

Integrated computer-aided architectural and structural design

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ABSTRACT | A programme of research was carried out to provide an integrated design tool for interactive design of architectural layout and structural system of regular multistorey buildings. The outline of the system is as follows. The user works with architectural spaces and defines the final arrangement of spaces in terms of geometry by drawing them in AutoCAD. The plan of designed spaces or "blocks" is used to generate a set of gridlines the intersections of which produce "nodes". Certain rules are applied to render the nodes into structural nodes forming the end points of structural members. Once the geometry of structure is defined, data is passed to a structural steel design module using an approximate method which generates the initial sizing of members. For a more accurate result, two sophisticated analysis programs are used for strength and serviceability. Conformance to standards is carried out by another module and due modifications are made to the structure. A cost estimate of the building structure is finally produced.

KEYWORDS | integrated design, computer-aided building design, structural design, integrated CAL

1 Introduction

The decisions made at the early stages of building design, which generally take place in the architectural office, have major impacts on many aspects of building, including the structural form, the mechanical and electrical services, the construction planning, and the overall cost - both capital and recurring - of the project.

It is of prime importance that the effect of decisions which the architect makes in the initial stages of building design can be assessed; particularly vital is the influence of decisions on the spatial arrangement within the building. The earlier in the design process these issues are addressed, the more likely it is that later difficulties can be avoided.

Many of the design jobs in architectural practices and structural engineering consultancies are concerned with regular buildings with rectilinear overall shape

and rectilinear internal spaces. Much time is spent in designing such buildings which are in many aspects replications of past designs. The repetitious nature of the design procedures which are repeated for all floors of high-rise buildings absorbs enormous efforts that otherwise could be saved for novel and creative designs.

The work described in this paper is an attempt to automate and integrate the activities that take place in architectural and structural design practices for designing the layout and the structure of regular rectilinear multistorey buildings. This should free the designers from the repetitive tasks involved in the design of regular buildings, and as a result, leave more energy for designers' creativity.

The design process as viewed in the present work is described herein. Initially, the architectural practice

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carries out initially analysis, space needs analysis, interaction and grouping analysis, and spatial synthesis, followed by an initial (and very rough) cost estimate that complements the feasibility analysis. The schematic design of building then follows that involves sketching a number of alternatives, selecting the most suitable ones, and developing these suitable schemes. Once these schemes are developed in more detail, selection of the most promising scheme becomes possible. This scheme is then developed further, the outcome of which is the general arrangement drawings, issued for further work by other practitioners, e.g. engineers and quantity surveyors. The outcome of each stage is presented to the client as appropriate, and the client's needs are taken into account as the design proceeds.

A soft copy of floor plans, normally in the form of computer diskettes, is often available to the structural engineer. The plans contain the layout of spaces, with a series of gridlines corresponding to the modularity of spaces in the architect's mind. These gridlines may not coincide with those drawn by the structural engineer, thus, a series of gridlines are created corresponding to the structural modularity in the structural engineer's mind. Once adjusted to the technical constraints, including the overall structural continuity, these gridlines are the basis for allocating structural elements.

The structural engineer considers a number of alternative solutions in line with the design brief and technical specifications of the project. The appropriate schemes are selected and developed further so that the most suitable one can be selected. This scheme is then developed in more detail, and provided that proper channels of communication exist, it is checked against the requirements of other practitioners.

For buildings of structural reinforced concrete and steel, the structural model is in fact a space frame, the engineer however views it as a number of planar frames the interactions of which are to be taken into account. In effect, the engineer decomposes the com-

plex structure of the three-dimensional frame into a number of less complex two-dimensional frames composed of beams and columns.

The columns are located at the intersection points of gridlines, and the lines connecting these points in plan are taken as beams. The primary decision to be made is the selection of the type of planar frames in respect of their resistance to lateral loads such as wind and earthquake. Assuming a steel structure, two main alternative structural systems are rigid frame and braced frame. Once this conceptual selection is made, the physical system is developed by designing beams, columns and connections.

In the proposed system, semi-rigid steel frames comprising bare steel beams and columns are assumed for the structure of building. The semi-rigidity of frames eliminates the need for provision of bracing in the plane of steel frames (this feature is attractive in that the bracing does not exist to interfere with openings in the building). The resistance to lateral loads, such as wind, is provided by the moment resisting beam-to-column connections. A semi-rigid frame in which the behaviour of joints are taken into account is considered more economical compared to a rigid frame provided that lateral displacements are within the limits.[1]

Normally, structural analysis of building frames requires sizes of structural components for calculating forces and displacements of members. If the resulting stresses and displacements exceed the allowable values, components' sizes should be altered and the frame reanalysed. However, this system eliminates the need for initial sizing of structural elements. In fact, the approximate design method provides initial sizes for a "rigorous" analysis.

2 System Implementation

In order to make appropriate decisions on the implementation aspects of the system, a study was under-

taken of computer use in education and practice. A large number of reported works describe software systems for structural analysis and design, but some recent attempts focus on integrated intelligent systems that include other design tasks. However, these have been developed merely within research programmes. Software vendors, on the other hand, have marketed a variety of packages with almost no element of “intelligence” incorporated into their procedures.

Reference [2] summarises research attempts at automation of layout and space planning, and reviews intelligent systems for structural analysis and design, and concludes that they provide automation at the cost of minimising user interaction. Reference [2] reviews also commercial integrated structural design packages and considers that a common feature of these systems is that they provide facilities towards the detailing end of the structural design process, rather than extending beyond the preliminary design stage, i.e. conceptual design stage, let alone integrating schematic architectural design. The input to these systems is the fixed geometry of the building structure, and they do not perform manipulation of the geometry of the building. The proposed system is capable of manipulating the architectural geometric attributes of the building in

order to create a suitable structural model. Modifications to the architectural plans are possible at any stage, and effectively after each assessment of design, on the graphical screen, thus providing a convenient facility for iterative cycles of architectural and structural design.

A review of the works presented in recent conferences[3][4] affirms the need for further work in the area of integration, particularly covering conceptual design tasks due to the impact of decisions made at early stages of design on the whole life cycle of buildings. The use of object oriented paradigm is increasingly appealing because of its many useful features and the nature of design activities. However, in order to provide a consistent flow of data between modules of the system, the author made use of the facilities provided within AutoCAD.

The proposed system consists of three main modules each undertaking a part of the intended design procedure as shown in Fig. 1. The figure shows the proposed system in two levels: the software environment, and the user interface which comprises the communication media between the software and the user.

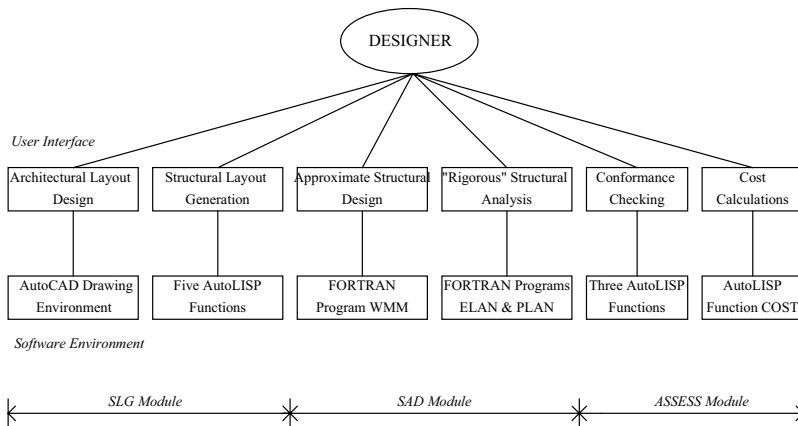


Figure 1. The system organisation as relates to design activities at the interface and software levels

The input to the system is in the form of drawing files in which functional spaces are defined as rectangles by their four vertices. The sketch or drawing is initially prepared in AutoCAD consisting of a number of "polylines".

The first module in the system is the structural layout generator (SLG). This module performs initial geometrical manipulations for all floors in the realm of architecture, i.e. it establishes the geometry of the building, sets architectural grids, and prepares various lists of entities including polylines, gridlines and nodes. The module then performs a process of allocating nodes in each floor, applying various rules resulted from different structural constraints. This module finally generates data required by the analysis and design module that includes the configuration of all planar frames and loadings.

The structural analysis and design module (SAD) is composed of three programs. Initially, the structural elements of the bare steel frames are designed using an approximate but well established method referred to as the "wind-moment" method[5] so that the design may be considered complete at this stage if the user so wishes (justification of the use of this method for multi-storey buildings is discussed later in this paper). However, for more accurate analysis, two sophisticated structural analysis programs are available with advanced features. The system uses the results of the elastic-plastic program for checking conformity to strength requirements. The elastic program is used after design for strength is complete, in order to perform conformity checking to serviceability requirements. The assessment of structural adequacy is undertaken by the assessment module.

The assessment module (ASSESS) carries out the required conformance checking to the design standard for structural steel design.[6] The module makes an estimate of the costs using the technical specification of the structural elements as provided by the programs which perform conformity checking. It calculates the

weight of the steelwork and fabrication costs, and outputs lists of quantities and cost estimates. The cost of a particular design resulting from a set of parameters determined by the user during the design process is stored to be compared with later cost estimates generated by running the system with other sets of parameters.

A further module controls the execution of the programs and the data flow between the programs. The data management and storage system is based on the concept of separated project data and common data. The former includes the building geometry, CAD data, input/output data and solution data. The latter consists of libraries of computational, detailing and estimating data. The database system is shown in Fig.2. Each module in the system needs access to certain sources of data. Fig. 3 shows the information that is accessed by different modules of the system.

3 Control Mechanism and User Interface

The idea of a blackboard type mechanism[7][8] has been developed for the control of the modules and communication with the system database. The proposed mechanism that holds together the modules and the database is independent of the modules, but calls to different programs and pointing to data are embedded in the modules. This mechanism provides both procedural execution of the modules and flexible reference to the design data, as well as localised interactions of the parts of the system with the environment.

The hierarchical directory structure of the modules and programs on the one hand, and the data files on the other, provides an infrastructure for the system that facilitates exchange of information. The design process is viewed as a directed graph, where nodes represent either modules or databases and arcs represent either flow of data or control. Conceptually, the design process is derived from design goals and design constraints specified by the design task. This process can

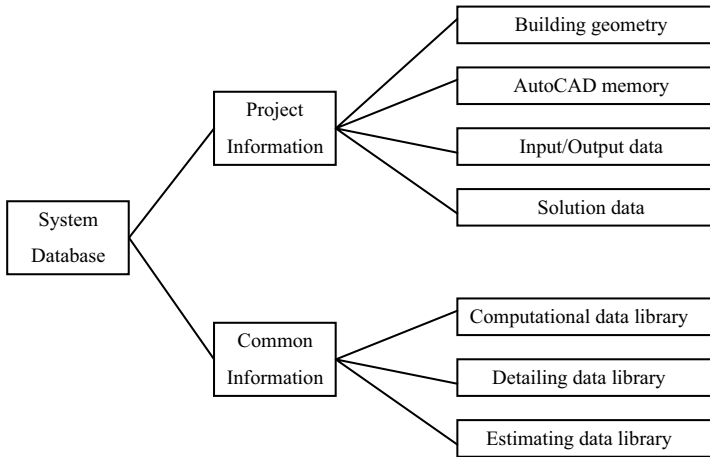


Figure 2. The system database

be done manually by the user, but is performed automatically in the present system.

The following points were considered and implemented in the design of the control mechanism and the user interface of the proposed system:

1. The modular decomposition should result in a manageable structure for the system.
2. The integration of design modules should be in a way that enables entering and exiting at any stage of design.
3. Returns to previous stages of design should be possible.
4. It should be possible to add, remove or modify a module with minimal impact on the rest of the system.
5. Learning how to run the system should require minimum effort.
6. The user should be informed of the current and next step in the process.
7. The system should comprise explanatory facilities, both for help in running the system and information on the knowledge incorporated into the system.
8. Making changes to design parameters should be straightforward.

9. The data flow between programs should be consistent.

10. The user interface should be consistent, taking ergonomics and cognitive characteristics into account.

Various interprogram communication technologies were considered, including object linking and embedding (OLE) which is in fact data-oriented. This means that the user is primarily concerned with where the design data is stored and how it is retrieved. In effect, the design activities which are the real tasks to be conducted in the conscience of the user become secondary to the abstract data represented in the spreadsheet format. This is not compatible with the way real design activities take place. In reality, the designer's prime interface with his/her design is through visualisation. The assessment, criticism and discussion of the design synthesis all take place basically around a visual model of the design.

The view taken was that the proposed integrated system should be design-oriented. This means that the prime concern should be the advancement of design, and the system implementation should be such that the designer remains in touch with his/her design during the process. Consequently, the graphical interface that is provided by the CAD software should play a central role

throughout the design process, and the data generated by the system should be accessed conveniently when the user wishes. In retrospect, the system was designed in a way that the user starts sketching in the AutoCAD graphical screen, the structural layout is generated within the same environment, the approximate design and analysis programs are invoked from AutoCAD, and stability and serviceability checking, as well as cost estimation, are all carried out in the same environment using the capabilities of AutoLISP. This provides a consistency not only in the user interface with the system, but also in the design process as a whole.

The AutoCAD graphical interface is maintained throughout the design process. The user interaction with the system is provided through graphical and text screens and dialogue boxes. The representation of design data is through graphical and text screens:

- a) The AutoCAD graphical screen displays the geometry of the building as the main drawing canvas (see Fig. 4).
- b) The AutoCAD text screen displays design data in the form of text. For instance, the details of the total cost estimate is printed on the screen as a single information sheet (Fig. 5).
- c) The Microsoft Fortran Power Station text screen displays the advancement of analysis and design process as the programs act on each frame.

The dialogue boxes present design knowledge (such as information on steel grades, types of joints, loading, etc.) and obtain user input (see Fig. 6). The edit boxes are supplied with default values, and the user-supplied values can be typed in the edit boxes. The dialogue boxes have been designed so that the system may be used for educational purposes.

4 Generation of Structural Layouts

The AutoCAD drawing information may be accessed in two ways. If the drawing is active in memory as a

DWG file, the drawing information can be reached directly from memory. AutoLISP provides access to and manipulation of AutoCAD drawing entities by retrieving the information from the system database. However, there is another way, that is to store drawing information in a DXF file, and using that via an application program from outside AutoCAD. These two approaches are referred to as *internal* and *external* approaches.

The author adopted the *internal* approach which eliminates the need for transferring control to external modules and back to the drawing software, which in turn provides a consistent process and smooth flow of data. The *internal* approach allows the drawing of new entities in different layers, such as gridlines and structural elements, as generated by the AutoLISP code while the program proceeds. The layers used in the proposed system are named according to the layer naming convention[9] and the CI/SfB code[10] as follows:

- "A20000Bn" for a layer containing architectural layout plan,
- "A03100Bn" for a layer containing architectural setting out grids,
- "S03200Bn" for a layer containing structural gridlines,
- "S28100Bn" for a layer containing structural metal columns,
- "S283000n" for a layer containing structural metal beams.

"B" denotes "Below", meaning the architectural or structural subject is "below" the level specified by "n". The structural beams are assumed to be located "at" level "n", hence figure "0" is used instead of letter "B".

The following *functions* perform the generation of structural layout concepts and data for the structural analysis and design module (detailed information may be obtained from Reference [2]):

- a) ARCHMAN, performs geometrical manipulations in the realm of architecture. It operates on each floor in

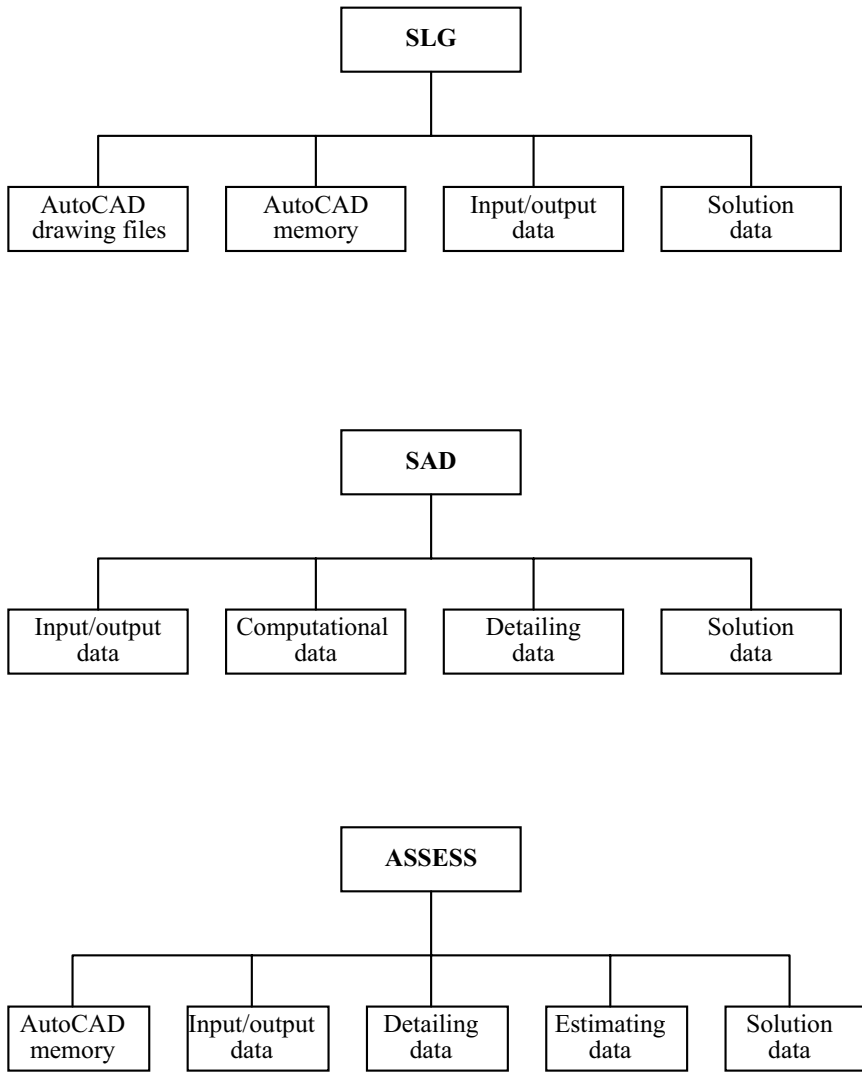


Figure 3. Each module needs access to certain sources of data

turn, makes a list of all "blocks" in the floor, arranges block vertices in ascending order, and draws architectural grids. The intersections of gridlines are found and those outside the layout plan are eliminated. The resulting list contains coordinates of "nodes". Another list contains those nodes which are located at

the corners. This list is important since, in general, a column should be located at each and every corner unless a specified rule requires otherwise.

b) WHOLE, applies a philosophy for structural layout generation, based on the consideration of the way designers create the initial concept of structural

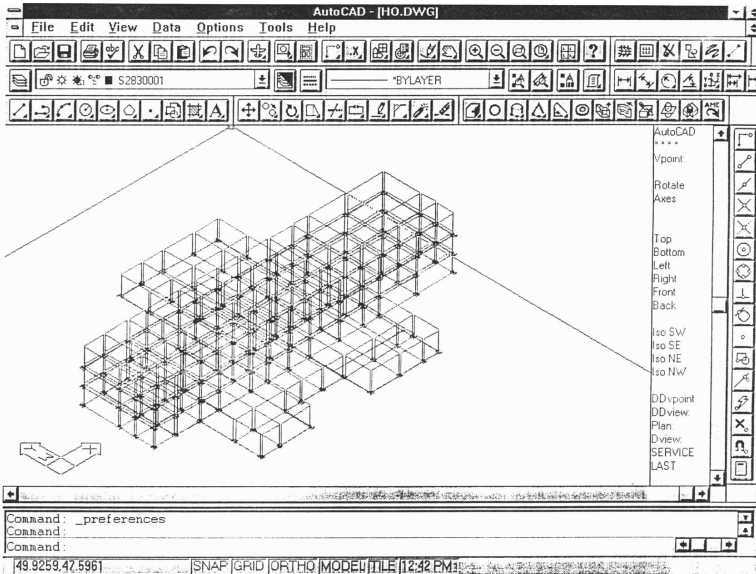


Figure 4. The isometric view of the main structure of a hotel building generated by the system

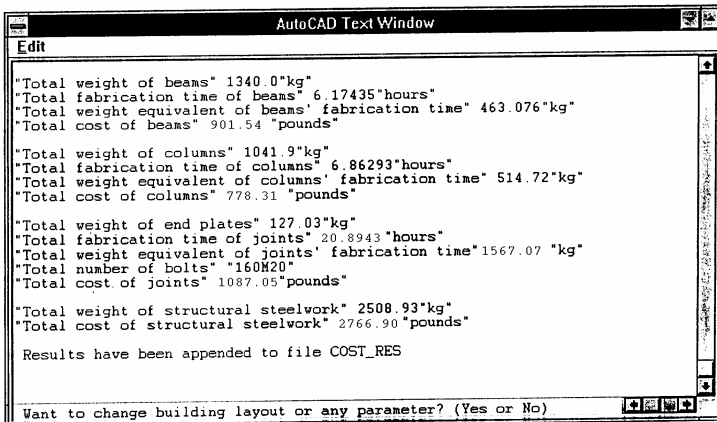


Figure 5. An example of a text screen containing information on the cost of a single structural frame

form by examining the floor plans. The adopted approach is in fact a "holistic" one; the whole building is taken into consideration, the architectural nodes in all floors are copied to a "fictitious" floor, and lists of all coordinates, all blocks, all nodes and all corners are created.

c) STRUCMAN, performs manipulations on the layout based on structural constraints. The structural rules

are applied to the "fictitious" entities to generate "structural nodes" from "architectural nodes". Initially, it requires input by the user specifying minimum and maximum span limits in both x and y directions. The primary aim is to construct new lists of x and y coordinates the difference between elements of which conform to the structural constraints. However, there are a number of additional rules to

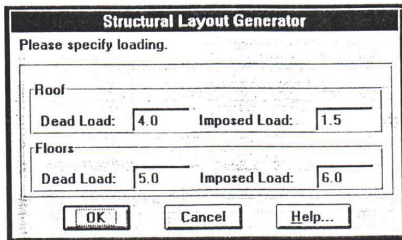
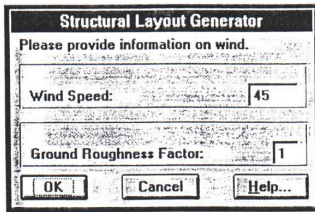
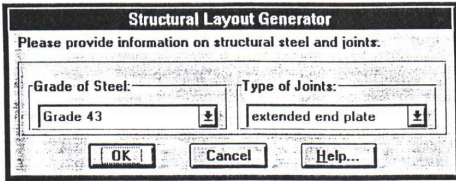


Figure 6. Dialogue boxes relating to steel grade, type of connections, wind, and gravity loading

deal with situations such as creating a canopy or a balcony. The resulting list contains all nodes in the "fictitious" floor to be used by the next function for constructing lists of structural nodes in each floor.

- d) STDRAW, draws gridlines and plans of column sections and beams. The structural nodes that lie within the blocks in each floor are selected. Each floor is checked to ensure that it contains all the nodes in a floor above, otherwise, the missing node is inserted. The structural grids are drawn for floors, and a column section is inserted at the location of each and every node. The layout of columns may be changed interactively by deleting selected columns, and affected lists are updated (a corner column cannot be deleted). Finally, the beams are drawn in two directions between the nodes. The user can proceed

to analysis and design of the building structure, or return to the beginning to make changes in the architectural layout, or redefine the parameters and generate a new structural layout.

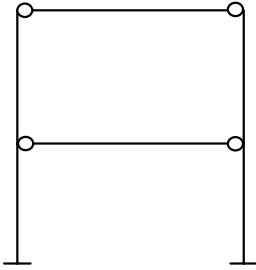
- e) DAGEN, generates data for the structural analysis and design module. Assuming that planar frames lie in the z-y plane, structural gridlines in the x direction represent the centrelines of the frames in plan. Some input by the user is required, including Grade of steel, type of structural joints, information on wind and vertical loading for roof and floors. Default values are provided in all dialogue boxes. Each frame is given a name for which data required for approximate design is generated and stored in a file.

5 Analysis and Design of Structural Frames

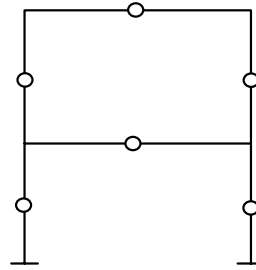
The data produced by Structural Layout Generator (SLG) is used by the initial design program to assign standard structural sections to beams and columns and to design beam-to-column connections. This program employs the "wind-moment" method which is an approximate method useful for initial sizing of structural elements, though the method is widely used for final design of frames.[5]

The method assumes that, (a) under gravity load the connections act as pins, and (b) under wind load the connections behave as rigid joints with points of contraflexure at the mid-height of columns and mid-spans of beams (Fig. 7). The former assumption results in designing beams as simply supported, while the latter leads to assuming hinges at the points of contraflexure, hence rendering structure statically determinate. Therefore, the appropriate types of beam-to-column joints are semi-rigid ones such as end plate connections. The user can select one of flush or extended end plate connections.

The justification of the method has been partly due to the fact that buildings designed on this basis have



(a) Frame under gravity load



(b) Frame under wind load

Figure 7. Assumptions of the wind-moment method

proved satisfactory in use. In recent years, the method has been regarded as a form of semi-rigid design and analytical justification has been carried out on this basis. The Steel Construction Institute has undertaken a study of the method and its applicability to multi-storey semi-rigid steel frames.[5] The study denotes references in which previous studies on the method are summarised, and verifies the use of the method for the scope of its study (i.e. number of storeys between 2 and 8; number of bays between 1 and 4; types of joints: extended and flush end plates). Another study[11] concluded that the method should not be used for frames having more than nine storeys. Therefore, the method must be used restrictively for initial sizing of higher frames.

The initial design routine produces two sets of data files for two analysis programs: one set for elastic analysis and one set for elastic-plastic analysis. These programs[12][13] incorporate some advanced features such as the inclusion of joint behaviour and geometrical non-linearities. The configuration of connections and their behaviour are taken from Annex J of Eurocode 3.[14] The structural analysis requires iterative procedures the rapid convergence of which is vital in an automated design environment. This necessitated some mechanisms to be devised in the programs. After approximate design is complete, the elastic-plastic analysis is first run for obtaining values required for ultimate limit state design. The elastic program is run

when design for ULS is complete in order to obtain values required for serviceability limit state design. The results are stored in separate files, each belonging to a structural frame. A cost estimate of the building structure is then possible using the specification of components produced in the final design.

The three programs explained in this section form the Structural Analysis and Design module (SAD). These programs are executed by executive programs, built by Microsoft Fortran Power Station. The programs manage the dialogue boxes which are designed using the facility provided by the software. The execution of the programs is invoked from AutoLISP *functions*.

6 Checking for Structural Adequacy

The approximate design is sufficiently accurate for the assessment of the structure in respect of the viability of the generated layout and an approximate estimate of the cost of the structure. It enables the architect to judge the floor plans which he/she had set out in the beginning of the process and to consider the effect of subsequent changes in the layout or design parameters.

However, if a more accurate structural design is desired, which is usually the job of the structural engineer, the system provides tools for “rigorous” analysis of structural frames, but the results of analysis require

conformance checking. Conformity checking is a subject in its own right in computer-aided design, and involves compliance with the codes of practice. The values of internal member forces and node displacements should be checked against code requirements such as those for local buckling and lateral torsional buckling, as well as those which limit displacements.

This section is concerned with the assessment of results of structural analysis. The iterative nature of the assessment process necessitated a number of implementation issues to be addressed in order for the programs to operate and communicate in an efficient and seamless manner. A methodology for assessing structural data was set out for ultimate and serviceability limit states.

Three types of information needed be dealt with in ASSESS module which are extracted and arranged into *association lists* as follows (examples show instances of each *entity type*; A denotes frame identification; numbers denote storey level and gridline number):

- a) Information on structural beams, columns and end-plate joints:

```
("BEAM" "A010203") ("Section"
"305x102UB028") ("Length" 5160.0) ("Weight"
144.48))
```

```
("COLUMN" "AB103") ("Section"
"152x152UC023") ("Length" 2850.0) ("Weight"
85.1))
```

```
("JOINT" "A01020303") ("Breadth" 150.0)
("Length" 465.0) ("Thickness" 15.0)
("BoltSize" "M20") ("BoltNo" 8) ("FlangeWeld"
8.0) ("WebWeld" 6.0))
```

- b) Information relating to stability/strength that is produced by the elastic-plastic program:

```
("BEAM" "A030203") ("Axial" 11.645) ("Shear"
19.533) ("Moment1" -24.225)
("MidMoment" 55.445) ("Moment2" -13.550))
```

```
("COLUMN" "AB302") ("Axial" -96.556)
("Shear" -23.611) ("Moment1" -40.212)
("Moment2" -42.425) ("MomentY" 11.517)
```

- c) Information relating to serviceability that is produced by the elastic analysis program. This includes values of horizontal and vertical displacements together with allowable values:

```
("AB5" 7.75 9.5) ("AB4" 6.89 9.5) ("AB3" 8.6
9.5) ("AB2" 7.26 9.5) ("AB1" 10.6 12.3333)
("TotalSway" "A" 41.1 50.3333)
```

The possible approaches and the one adopted by the author for structural adequacy are explained in reference [2]. In brief, the adopted approach is based on comparing the "Demand" values with "Capacity" values. The term "Demand" denotes the actual value of force or moment, and the term "Capacity" denotes the allowable value of force or moment. In this approach, the ratios of Capacity/Demand are found for all members' axial force, shear force and bending moments. Where the resulting ratio is less than unity, the section needs to be replaced by a stronger section. The nearest section whose plastic capacity values are equal to or greater than the Demand values replaces the weak section. On the other hand, where the resulting ratio is considerably greater than unity (> 1.2), the section can be replaced by a weaker section to achieve economy. Alternative approaches are based on the path that the frame follows to arrive at a plastic mechanism.

Where a section is replaced by a stronger section in a loading case, it is not changed again if the original section is found inadequate in another loading case. The change in structural sections necessitates updating association lists and reanalysing frames. The change in beam and column sizes affects the behaviour of beam-to-column connections, therefore, connections need to

be redesigned and their moment-rotation characteristics recalculated in accordance with Annex J of Eurocode 3. New characteristics replace the old ones in the input files. The analysis program is invoked and the results are again subjected to checking for ULS. This procedure continues until no further change is required. The input file for elastic analysis is then replaced with a new file created at the end of the above process.

All members are checked for local capacity and overall buckling, and beams for lateral torsional buckling also, according to BS5950: Pt1. This is done when a frame is reanalysed after a change has been made. This is because similar checks had been made when the approximate design of the frame was carried out. The effective length of beams and columns is taken as their actual length. The buckling resistance of members are calculated using the formulae given in Appendix B of BS5950. The resistance values of shear and axial force and the values of reduced bending moments of members due to the presence of axial load are calculated by the analysis program.

For serviceability, the ratio of midspan deflection to allowable deflection ($\text{span}/360$ for brittle finish according to BS5950: Pt 1) is calculated for each beam. If this ratio is greater than 1.0, the next stronger section size is selected from the standard data files. This is repeated for all beams in all frames and due modifications are made in the association lists and input files for elastic analysis. Where a beam is replaced by a stronger section in a loading case, it is not changed again if the original section is found inadequate in another loading case.

The ratios of interstorey drift to allowable drift ($\text{storey height}/300$ according to BS5950: Pt 1) is then calculated for all storeys for the loading case that includes wind. If a ratio is greater than 1.0, only the end columns in the storey (first and last columns) are replaced by the next stronger column section. This is based on the concept that a multistorey frame acts as a cantilever[15], assuming that it is fixed at the base which is

the assumption made also in the analysis of frames in the proposed system. As a result, if the outermost tension and compression cords are strengthened, the deflection of the cantilever will decrease.

If no change is required in either the beams or columns, the overall sway is checked. The ratio of horizontal displacement at the roof level of each frame to its associated allowable value (total height/300 according to BS5950: Pt 1) is found from the association list. If this ratio is greater than 1.0, the values of interstorey drifts are browsed and the storey with the minimum difference between the actual and allowable sways is selected whose outermost columns are to be replaced by stronger sections.

The frames are re-analysed with the new section sizes and new moment-rotation characteristics resulting from changes in beam and column sections. Although increase in section sizes would result in the section absorbing more bending moments, the frames are not reanalysed for strength. This is justified partly by the plastic theory which implies that the distribution of moments in a conservatively designed frame is such that in no location the moment exceeds the moment capacity of the section.[16]

7 Cost Appraisal

Many of the CAD systems reported so far produce an estimate of the total weight of steel structure only, and do not provide a cost analysis of fabrication of structural members and components. The proposed system calculates the fabrication time for beams, columns and joints separately, in addition to the weight of individual elements and the total weight of the structure. Knowing the fabrication cost per hour, the total cost of steel structure can be calculated. Additionally, the cost of fasteners is included in the total cost.

The calculation of fabrication time developed in the proposed system is based on the information provided

by Gibbons.[1] Gibbons compares the fabrication cost of beam-to-column connections to the cost of connected beams by dividing fabricated beams into “simple”, “moderate” and “complex”. He then gives the fabrication time in hours required for fabricating the main beam and each type of simple, moderate and complex connections separately. The extended and flush end plate connections used in the proposed system are considered as “moderate” according to Gibbons.

A study was made of possible ways of using the above information. Parabolic curves adequately model the relationship between time and beam depth for both beam and joint. The following relationships were developed (in terms of hour and meter):

$$(\text{beam's fabrication time}) = 0.40 + 2.49 (\text{beam depth})^2$$

$$(\text{joints' fabrication time}) = 1.50 + 6.75 (\text{beam depth})^2$$

Gibbons states that one hour of fabrication time is equivalent to 75 kg of steel. He does not specify what grade of steel nor clarify how he relates the labour cost and the material cost. Although it is evident that the relationship between the two costs is not a direct one and will change with time, this simple linear relationship may be used for a rough estimate of the fabrication cost. Thus, the calculated time in hours is multiplied by 75 to find the equivalent weight of the fabrication effort. This weight is multiplied by the cost of the steel material.

The cost calculations are performed by *function* COST. One structural frame is taken at a time. Beams, columns and joints are dealt with separately. Computed values are stored in the database in the form of lists, and the total sum of times, weights and costs are printed on the screen.

At this stage the user is asked whether he/she wants to make any changes in the building layout or parameters. If the response is positive, the user is provided with the

graphical screen of AutoCAD and is asked to open a drawing file (the current drawing is supplied as the default). The results of cost calculations for the new drawing will be appended to the previously created file to facilitate comparison between various designs based on different building layouts or sets of parameters.

8 Examples

Among a number of buildings with various degrees of complexity which were used during the development of the system to test its functionality, two buildings have been selected to demonstrate the system’s performance. The first building is a students residence for which the structural design information and some information on costs were provided by the consultant firm and the quantity surveyors. The second building is another multistorey educational building for which no structural design or cost of the structure was available.

The students residence building

The typical floor plan is given in Fig. 8, and the specifications of structural members produced by the system are tabulated in Tables 1 and 2 for beams and columns respectively. A general comparison between these tables and section sizes given by the consultant confirms the rationality of the structural design by the proposed system.

It is useful to see the cost of the structure as designed by the system. The values of material cost and fabrication cost are given in the following table for beams, columns and joints separately:

	Material cost	Fabrication cost	Total
Beams	£ 11003	£ 3472	£ 14475
Columns	£ 18265	£ 3863	£ 22128
Connections	£ 3760	£ 14502	£ 18262
Total	£ 33028	£ 21837	£ 54865

The costs have been calculated taking the price of Grade 43 steel as £500 per ton, and an 8.8 M20 bolt

Table 1. Beam section sizes generated by the system for the residence building

Frame ID	Roof Beams Bay 1	Roof Beams Bay 2	Floor Beams Bay 1	Floor Beams Bay 2
A	254x102x22 UB	254x102x22 UB	305x102x25 UB	305x102x25 UB
B	254x102x22 UB	254x102x22 UB	356x127x33 UB	406x140x39 UB
C	254x102x22 UB	254x102x22 UB	305x102x28 UB	356x127x33 UB
D	254x102x22 UB	254x102x22 UB	305x102x28 UB	356x127x33 UB
E	254x102x22 UB	254x102x22 UB	356x127x33 UB	406x140x39 UB
F	254x102x22 UB	254x102x22 UB	356x127x33 UB	406x140x39 UB
G	254x102x22 UB	254x102x22 UB	356x127x33 UB	406x140x39 UB
H	254x102x22 UB	254x102x22 UB	305x102x28 UB	356x127x33 UB
I	254x102x22 UB	254x102x22 UB	305x102x28 UB	356x127x33 UB
J	254x102x22 UB	254x102x22 UB	356x127x33 UB	406x140x39 UB
K	254x102x22 UB	254x102x22 UB	305x102x25 UB	305x102x25 UB

Table 2. Column section sizes generated by the system for the residence building (all sections UC)

Frame ID	Storey 1 External	Storey 1 Internal	Storeys 2&3 External	Storeys 2&3 Internal	Storeys 4&5 External	Storeys 4&5 Internal	Storeys 6&7 External	Storeys 6&7 Internal
A	152x30	152x37	152x23	152x30	152x23	152x23	-	-
B	203x60	254x73	203x46	203x60	152x37	203x46	152x23	152x30
C	203x46	203x60	152x37	203x46	152x30	152x37	152x23	152x23
D	203x46	203x60	152x37	203x46	152x30	152x37	152x23	152x23
E	203x60	254x73	203x46	203x60	152x37	203x46	152x23	152x30
F	203x60	254x73	203x46	203x60	152x37	203x46	152x23	152x30
G	203x60	254x73	203x46	203x60	152x37	203x46	152x23	152x30
H	203x46	203x71	203x46	203x52	152x30	152x37	152x23	152x23
I	203x52	254x73	203x46	203x52	152x30	203x46	152x23	152x23
J	203x60	254x89	203x46	203x71	152x37	203x46	152x23	152x30
K	203x46	203x71	203x46	203x52	152x30	152x37	152x23	152x23

as £1.50 (greater bolt sizes 15% added to the smaller size). The total values of material and fabrication cost are also given. These generally show that the method used for costing the structure is justifiable and the results are acceptable particularly when the conceptual design stage is concerned. The total fabrication cost is about 40% of the total cost of the structure.

It is useful to note that the cost of connections is often overlooked. Although their material cost is small compared to main members, their fabrication is very costly. Based on the assumptions made, the cost of connections amount to about one-third of the total cost of a steel structure.

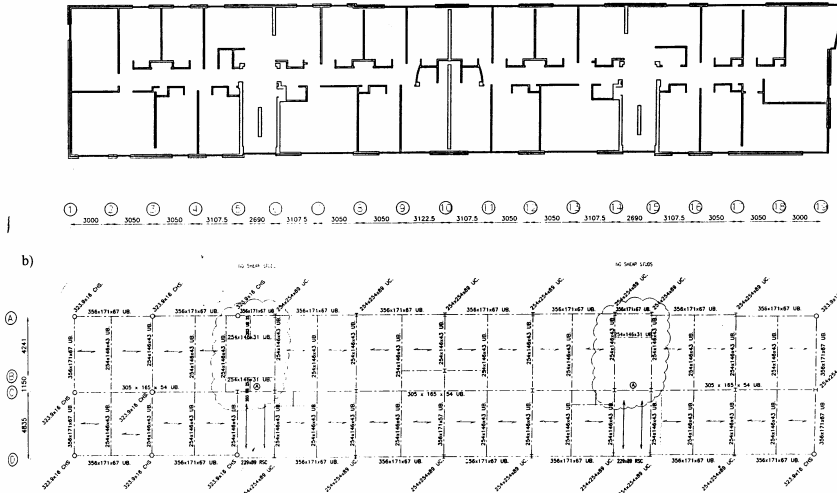


Figure 8. The typical floor plan and structural layout of the student residence

In the design by the consultant, a light roof was assumed with dead and live loads taken as 0.75 and 0.6 kN/m² respectively. The dead and live loads were taken as 3.0 and 2.5 kN/m² respectively for floors which are appropriate for a students residence. However, a heavier roof and greater values of dead and live loads can be assumed in order to observe the impact of loading on the sizing of structural sections. The following have been used in the new design:

Roof dead load	4.0 kN/m ²
Roof live load	1.5 kN/m ²
Floors dead load	5.0 kN/m ²
Floors live load	6.0 kN/m ²

The comparison between the sizes of structural sections shows considerable increase in the section sizes. This results in a total cost of £67751 compared to the previous total cost of £54937 showing an increase in cost of approximately 25%.

The educational building

The only information available on this school building was a sketch drawing of its typical plan, containing the functional spaces as given in Fig. 9(a). The following assumptions have been made in generating the structural layout of the school building:

1. minimum span limit in the X direction 5.0m
2. maximum span limit in the X direction 8.0m
3. minimum span limit in the Y direction 4.0m
4. maximum span limit in the Y direction 8.0m

The beams and columns layout is given in Fig. 9(b). The building's architectural layout has an overall irregular form and includes too many corners on its perimeter in contrast to the students residence that had a regular rectilinear layout. However, it is seen from the figures that the structural layout has been generated in a harmonious manner that appropriately spans the spaces within the building. The structural layout efficiently distributes the floor loadings to the columns. The generation of drawing entities by the system which are required for technical drawings is also significant.

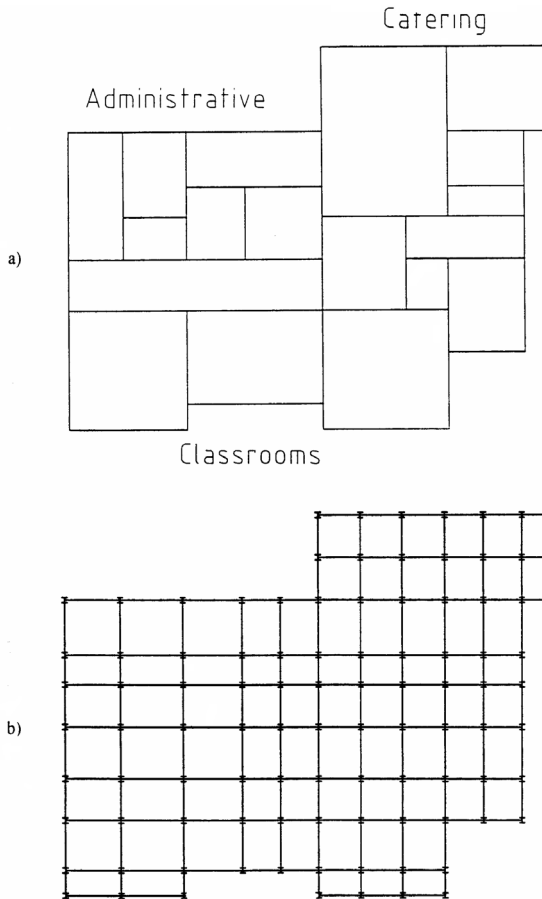


Figure 9. (a) Typical floor plan of the educational building and (b) layout of structural members

9 Concluding Remarks

The proposed system described in this paper is an attempt to integrate various design stages into a continuous design process involving interactive communication between the designer and the computer, and interplay of information among different activities within the system.

The system enables architects to prepare the sketch design of the arrangement of spaces within a building, generate the structural layout for this arrangement, perform an approximate design of the building structure, and make a cost estimate of the structural steel-

work which includes both material and fabrication costs. The architect is able to change the initial architectural layout or the consequent structural layout, as well as the parameters assumed during the design process, in order to compare the results and make a decision to proceed to the subsequent stages of the design. The following are instances of interacting with the system:

- a) Change in the architectural layout by deleting or adding spatial blocks; this feature shows the flexibility of the system as regards to the creativity of the architect. The graphical user interface is available through the process as a drawing canvas for the

architect to enable changes in the layout plans. The spatial synthesis requires altering the grouping of spaces and their accessibility and examining the impacts of these alterations on the structural arrangement of the building.

- b) Change in the span limits; in fact, an infinite number of combinations of span limits in X and Y direction may be assumed in a design. The generated arrangement can be put to the system for structural analysis and design to observe the impact that such decisions would make on the structure of the building. The associated cost can also be calculated and compared to previous structural arrangements.
- c) Interactive deletion of columns that results in the beams having to cover larger spans that in turn will result in larger beam sizes primarily for these beams, and secondarily for the others. This is because larger moments are transferred to the columns that in some cases are added to those of the beams. Additionally, larger column sizes will be required for some columns as their loading area is larger than previously. Once the structure is designed by the system, the costs of the previously designed structure and the current structure can be compared. Such a comparison of the costs involved would help the architect or engineer to make rational decisions.

The proposed system enables structural engineers to work on a given architectural layout, generate the structural layout for the given plans, perform an approximate structural design, use the results of this design for the initial sizing of structural members to be used in "rigorous" analysis of building frames, subject the analysis results to conformance checking, and make an estimate of the cost of the structure. Returns to previous steps to make changes are possible, and the results can be compared in order to make decisions on the building structure. When the structural concept is decided, either by the approximate design or the more accurate design, the engineer can proceed to the pre-

liminary or detailed stages of the design of the structure.

The main aim in developing the proposed system has been to provide designers with an intelligent assistant realised within an environment that integrates and automates design activities. The processes of generating the structural layout and checking for structural adequacy make use of intelligence techniques. The integration that is achieved is multi-faceted: integration of the computer into the design process, integration across disciplines, integration within disciplines, integration of activities and stages of design, and potential integration of practice and education.

In addition, the system can be used as a computer-aided learning tool for students of architecture so that they examine the effects of the decisions they make at the initial stages of design on the structure of the building. They can observe how the architectural design of a building may be influenced by its structural arrangement. They also acquire a general understanding of the process of structural design and the use of structural steelwork in buildings.

The above capability is equally applicable to students of structural engineering. An explanatory facility will make this system much more useful for the purpose of teaching structural design as it renders the system a self-learning tool.

An important feature of the system is that each of its modules may be run independently of the others, and the user may enter and exit the system in any stage at will. Each program has been verified independently and the whole system has been tested on buildings with varying degrees of complexity. However, the system is limited to regular rectilinear multistorey buildings. Future development of the system may include modifications to the system as a whole, e.g. using SQL for database management, or to the individual parts of the system, e. g. adding more constraints for generation of structural layouts and devising a more sophisticated

method for cost estimation. On the other hand, the system may be used as a platform for developing a large integrated system including, for instance, environmental design or fire safety engineering.

There are a number of limitations to the system, including:

1. The overall form of the building and the functional spaces must be rectilinear.
2. The geometry of the building must be so that rectilinear structural frames with regular intersections are resulted; a space cannot have a ceiling higher or lower than other spaces in the floor.
3. The structural system consists of an unbraced frame in one direction, and a braced frame in the other direction. The bracing is not designed in the present state of the system.
4. The structural beams and columns are designed as bare steel members, therefore the system cannot deal with composite construction.
5. Where approximate design is used without a "rigorous" analysis, the structural frame should conform to limitations stated in Reference [5], e.g. the frame must not exceed nine storeys.
6. The cost estimate is approximate and takes account of material and fabrication costs, but does not include other costs such as the costs of design and erection of steel structures.

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- REFERENCES |
- [1] Gibbons C., "Economic steelwork design", *The Structural Engineer*, Vol. 73, No. 15, 1995, pp. 250-3
 - [2] Najafi A. A., "An Integrated Generative System for Architectural and Structural design", PhD Thesis, University of Strathclyde, UK, 1997
 - [3] The Proceedings of the 2nd International Conference on Concurrent Engineering in Construction, 25-27 August 1999, Espoo, Finland
 - [4] The Proceedings of Construction Information Technology 2000, 28-30 June 2000, Reykjavik, Iceland
 - [5] Anderson D., Reading S. J., Kavianpour K., "Wind-Moment Design for Unbraced Frames", The Steel Construction Institute, Publication No. 082, 1991
 - [6] BS 5950: Pt 1, "Structural use of steelwork in building, Part 1: Code of practice for design in simple and continuous construction", British Standards Institution, 1990
 - [7] Daniell J. & Director S.W., "An object oriented approach to cad tool control within a design framework", Technical Report, Engineering Design Research Center, CMU, Pittsburgh, PA, USA, 1989
 - [8] Vidovic N., Siewiorek D. P., Vrsalovic D. F., Segall Z., "Towards a consistent view of the design tools and process in distributed problem solving environment", Technical Report, Engineering Design Research Center, CMU, Pittsburgh, PA, USA, 1990
 - [9] BS 1192: Pt 5, "Construction drawing practice, Part 5: Guide for structuring of computer graphic information, British Standards Institution, 1990
 - [10] "CI/SfB Construction indexing manual", Abridged reprint of the 1976 edition, SfB Agency UK, RIBA Publications, 1991
 - [11] Ackroyd M., "Design of flexibly connected unbraced steel building frames", *Journal of Constructional Steel Research*, Vol. 8, 1987, pp. 261-286
 - [12] Benterkia Z., "End-Plate Connections and analysis of Semi-Rigid Steel Frames", PhD Thesis, University of Warwick, UK, 1991
 - [13] Kavianpour K., "Design and analysis of unbraced steel frames", PhD Thesis, University of Warwick, UK, 1990

- [14] Eurocode 3, "Design of steel structures, Part 1: General rules and rules for buildings", Commission of the European Communities, 1997
- [15] Fuyama H., Law K. H., Krawinkler H., "An Interactive Computer Assisted System for Conceptual Structural Design of Steel Buildings", *Computers & Structures*, Vol. 63, No. 4, 1997, pp. 647-62
- [16] Horne M. R., Morris L. J., "Plastic Design of Low Rise Frames", Granada Publishing Ltd, London, 1981