement varying from 0.2 to 1.5%. The ultimate loads are expressed as a function of breadth-to-depth ratios *k*, (varying from 15 to 40) in the design equations. The estimation of load for the slab having breadth-to-depth ratios of 20 and percentage reinforcement of 1.0%, is shown by lines with arrows in Fig. 4. For a slab with percentage reinforcement of 0.75%, a linear interpolation between 0.5 and 1.0% should be adopted. The best fit equations can also be used for design purposes.

2.4 Comparative study of design charts

The accuracy of the charts for prediction purposes is tested by using them to predict the peak

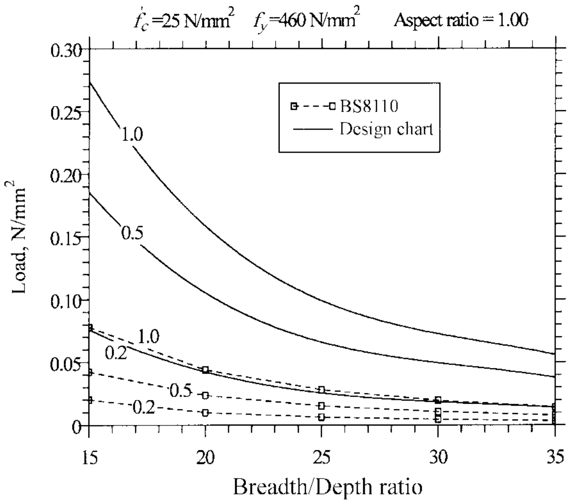


Fig. 6 Comparative study of different predictions

loads of representative experimental slabs and comparing the results with actual experimental values. It has been found that (Famiyesin and Hossain 1998, Hossain and Famiyesin 1997, 1998) the design charts are almost as accurate as direct finite element prediction. Peak load predictions from the yield line method of analysis (Lee and Bernal 1996) and design calculations based on BS8110 (1985) are compared with experimental results of 92 test slabs. The yield line method is noted to under-predict the strength of the slabs as it neglects the in-plane forces which results in membrane action. The degree of under-prediction is highest in the case of fully clamped (Class I) slabs and lowest for simply supported (Class IV) slabs, as the membrane action decreases with increasing flexibility at the support.

Analysis of 42 class I slabs (Famiyesin and Hossain 1998) revealed that the yield line method under-predicts the capacity by as much as 8 times, for slabs fully fixed with rigid lateral restraint. Even in the case of class IV (simply supported) slabs where the effect of membrane action is minimum, the yield line method under predicts the ultimate load by up to 1.8 times with a mean value of 1.28 as revealed from 15 experimental slabs (Hossain and Famiyesin 1997). A comparative study with the BS8110 calculations also revealed that the ultimate load capacity was under predicted by as much as 6.5 times, with a mean value of 4.33. Fig. 6 shows the comparison of the developed chart and BS8110 predictions, for typical simply supported slabs (Class IV).

The design charts and equations predict the actual ultimate load capacity of the slabs as confirmed from the experimental results. Using the charts and equations, the designer is able to estimate the actual load capacity of the slabs and with the choice of appropriate safety factor, optimize the use of the material thus producing economic design. The charts can also be used as a design assistance tool which can be used alongside conventional code-of-practice based design, to indicate the global factor of safety achieved in the code-based design.

3. Knowledge based system

The expert system under current development is focused on reinforced concrete slabs with different boundary conditions. The main logic of the system is to combine the experimental results of 92 test slabs carried out by from different researchers (Powell 1956, Park 1964, Taylor *et al.* 1966) with the FE generated design equations from the prediction of almost 2000 computer model slabs, to form a primary database. The expert system is designed in such a way as to utilize the input data by the user to process the primary database and to produce, if necessary (when there is no perfect matching of parameters), a secondary database through systems of interpolation, from which design options are recommended. The steps adopted to create the primary database is summarized in Fig. 7.

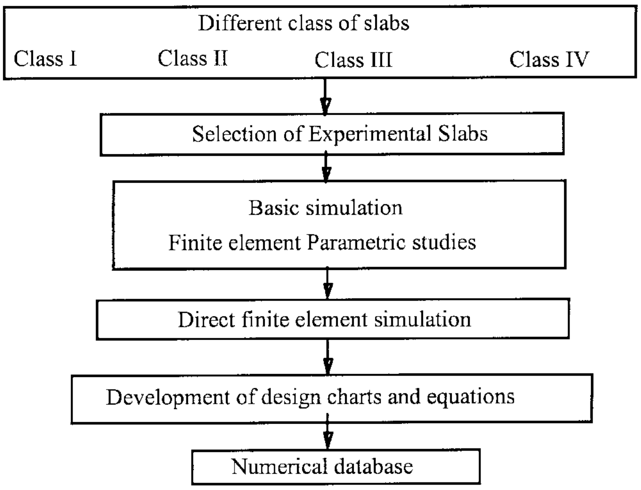


Fig. 7 Creation of primary database

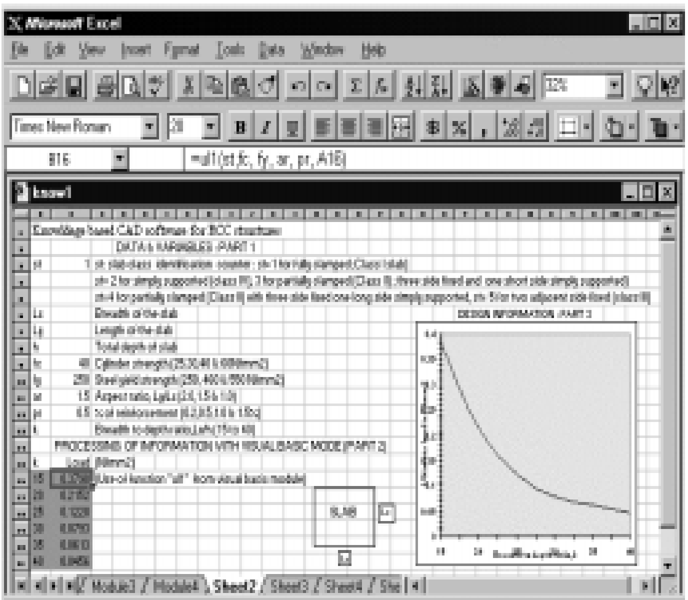


Fig. 8 Snap shot of the expert system

3.1 Software development

The current version of the knowledge based system is developed within Microsoft Excel with Visual Basic interface. The system processes the data provided by the user within the database and retrieves design options as recommendations, to the user. The system utilizes the graphic and computational capabilities of the software to demonstrate visually, the effect of various parameters in the design process. The program consists of three main parts. A concise version identifying these three parts of the system is presented in Fig. 8 and a typical flow chart, which operates when all the input data are supplied, is shown in Fig. 9.

Part 1 includes data and variables to be supplied by the user. Such variables include the slab class identification counter *st*, concrete compressive strength *fc*, steel yield strength *fy*, aspect ratio of slab *ar*, percentage of reinforcement in slab *pr* and the breadth to depth ratio of slabs *k*. The user can choose values of *st* varying from 1 to 5 depending on the class of slabs, the geometric properties can vary (by choosing the values of *ar* from 1.0 to 2.0 and *k* from 15 to 40). The material properties can also vary, (*fc* varies from 15 to 60 N/mm^2 and *fy* varies from 250 to 550 N/mm^2). The percentage of reinforcement in the slab *pr* can also be varied from 0.2 to 1.5%. The user therefore has a wide range of options to choose from as input, which will be processed to generate design information.

The Part 2 section titled 'Processing of information' is the main body of the system. It contains the primary database of the system, accumulated from all the equations generated from finite

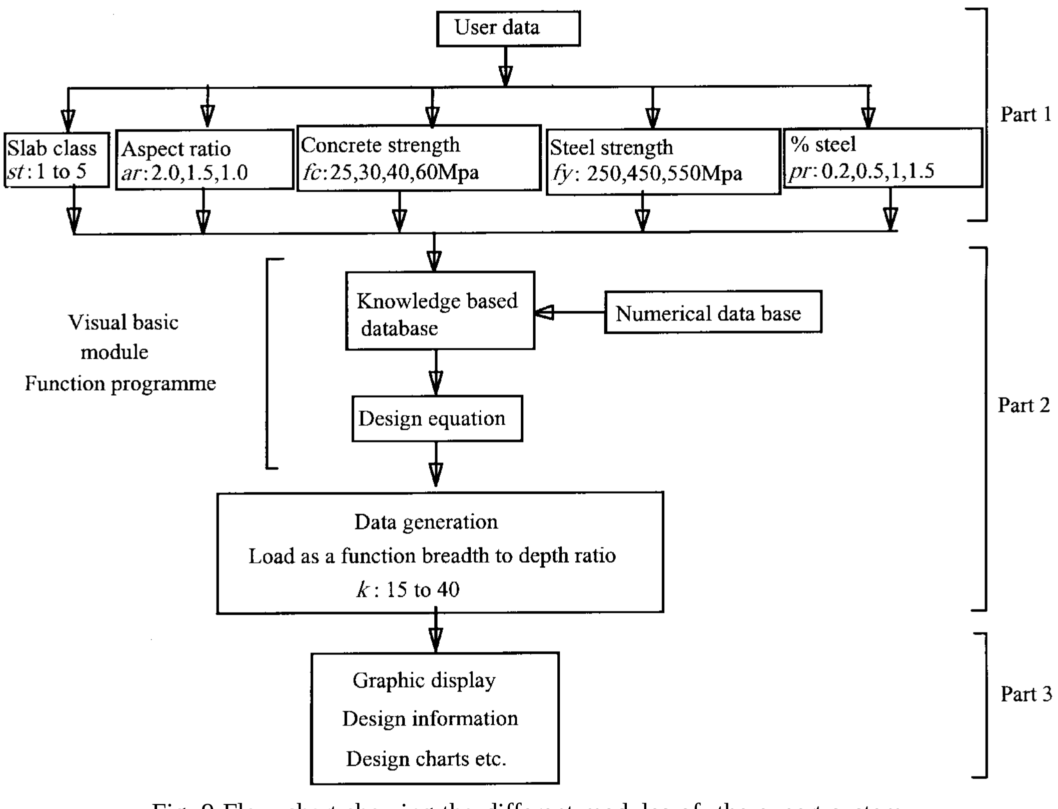


Fig. 9 Flow chart showing the different modules of the expert system

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'Functions creating knowledge based database for slab design'
st = slab type according to boundary conditions',
fc = Concrete cylinder strength in N/mm2'
fy =Yield strength of steel in N/mm2',k=breadth to depth ratio',
pr = % of reinforcement'
Function ul1(st, fc, fy, ar, pr, k)
If (st = ?) And (ar = ?) And (fc = ?) And (fy = ?) And (pr = ?) Then   (typical format of
condition)
ul1 = -1.85 * k ^ 3 / 100000 + 0.00203 * k ^ 2 - 0.077 * k + 1.03   (design equation)
ElseIf (st = 1) And (ar = 2) And (fc = 25) And (fy = 250) And (pr = 0.5) Then
(example of condition)
ul1 = -2.22 * k ^ 3 / 100000 + 0.00238 * k ^ 2 - 0.0872 * k + 1.14   (design equation )

.and so on     (if statement continues until all the conditions resulting from the
          combination of variables are included)

.EndIf
.End Function
```

Fig. 10 Format of a typical module Function *ul*

element predictions. The database is created as a function named *ul* consisting of several worksheet modules, (a typical module named *ul*1 is shown in Fig. 8), using Visual Basic interface. Each design equation is identified by the geometric (*ar*) and material (*fc* and *fy*) properties of the slabs, the class of slabs (*st*) and percentage of reinforcement (*pr*). The primary database consists of 360 design equations which are incorporated into the knowledge based system. The execution of any of the functions *ul* from the main worksheet will be able to select a specific design equation for the slab described by the user-supplied data, (which includes *st*, *ar*, *fc*, *fy* and *pr*). The basic format of a typical function program *ul* that performs this operation is presented in Fig. 10 which comprises of block IF statements so that specific design equations can be linked with particular conditions.

The design equation expresses the load capacity of the slab as a function of the breadth-to-depth ratio *k*. Hence, once the execution of the function *ul* identifies the design equation for the chosen slab, the ultimate load associated with various values of *k* can be evaluated. The programming area in the main worksheet for typical evaluation of ultimate loads for various values of *k* is identified as the shaded region in Fig. 8. The equations contained in the primary database were developed for specific slab material and geometric values covering the range generally encountered in practice. In the event that there is no perfect match between the supplied data and the equations in the primary database, a series of interpolation operations will be initiated whereby the relevant equation for the supplied data is constructed on the basis of the information in the primary database. Where only a few of the input parameters are supplied, the expert system will construct all possible scenarios accounting for the data not supplied, and present these to the user as design options.

Part 3 displays the design information in the graphic mode. The system is able to create the design chart for any arbitrary slab by specifying the values of the five variables *st*, *ar*, *fc*, *fy* and *pr*, which are used to identify the relevant equation from the primary database or construct a new one and there is no perfect match between any of the supplied parameters and values in the database. This will enable the user to find out the actual ultimate load of the slab for a particular value of *k*. Alternatively, the value of *k* can be chosen for a particular design load which will lead to the determination of the other slab details.

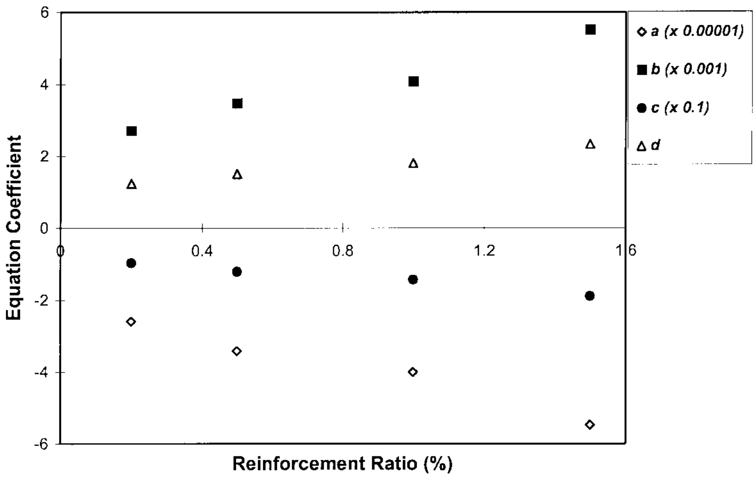

Fig. 11 Variation of equation coefficients with reinforcement ratios (%)

Table 3 Parameters of computer-model slabs

Class of slabs	Aspect ratio, $ar\ L_y/L_x$	Breadth to depth ratio, k, L_x/h	Concrete strength f_c' N/mm^2	Steel yield strength f_y, N/mm^2	% of steel pr
Class I	2.0,1.5,1.0	15,20,25,30,35,40	25,30,40,60	250,460, 550	0.2,0.5,1.0, 1.5
Class II	2.0,1.5,1.0	15, 20,25,30,35	25, 40,60	250, 460	0.2,0.5, 1.0
Class III	2.0,1.5,1.0	15, 20,25,30,35	25, 40,60	250, 460	0.2,0.5, 1.0
Class IV	2.0,1.5,1.0	15, 20,25,30,35	25, 40,60	250, 460	0.2,0.5, 1.0

3.2 Interpolation strategies

The nature and number of interpolations to be carried out within the system depends on the number of input data that does not have a perfect match in the primary database. While one mismatch may require only a single step interpolation two mismatches may require four or more interpolations, and so on. Apart from the direct interpolation between individual values in the database another flexible way found for constructing new design charts from those in the primary database (for some input data) involve interpolation between the coefficients of adjacent equations. The equations of the charts in the primary database are of the form (see Fig. 5):

$$ul = \boldsymbol{a}.k^3 + \boldsymbol{b}.k^2 + \boldsymbol{c}.k + d \qquad (1)$$

This interpolation strategy is made possible because an almost linear variation exists between the coefficients and say, the reinforcement ratios, as illustrated typically in Fig. 11.

3.3 Performance of the intelligence system

A series of partially clamped test slabs belonging to Classes II and III are used in this section to illustrate the predictive ability of the developed system. These slabs were tested by Park (1964) and Hung and Nawy (1971), and their details are summarized in Tables 4 and 5 for the two classes of slabs. Tables 6 and 7 compare the predictions from the developed CAD system with experimental values. The CAD system is noted to generally over-predict the ultimate load for the class II slabs

Table 4 Details of Typical Class II slabs (see Fig. 1)

Slab No.	% of Steel				f_y N/mm^2	f_c
	Short span		Long span			
	Top	Bottom	Top	Bottom		
Park's series B slabs (1964): Three edges fixed, one short edge simply supported. $L_y \times L_x \times h$: 1524×1016× 50.8 mm; L_y/L_x =1.5, L_x/h = 20						
B1	0.38	0.19	0.41	0.20	327.6	24.6
B2	0.84	0.42	0.43	0.21	327.6	24.9
B3	1.44	0.72	0.45	0.22	327.6	25.8
B4	2.42	1.21	0.47	0.23	327.6	26.0
Hung and Nawy's slabs (1971): Three edges fixed, one long edge simply supported. $L_y \times L_x \times h$=1651 × 1194 × 63.5 mm; L_y/L_x = 1.38; L_x/h=18.8						
C5-1	0.36	0.36	0.36	0.36	475.2	27.1
C5-2	0.28	0.28	0.28	0.28	471.0	27.1
C5-3	0.58	0.58	0.58	0.58	471.0	34.1
C5-4	0.58	0.58	0.58	0.58	286.9	34.1
Hung and Nawy's square slabs (1971): Three side fixed, one edge simply supported. $L_y \times L_x \times h$=1651 × 1651 × 63.5 mm; L_y/L_x = 1.00; L_x/h=26						
C2-1	0.58	0.58	0.58	0.58	471.0	38.6
C2-2	0.28	0.28	0.28	0.28	471.0	38.6
C2-3	0.36	0.36	0.36	0.36	475.2	41.9
C2-4	0.38	0.38	0.38	0.38	471.0	41.9
C2-5	0.58	0.58	0.58	0.58	286.9	39.0

Table 5 Details of Class III slabs tested by Hung and Nawy (1971) (Two adjacent edges fixed and two simply supported, see Fig. 1)

Slab No.	% of Steel				f_y N/mm^2	f_c
	Short span		Long span			
	Top	Bottom	Top	Bottom		
Rectangular slabs: $L_y \times L_x \times h$= 1651 × 1194 × 63.5 mm; L_y/L_x =1.38; L_x/h=18.8						
C6-1	0.28	0.28	0.28	0.28	471.0	29.8
C6-2	0.36	0.36	0.36	0.36	475.0	29.8
C6-3	0.58	0.58	0.58	0.58	286.9	30.0
Square slabs: $L_y \times L_x \times h$= 1651 × 1651 × 63.5 mm; L_y/L_x =1.00; L_x/h=26						
C3-1	0.58	0.58	0.58	0.58	286.9	28.3
C3-2	0.58	0.58	0.58	0.58	471.0	28.3
C3-3	0.28	0.28	0.28	0.28	471.0	35.9
C3-4	0.38	0.38	0.38	0.38	471.0	35.2
C3-5	0.36	0.36	0.36	0.36	475.2	33.0

considered, by a mean value less than 8%, while it under-predicts the class III slabs with a mean value less than 3%. The yield line calculation for the slabs has been found to generally under-

Table 6 Performance of CAD predictions for Class II slabs (Partially clamped; three edges fixed and one edge simply supported)

Slab Type	Peak Load, N/mm^2			
	Experiment	Direct FE Analysis	Knowledge based system CAD	Ratio Expt./CAD
Hung and Nawy (1971)				
C2-1	0.135	0.16	0.156	0.87
C2-2	0.109	0.13	0.124	0.879
C2-3	0.128	0.14	0.132	0.97
C2-4	0.145	0.14	0.14	1.036
C2-5	0.134	0.14	0.143	0.937
C5-1	0.142	0.16	0.156	0.910
C5-2	0.13	0.14	0.143	0.91
C5-3	0.20	0.21	- [a]	- [a]
C5-4	0.18	0.18	- [a]	- [a]
Park's Slab (1964)				
B1	0.14	0.17	0.167	0.838
B2	0.166	0.20	0.196	0.847
B3	0.177	0.22	0.213	0.831
B4	0.227	0.24	0.235	0.966
Park's Slab (1964)				
C1	0.115	0.11	0.107	1.075
C2	0.13	0.13	0.13	1.0
C3	0.125	0.15	0.143	0.874
C4	0.183	0.20	0.195	0.939
			Avrg. Ratio:	0.926

a: slab details outside the range of parameters used for software development (see Table 3).

Table 7 Performance of CAD predictions for Class III slabs -Partially clamped; two adjacent edges fixed and two simply supported (Hung and Nawy 1971)

Slab Type	Load, N/mm^2			
	Experiment	Direct FE Analysis	Knowledge based system (**CAD)**	Ratio Expt./CAD
C3-1	0.125	0.12	0.123	1.016
C3-2	0.142	0.14	0.134	1.060
C3-3	0.113	0.10	0.104	1.087
C3-4	0.122	0.12	0.126	0.968
C3-5	0.11	0.10	0.105	1.048
C6-1	0.1212	0.119	0.12	1.010
C6-2	0.1249	0.124	0.123	1.015
C6-3	0.163	0.166	0.161	1.012
			Avrg. Ratio:	1.027

predict the ultimate loads by factors ranging from 1.02 to 2.07, for the class II partially clamped slabs considered. For fully restrained slabs factors of up to 8 have been recorded between the finite element and yield line analysis (Famiyesin and Hossain 1998).

3.4 Advantages of the CAD system

The expert system provides a useful means of generating design information for different classes of reinforced concrete slabs. The following features of the system can be highlighted :

- It is easy to use. The Microsoft Excel environment and the Visual Basic with graphics capability provide excellent tools for the system development. Only a basic knowledge of Excel and the design of concrete slabs are required by the user.
- As the database was developed from data generated from nonlinear analysis of reinforced concrete slabs, the values returned to the user by the system would be more accurate than predictions from the yield line theory.
- The system can be used for design-assistance purposes. Current design codes adopt partial factors of safety for material and loading variability which, while resulting in a safe (and oftentimes overly conservative) design, does not give an indication of the global safety factor achieved. When used alongside conventional design method, the knowledge based data provides such vital information.
- The ultimate load prediction of the slab takes into account the strength enhancement due to non-linear membrane action. Knowledge of the actual capacity of the slab will increase the confidence of the designer enabling him to choose his own factor of safety, thereby optimizing the construction cost.

Much time and effort are expended during the conceptual and preliminary design stages to assess the viability of possible design options. The developed system will undoubtedly assist the engineer during this stages as a lot of options can be considered in a much quicker time, since the user can vary the geometric and material properties as he desires.

4. Conclusions

The experimental results of tests on reinforced concrete slabs have been used to identify the parameter values, (for a finite element model), and the computational conditions that guarantee reliable numerical predictions. The calibrated model was used in the finite element prediction of about two thousand computer model slabs belonging to four classes of boundary conditions. The data generated and equations developed from the extensive numerical simulations form the basis of a primary database which is used to develop the knowledge based system. The developed system is capable of providing different design options quickly based on the user-supplied data which will assist the engineer to choose a preferred design. The software has been developed in Microsoft Excel with Visual Basic, it is easy to use and should prove useful to practicing engineers and for teaching purposes.

The software has been developed and validated for reinforced concrete slabs with different boundary conditions but also has the capability of incorporating other structural elements, as well as some safety-critical design details, (such as the slab-beam and beam-column joint evaluation). Work is currently underway to incorporate the design of composite slabs with profile steel sheeting. Other areas of improvement to be considered for the software include incorporating equations from the code-of-practice based design within the graphics display and improving its user friendliness.

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