A computer program for studying the design of reinforced concrete structures supported on columns

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Many authorities are now convinced that too much time and effort is being expended on refined methods of analysis of structures using electronic computers, and therefore the Author is to be congratulated on an ambitious attempt to solve some of the problems involved in structural design—a topic which has received much less attention than analysis.

50. I would be interested in his views on whether he considers his program system as a research tool or as a practical design approach. If the latter, its use for bridge structures would seem to have considerable merit, but there are strong arguments against its use for the design of multi-storey framed buildings.

51. Three main reasons for doubting the value of the system in the practical design of multi-storey reinforced concrete buildings are:

- (a) the increasing use of limit-state design;
- (b) the extravagant demands on computing time required for the necessary iterations in the elastic analysis of even a relatively small multi-storey building;
- (c) the fact that the system as outlined does not appear to include facilities for the engineer to specify arbitrary requirements, e.g., maximum or minimum cross section dimensions, to conform to the architectural specification or Codes of Practice.

52. Although presumably obtained by using a modular ratio analysis, Fig. 15 indicates that minimum cost cannot always be the design criterion. Due to architectural considerations, the necessity of reducing the size of columns in a multi-storey building to a minimum takes priority over cost analysis. Also, the increase in column size apparently required for Project 3 would be rejected by the practising engineer.

53. The alternative load-factor method for the design of beams has a considerable effect on the cost analysis. It can be shown that a beam designed so that the maximum support moment is between 0.4 and $0.5 \times p_{cb} b d_1^2$ will have the least structural cost. A value of d_1 less than that given by the above equivalence may frequently be preferred to reduce the overall height, and thus cost, of the building. The extreme case of this would be the flat slab type of construction.

54. A computer system for selecting sizes of beam and columns for many types of multi-storey reinforced concrete framed buildings is now in course of development under my direction as a proposed sub-system of GENESYS. This would appear to satisfy the objections to the Author's system listed above. Some extracts from the specification for the proposed system for the selection of frame member sizes for reinforced concrete buildings are given for comparison.

55. The user must specify:

- (a) the form of the building shape and all dimensions relating to the structural shape;

DISCUSSION

- (b) floor loadings (including self-weight and superimposed loads);
- (c) beam loadings (cladding or partition loads);
- (d) the system for transferring floor loading to beams, i.e., one-way or two-way spanning slabs, or flat slabs.

Optionally, the user may specify:

- (e) allowable stresses in steel and concrete;
- (f) minimum sizes for beams and columns;
- (g) specific sizes relating to beams and columns;
- (h) increments used in selecting sizes of beams and columns;
- (i) minimum and maximum percentages of column reinforcement;
- (j) concrete cover to beams and columns.

For all the latter, if the user does not specify values, default values are used.

56. The output will give the sizes of all beams (arranged so that the size of beam in any row is constant unless there is an abrupt change in span and/or loading along any given row), the sizes of all columns for each floor height (plus design concrete stress and percentage of steel), and finally the lengths, section properties and loadings on all the beams and columns in each plane frame forming part of the total structure, in a form suitable for re-input to a structural analysis program. The critical loading cases required to obtain the maximum moment diagrams are also included. Each section of the above outputs is optional at the user's discretion.

57. The selection of the beam size for any row or part row of beams is carried out by determining the maximum support moment using approximate formulae and then selecting b and d such that $d = d_1/0.85$ and $M_{max} > p_{cs} b d_1^2 / \phi_1$ where ϕ_1 is termed the beam design factor. A probable value of ϕ_1 for optimum design is about 2.

58. The design of the columns is carried out by first determining the support moments (approximate values) applied by beams framing into the column from the two orthogonal directions. For all outer columns (except corner columns), the resultant applied moment is likely to be much greater in one direction than in the other and the larger value is used to select a suitable column size by load factor methods. For corner columns, the sum of the two resultant moments is multiplied by ϕ_2 (where ϕ is an empirically derived 'column design factor'), and then treated as though subject to bending about one axis only.

59. The above extracts from the specification for the proposed system indicate the extent to which the needs of the practising engineer are satisfied. It is intended that output will occur after the second iteration. For any given computer, the time required will depend only on the size of the frame.

Dr Bond

The interesting contribution of **Mr Mills** to the discussion on this Paper and his helpful comments are appreciated. I agree with him that electronic computers have enabled structural analysis to reach a stage where many types of complete structures can be analysed to a sufficient degree of refinement for practical purposes.

61. I have tried to concentrate my own research efforts, and those of the two research students who have recently joined me, on the continuing study by computer of the problems which occur in the automated design of completely integrated reinforced concrete structures. However, one is tempted to examine further improvements to the structural analysis when it becomes evident that this is necessary for design purposes. I give two examples of these which are currently being investigated by us.

62. In the program which is described in this Paper each column is joined to one nodal point of a slab element. If beam junctions also occur here, the problem is not so critical. But in the case of flat slab construction, in particular, the computed moments within the slab are influenced by the column shape and size. This problem has already been discussed in some detail elsewhere.¹⁴ We are attempting to find a

solution to this problem which will not increase the computer storage requirements significantly and which will be suitable for incorporation in the main program.

63. The examination of the interaction of T- or L-beams with slabs which form their flanges during the design iteration depends on an accurate analysis. This interaction is normally expressed in terms of an equivalent flange width, the value of which can be found by classical elastic theory only for certain loading cases and support conditions. We are attempting to solve this problem iteratively, taking into account in-plane stresses in the slab elements.

64. Mr Mills asks in § 50 whether the program is intended to be a practical design approach. It is being developed as a research tool to examine the influence of design instructions on the final shapes and costs of structures. The practical problems of design are taken into consideration, but the temptation to make the program dependent on a particular code of practice has so far been resisted. It is, of course, independent of the units which are chosen, and any consistent set of units, such as lb ft or N m, can be used. Advantage is taken of the analysis which enables an idealized elastic examination of the complete, integrated structure to be undertaken. It is not necessary to make simplifying general assumptions relating to support conditions or to the partial interconnexion of structural members, unless these occur in the real structure. Hinged bridge supports are an example. For this reason the modular ratio method is still used for the design of cross sections so that the whole procedure is still elastic. When the new British unified Code of Practice for structural concrete is published it will be necessary to consider the limit states of collapse, local damage, and deformation in the spirit of lower-bound limit-state requirements. The additional segments for this can be included in the existing program without any reorganization of the program structure.

65. Mr Mills mentions in § 51(a) the increasing use of limit-state analysis in design. Although upper-bound solutions such as yield-line theory or the Hillerborg strip method are permitted for the design of slabs, Professor R. H. Wood has found that it is difficult to improve on an elastic analysis by computer for minimizing the reinforcement.^{13,15} It is interesting to observe that recent codes of practice recommend for general use an elastic analysis even for the collapse state, in accordance with lower-bound limit analysis.

66. Mr Mills anticipates that buildings will be designed after two iterations using his method (§ 59). I showed in Figs 6 and 9 that iteration was slower when there was mutual adjustment between slab elements during the design. But it can be seen in Fig. 12 that when slabs had flat soffits the iteration was more rapid. The dimensions were near their final values after one cycle, even though for the purpose of demonstration the initial values were chosen arbitrarily and were further from the true values than could be estimated using simple rules. It must be admitted, however, that the program as it exists would require considerable storage and therefore computing time for the design of a tall building. We are at present developing a modification to the program which uses a combination of iteration and Gaussian elimination to reduce the storage requirements considerably.

67. As stated in § 51(c), the program does not include full facilities for specifying arbitrary requirements. It does, however already include the specification of minimum cross-sectional dimensions of slabs, beams and columns. The program could be modified to specify also their maximum or specific values.

68. I agree that minimum cost cannot in practice always be the design criterion, although the present application of the program has this in mind. The sizes of columns of Project 3 are mentioned in § 52. The building was designed to withstand wind loading and unsymmetric floor loading without shear panels. These could have been included. Alternatively, the concrete and steel permissible stresses as shown in Table 1, or even the quantity of reinforcement could have been increased in order to reduce the column sizes.

69. It would appear that at present my terms of reference and those of Mr Mills

DISCUSSION

differ, although our interests are closely related. Taking into consideration the size, speed and running costs of existing computers the frame analysis of Mr Mills is ideally suited to the immediate requirements of designers of conventional buildings. But my program considers the structure, including slabs, to be completely integral. This policy anticipates that within a short time computers will be approximately fifteen times faster than the existing Atlas computer,⁷ and in the foreseeable future they will be even more powerful.

70. I have attempted to summarize the input requirements of my program as briefly as possible for comparison with those of Mr Mills. The user must specify:

- (a) the shape of the structure and its general dimensions;
- (b) the vertical and horizontal superimposed loading and the concrete density;
- (c) whether foundation design is required and the moduli of subgrade reactions;
- (d) for slabs, beams and columns separately the percentages of steel, permissible stresses in concrete and steel, the degree to which the reinforcement contributes to the stiffness of each member, minimum cross-sectional dimensions, minimum cover, maximum bar diameter;
- (e) the modulus of elasticity and Poisson's ratio of concrete, and the modular ratio.

Table 4. Project 2. Highway bridge. Final dimensions : ft

Slab element type		Members which have their main reinforcement included in their stiffnesses *		
		columns only	no members	all members
1	Slab thickness	1.00	1.00	1.00
2		1.00	1.00	1.00
3		1.00	1.00	1.00
4		1.00	1.18	1.00
5		1.40	1.54	1.47
6		3.10	2.82	3.10
7		1.98	2.10	2.08
8		1.58	1.59	1.62
9		1.00	1.26	1.00
10		1.15	1.38	1.26
11		1.21	1.42	1.32
Column position				
end columns	Column width	1.00	1.13	1.01
intermediate columns		2.38	2.00	2.37

* In every case the whole concrete area is included in each stiffness.

The inclusion of the influence of the reinforcement on the stiffness of any member is a recent addition and it is of interest to note its effect on Project 2, for example. This is shown in Table 4.

71. It is intended that the program should remain as general as possible. For this reason the preparation of data for it is probably more time-consuming than that for Mr Mills's program. This difficulty will be overcome by using preliminary programs which can be run on a small computer. Each program will be for a particular type of structure and it will have built-in default values as recommended by Mr Mills in § 55, together with standard element layouts and loading patterns. It will cause the computer to punch the complete set of data cards for the main program, thus reducing considerably the data which the user must prepare.

References

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15. WOOD R. H. The reinforcement of slabs in accordance with a predetermined field of moments. *Concr. Mag.*, 1968, **2** (2), 69–76.