THE USE OF STRUDL IN REINFORCED CONCRETE BUILDING DESIGN

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Describes the complete reinforced concrete capabilities in the STRUDL II (the Structural Design Language) subsystem of the ICES (Integrated Civil Engineering) computer software system. The analysis of entire building frames and the proportioning of structural members may be performed within one computer system. The problem-oriented language input, and printouts of typical beam, slab and column designs are illustrated in an example. The system is freely available for use on IBM/360 computers.

Keywords: beams (supports); buildings; columns (supports); *computer programs;* detailing; flat concrete slabs; frames; *reinforced concrete; structural analysis; structural design;* ultimate strength method; working stress method.

INTRODUCTION

☐ Structural engineers were quick to recognize the value of the computer in their work and have used it extensively. However, the effectiveness of computer usage has been limited by inadequacies in programming techniques, as well as by the narrow scope of programs available. As a consequence, computers are still used in engineering primarily for their calculating capabilities. Engineering problems, however, usually involve a considerable amount of information storage, retrieval and manipulating in addition to numerical calculations. Computers can be used with considerably greater effectiveness when adapted to this, more general, view of engineering problems. The paper describes such an application of STRUDL (the Structural Design Language) to the field of reinforced concrete building design.

CRITERIA FOR AN INFORMATION SYSTEM

The process of structural design is basically one of trial-and-error. The designer makes initial decisions based on data that are currently available to him. These decisions are subject to continual revision as the data become more complete, or as conditions arise which have not yet been taken into account. The success of integrating the computer into the design process is dependent upon the ease with which the engineer can utilize the computer, the degree of flexibility it provides, and the generality or range of applications for which it may be used.

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A computer-aided design system is a collection of programs, each of which performs some particular operation for the user. The programs are of two types: those which perform the computational design tasks, and those which perform the information handling and linkage between design tasks. The flexibility of a computer-aided design system is provided primarily by the latter category, or system programs. The characteristics of the system programs are derived from the following characteristics of the design process:

1. The large size and variability of problem data.
2. The need to create, use, and modify information beyond the scope of a single problem.
3. The need for the designer to control the order in which design tasks are performed.
4. The need for updating, expanding and modifying the design system.

Utilizing the system programs, the computational design programs operate on a common data base, accepting information and storing results according to a prescribed set of conventions. In this way a computer aided design system can be expanded indefinitely, as long as the conventions (as opposed to programs) or their expansions are applicable.

SYSTEM CHARACTERISTICS

One of the basic features of STRUDL is the data structure upon which the system is based, and which facilitates interaction between the various components of the system. All data are stored in dynamic forms which are accessible from, and may be extended or modified by, any program. Preliminary design information, such as estimated member properties, are thus stored and are revised as the design proceeds. Calculated information is stored similarly and is also available as input for subsequent operations. For example, the computed details of reinforcement in a member are available for subsequent investigations of member capacity, for display if desired by the user, and for inclusion in a quantity take off for the structure.

STRUDL is a modular system designed to operate around the information with which it deals. It appears modular both to the user and the computer. The user employs a command structured or problem-oriented language, each command initiating a specific function which is made evident by the wording of the command statement. Commands may be given in any sequence, except for obvious dependencies. The user can broaden his use of the system as his knowledge of the capabilities grows.

Similarly, new facilities and commands are continually being added by developers at MIT as well as user organizations which are tailoring STRUDL to their industry or organizational outlooks regarding structural engineering practice.

The first version was started in 1965 and was released to the engineering profession in 1967.[1] It provided a system with flexible data input, output and modification features, and some frame analysis capabilities. The user could specify an entire problem and then add, delete or modify, the problem at any time. For example; members could be added or deleted from the structural frame, member properties or loading conditions could be modified, supports could be made free, etc. If desired for study of local behavioral effects, the analysis operations could be applied to only a portion of the structure. Results from different analyses with different structure configurations could be combined to simulate a construction sequence. A SAVE feature enabled the user to store the problem, and its associated data, on disk. The problem could then be continued at a later date after the user had inspected the results up to that point.

STRUDL has undergone two kinds of major updates since this first release.[2] The structural analysis features have been enlarged considerably, and capabilities for the design of building components have been incorporated into the system. These expansions were achieved without sacrificing the philosophy or approach to information manipulation which characterized the initial version, even though operating on vastly more data with an order of magnitude more programs.

STRUDL now contains some of the most sophisticated analysis tools available to the structural engineer. An engineer can now solve in a realistic manner problems composed of any combination of frame members, plates, shells and solids. A broad stable of finite elements is available for modeling continuous components. Besides the static load analysis, the user may study the geometrical nonlinear, or buckling, behavior of his problem. Behavior under dynamic loads may also be studied.

These analytic facilities are coordinated with a variety of design capabilities, which include the design of members from tables subject to arbitrary design constraints and codes, and a discrete section design optimization procedure, in addition to the reinforced concrete design facilities described in this paper.

APPLICATION OF STRUDL TO RC BUILDINGS

In keeping with the general STRUDL concept, the reinforced concrete facilities are wide in scope and flexible in application so as to permit the designer to attack the total building design problem in one operation, and to do so in a manner compatible with the peculiarities of the particular problem and the designer's own personal preferences. RC STRUDL contains a set of capabilities which provide for the analysis and design of many of the components found in typical reinforced concrete buildings. The capabilities may be used in various degrees of detail and in practically any sequence desired. The general design procedures which the system permits are consistent with common practice so as to ensure usefulness, and yet are flexible so that the engineer does not have to subjugate his own ideas to the program.

The member design capabilities include rectangular or tee beams, rectangular or circular columns with ties or spirals, flat slabs with or without capitals and drop panels, and one-way solid or joist floor slabs. For the proportioning of such elements, the user may pre-specify one or more cross-section parameters or set upper and lower bounds on such parameters. He may also specify similarities (e.g., equal depth) or identities between members in advance of design. The design output consists of cross-section dimensions, all primary and secondary reinforcement, the location and length of all bars, and total material quantities. The printing of much of this information may be controlled by the user. All procedures are in accordance with ACI 318-63.

The reinforced concrete design programs utilize the member forces (moments, shears and axial loads) which have been calcualted by one of a number of available STRUDL analysis procedures. Virtually any structure configuration with any variety of loading conditions can be analyzed with the general STRUDL frame analysis capability. Skewed structures may be analyzed and the members need not necessarily be normal to each other at their intersections. However, the user must realize that STRUDL "sees" only a linear element subjected to a set of forces at each end, rather than the slab or beam which the user is attempting to simulate.

The system provides certain additional analytical tools which are especially intended for use with the more common rectangular, or orthogonal, frameworks of typical reinforced concrete buildings. These not only permit greater machine efficiency, but also permit the automatic consideration of special conditions (e.g., various live load positions) which cannot be specified conveniently with the more general analysis procedure. Thus the system has great generality with regard to type of structure and loading, and yet is efficient for the typical reinforced concrete building.

The special analysis features provided for orthogonal buildings in RC STRUDL include a "segmenting" procedure which allows a unique analysis to be performed for any member of the structure. The segment consists of that member and only those members in its vicinity which have a significant influence on its design forces. When a column is proportioned with segmenting, only the horizontal members framing into the top and the bottom of the column are considered along with the accumulated gravity load acting at the top of the column. On the other hand, the user has various options for controlling the size of segment with beam and slab proportioning. Typically, he will limit the segment to one or two spans on each side of the member being proportioned including columns which frame in from above and below. A conventional analysis by moment distribution is used to determine the moments in the segment.

The segmenting procedure is extremely useful because all potentially critical arrangements of live load can be considered automatically, whereas this is not possible in the general frame analysis procedure. Member designs are then based on the maximum moment and shear envelopes which are generated by the automatically selected loading conditions.

For wind analysis, the user has the option to: (a) make a complete three dimensional analysis of the structure, or (b) isolate vertical planes and make an analysis of such a plane independent of the rest of the structure. Shear walls and floor slabs may also be included in wind analysis and are treated as finite elements interconnected with the linear elements of the frame. For the design of columns, live load reduction and the effects of slenderness may be considered automatically.

In the common case of orthogonal buildings, live loads may be specified in terms of general floor intensities and wind loads as wall pressures. The resulting member loads are generated automatically, based on the load distribution corresponding to the type of floor system specified. Dead loads resulting from the weight of members are computed internally and, together with member properties, are updated automatically whenever a member is designed. Thus a recycling of analysis and design may be executed if desired. For member design, the code combinations of dead, live and wind loads are generated internally.

Although the engineer has numerous options in the use of the system, the sequence of input for a typical building design might proceed as follows. First, the user would define the geometry of the structure. The location of floors and walls would be given next together with the loading intensities on those surfaces. He might then design the floor slabs (in the case of a slab and beam system) which would provide an exact determination of most of the dead load. Next, the analysis of the frame for vertical and lateral loads would be executed by a stiffness analysis or, in the case of gravity loads, by the special segmenting procedure. Prior to the design of frame members, he would specify design information such as type of member, preferred bar sizes, constraints on cross-section dimensions, and desired similarities between members. This would be followed by the proportioning of members in any sequence desired. Member design could then be repeated, if necessary, taking into account the updated dead weights and member properties. Finally, the output of beam and column schedules, reinforcement details, and quantities would be requested.

INPUT FOR TYPICAL RC BUILDINGS

Special GRID commands are available in STRUDL to facilitate data input for typical rectangular reinforced concrete building frames. Consider the building shown in Fig. 1. It consists of one-way floor slabs supported by parallel, beam-and-column frames. The exterior walls are non-structural, except for shear walls in two opposite bays. The loading consists of dead and live floor loads, the self-weight of the frames, and wind pressure on the exterior walls.

The geometry is specified with the single statement,

GRID DEFINITION Y 7 AT 10., Z 5 AT 15., X 3 AT 20.

which defines all lines along which members may lie. For further reference, the planes in the grid are numbered sequentially along each coordinate axis, starting with one at the origin. Thus, plane Z2 is the plane normal to the Z-axis and 15 ft from the origin.

The actual location of members, as well as preliminary estimates of sizes, are indicated by commands such as,

GRID MEMBER X 2 3, Z 2 TO 5, BOUNDS 1 3 DIMENSIONS -
RECT B 12. H 16.

which indicates the columns lying on the intersections of planes X2 and X3 with planes Z2, Z3, Z4 and Z5. The bounds indicate that the estimated dimensions (12 X 16 in. rectangular) apply to columns in the lower three stories.

The floors and vertical loadings are specified by,

FLOOR Y 2 TO 7, T 0.5, ONE WAY Z, DL 20., LL 100.

This statement covers all floors, but not the roof, and estimates a slab thickness of 0.5 ft., indicates one-way behavior in the Z-direction, and gives dead (not including slab weight) and live loads of 20 and 100 psf, respectively.

The walls along the Z-axis are defined in,

WALL X 1, BOUNDS X 1 3, 4 5, T 0., WL 1 20.
WALL X 1, BOUNDS X 3 4, T 0.67, WL 1 20.

The first statement provides for the non-structural portions (indicated by zero thickness), and the second for the shear wall section. In both, wind load condition '1' is defined as a pressure of 20 psf.

In addition, special forces can also be specified separately to be included in the dead, live or wind loadings. Such forces can be concentrated at any location or distributed in some manner along members.

The first floor slab is analyzed and designed following the command,

ANALYZE AND DESIGN ONEWAY SLAB 380 381 382 383 384/

where the series of numbers identifies the five spans which are to be designed as a continuous element. In the case of one-way floor slabs, design is based on the moment and shear coefficients given in the ACI Building Code, rather than an elastic analysis. Unless otherwise specified, all spans will be of the same depth. The slabs on other floors could be made identical without further design.

If the wind analysis is to be based upon independent planar frame action, that for plane Z2 is executed by,

```
ACTIVATE PLANE Z 2
LOADING LIST '*WL/1' '*WL/2'
STIFFNESS ANALYSIS
```

This calls for a rigorous analysis of the plane, for wind load conditions '1' and '2', based on forces computed from the tributary wall areas. The resulting member forces are stored for later use in member design. If desired, some or all of these forces may be printed for checking purposes.

An important feature of the system is the ability to specify similarities between members, e.g., duplicating members for economy in construction, making all beams in a floor of the same depth, using the same column for two or three stories, etc. This is accomplished by statements such as the following:

```
GROUP 58 94 FOR DESIGN
MAKE 76 REVERSE OF 60 IDENTICAL TO 58
H 59 EQ H 58
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where the numbers identify individual members. The first statement requests a composite design for the two members based on the most severe forces in either. The second indicates that member 76 and the mirror image of 60 shall be made identical to member 58, both in dimensions and reinforcement. Only member 58 is actually designed. The last statement specifies that the depth of the two members shall be equal.

RC MEMBER PROPORTIONING

Beams, flat slabs and columns are considered as primary components of a building frame. The proportioning of such members begins with the member end forces which have been computed in one of the analysis procedures described previously. The proportioning programs take into account all of the loading conditions which the user has specified, or which have been selected automatically in the segmenting procedure. One-way slabs and joists, on the other hand, are considered as secondary components. Proportioning of such members is based on moment coefficients. All member proportioning utilizes the ultimate strength method of the ACI Building Code.

The beam design routines take into account flexure, shear, bond, deflection and minimum and maximum reinforcement requirements. Bars are selected at each critical section (usually at support faces and maximum positive moment section) and are distributed in a single layer if cover, stirrups and bar clearance requirements can be satisfied. Bar lengths are calculated for all bars taking anchorage requirements into account. If necessary, U shaped stirrups are designed. All reinforcement details are stored and may be printed out if desired by the user.

RC STRUDL will handle the proportioning of flat slab or flat plate floors in a building structure such as shown in Fig. 2. The elastic analysis method, Section 2103 of ACI 318-63, is followed and moments are distributed to column strips and middle strips as the basis for selecting bars. Column capitals and drop panels may be included in the proportioning procedure. The flat slab design programs consider flexure, beam shear, punching shear, column-slab moment transfer, minimum slab thickness, and minimum and maximum reinforcement requirements.

The column design routines utilize an iterative procedure in which column dimensions and number of bars are incremented until the capacity is slightly greater than the applied load. The column design programs utilize a rigorous method of cross-section analysis which accounts for bi-axial bending combined with axial load, and treats each bar in the cross section individually.

Slenderness effects on column capacity may be taken into account by a moment magnification procedure in which column moments are amplified by the factor $1/(1 - P_u/P_{cr})$ where P_u is the ultimate and P_{cr} is the buckling load. Determination of the buckling load is based on the elastic stability of the column, and the restraints provided by member framing into tops and bottoms of columns are computed automatically.

Beams, slabs and columns are proportioned with two comprehensive commands. The first, DESIGN DATA, is a preparatory one for specifying fixed data such as bar sizes and spacing, tie and stirrup sizes, concrete cover, etc. Most of this data is optional, and a standard value is assumed if the item is not specified by the user. For example, the following information might be given for proportioning rectangular tied columns with rectangular arrangement of bars,

```
DESIGN DATA MEMBERS 60 TO 94
TYPE COLUMN RECT, STEEL RECT, TIED
BARS COLUMN 7, 8
TIES 4
```

The last two lines, which are optional, specify that #4 ties are to be used, and that the main reinforcement shall be either #7 or #8 bars, the actual size to be determined by the program on the basis of an optimization algorithm.

The PROPORTION MEMBERS command initiates the execution of designs. For example, all beams of the structure in Fig. 1 could be designed with the following input:

```
SEGMENT TOLERANCE FRACTIONAL .03
PROPORTION MEMBERS 1 TO 114 GIVEN P .01 -
LIMITS HMAX 24.
```

The first line indicates that the design moments and shears shall be determined by the segmenting procedure previously mentioned, i.e., on the basis of a moment distribution analysis of an isolated segment of the total structure taken from the vicinity of the member being designed. The extent of that segment is determined by the tolerance .03 which refers to the maximum carry-over effect of the fixed-end moments from the member to the outer joints of the segment or from those joints into the member. The second statement calls for both the segment analysis and the proportioning of the members listed. It is also specified that the steel percentage shall be .01 but that the depths shall not exceed 24 in. If the latter instruction controls, the given steel ratio would be ignored. Utilizing alternative procedures, member thickness or width, or both, may be prespecified. When proportioning columns, the engineer also has considerable control over the relative amounts of steel in the four column faces. For all proportioned members, the details for both longitudinal steel and stirrups, and ties or spirals, including bar locations and lengths, are determined and stored automatically.

RC MEMBER INVESTIGATION

RC STRUDL also contains facilities which allow completed designs to be checked for adequacy of strength and for compliance with provisions of the ACI Building Code.

Beams may be investigated for flexure, shear, bond and deflections. Columns may be investigated for the combined effect of axial load and bending about one or two axes. Critical sections of flat slabs are checked for flexure, beam shear, minimum thickness and punching shear including the effect of column slab moment transfer. All of these investigations can be performed according to either the working stress or the ultimate strength method.

In order to perform member checks, the cross section dimensions of the members are defined with a MEMBER DIMENSIONS command. Details of the straight or bent primary reinforcement, as well as stirrups, ties or spirals are described in a MEMBER REINFORCEMENT command. The statement,

```
CHECK MEMBERS 'S2', 5, 24 FOR FLEXURE, SHEAR
```

will institute an investigation of the flexural capacity and the shear capacity of the named members at all potentially critical sections along their lengths. The potentially critical sections are selected automatically on the basis of the loading, support conditions, primary reinforcement and secondary reinforcement.

DISPLAY OF RESULTS

Examples of the output from proportioning beams and columns are shown in Fig. 3 and Fig. 4. In addition to cross-section and reinforcement information, the design moments and shears are also printed for use by the engineer in checking the reasonableness of the design.

When using RC STRUDL as a checking tool, the engineer may control the type of output with an OUTPUT FORMAT command. By this means, information ranging in completeness from short diagnostic messages regarding member capacity to the printing of complete data regarding section forces and section capacity at every critical section along the member length may be selected.

Having designed all members in the structure, and having recycled the process as necessary, the design information may be summarized by commands such as the following:

```
SCHEDULE BEAMS ALL
SCHEDULE COLUMNS ALL
PRINT ALL REINFORCEMENT ALL
QUANTITY TAKEOFF ALL
```

The first two statements cause the printing of conventional beam and column schedules in a condensed format. This may be done for the entire structure or for selected portions, e.g., only the beams in one floor are included if ALL is replaced by an identifier of that plane. Examples of such beam and column schedules are shown in Fig. 5.

The third statement above results in the printing of a detailed description of all reinforcement including the position of every bar in the cross-section, its location and length along the span, the location of hooks, etc. This output is very voluminous, but is necessary for bar detailing. The next step in system development might include some form of automatic transmission of these data to the bar fabricator. Beam and column details might also be displayed in graphical form to facilitate checking by the engineer.

The last statement above causes the computation and printing of the total quantities of concrete, reinforcement and formwork. The totals are subdivided by type of member and type of reinforcement (primary or secondary). Quantities may also be taken off for selected portions of the total structures, as illustrated in Fig. 6.

It is difficult to give accurate data regarding the operating costs involved in the use of STRUDL because of the many configurations of IBM System 360 on which the system can be run, and the flexibility of use which can be obtained with the various STRUDL capabilities. As an example, however, all floor slabs and all members in the typical interior frame, Plane Y2 shown in Fig. 1, were analyzed and proportioned on an IBM S/360 Model 65 computer in 10.2 min using 450K of core. In this particular example, the member similarities feature allowed the required number of unique member designs to be reduced to only six beams and six columns.

CONCLUSION

The primary purpose of the development reported herein was to provide a computer system with which the engineer could accomplish the structural design