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Interactive Limit States Design of Steel Frames

Calcul interactif, à l'état limite, de cadres métalliques

Interaktive Bruchbemessung von Stahlrahmen

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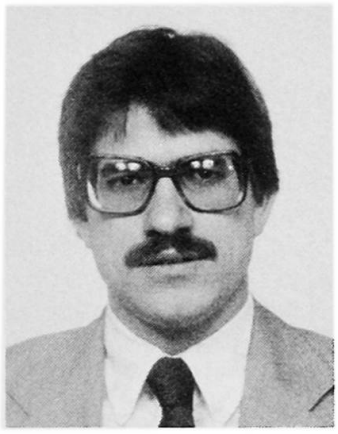

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SUMMARY
A computer-aided approach for the interactive limit-states design of steel frames is presented. A flexible scheme permits the engineer to define the design equations interactively. Both first- and second-order elastic analyses can be employed to predict the response of the structure to the applied loads.

RESUME
Une méthode de traitement assisté sur ordinateur pour la conception et l'analyse de structures en acier est présentée, pour les états limites. La méthode permet à l'ingénieur de définir les équations de manière interactive. L'analyse des forces élastiques du premier et du deuxième ordre peut être utilisée afin de prédire le comportement d'une structure à la charge qui lui est appliquée.

ZUSAMMENFASSUNG
Eine interaktive, computerunterstützte Methode für die Bruchbemessung von Stahlrahmenkonstruktionen unter extremen Bedingungen wird aufgezeigt. Ein anpassungsfähiges Schema erlaubt es dem Ingenieur, die Entwurfskriterien für gegebene Anforderungen zu bestimmen. Elastische Analysen sowohl erster als auch zweiter Ordnung werden angewendet, um die Reaktion der Konstruktion auf die Belastungen vorauszusagen.

1. INTRODUCTION

The authors and their colleagues have developed an interactive computer aided design system for three dimensional steel frame structures [References 1-4]. The system accommodates design by either a limit states, code related approach [Ref. 5], or through code independent methods that involve the use of geometric and material nonlinear analysis. In this paper the code based method is discussed. The assumptions and limitations are listed, some of the novel features of the system are described, and an illustrative example is presented. The use of full nonlinear analysis is also illustrated in the example.

2. FEATURES, ASSUMPTIONS, LIMITATIONS

In a typical problem, the structure geometry, boundary conditions, trial member sizes, and loads are first specified in the problem definition module -- an interactive graphics "preprocessor" [Ref. 2]. The load combinations for the limit states under consideration are then defined, the type of analysis to be used is selected, and the analysis is performed. The computer then evaluates the trial design by applying the relevant code equations to each member. Graphical displays aid in interpreting the results and the behavior of the structure. Successive iterations of re-design and analysis can be performed either automatically or under the direct, interactive control of the engineer until a system with well balanced strength properties is obtained. An additional feature, which is described in References 1 & 4 but not discussed here, is an optimality criterion based procedure for satisfying displacement limits.

In the present state of the development of the system all members are assumed to be compact, lateral buckling is prevented, and all connections are rigid. Work is in progress to remove these limitations.

3. STRENGTH DESIGN PROCEDURES

Figure 1 is a flow chart of the code related procedure for meeting strength requirements. The design algorithm can be summarized as follows: 1) An initial set of member sizes (a "design vector") is selected based on experience or rough preliminary calculations. 2) All the design rules from the applicable specification are defined as design equations. 3) For a single load combination, the structure is analyzed to obtain internal member forces and joint displacements. 4) The response of the structure to this load combination is evaluated. If the response is not satisfactory a new design is generated, either automatically or interactively. In the former case the program selects the lightest members that satisfy the controlling design equations. In the other option, the user selects the members. The results of the new design are stored in the "next design vector" as described in Section 3.1 below. 5) Steps 3 and 4 are repeated for each load combination. A design is considered feasible when for all possible load combinations the structural specifications are not violated. The ultimate goal is to find for each group of members an acceptable section with the least possible weight. After the last load combination is considered, a new design iteration is begun only if changes have occurred in the design vector since the previous iteration.

The design procedure is not a fully automatic one. At all times the engineer has control over the path to be followed. He can exit the loop at any time to modify the structure or to change any of the parameters that control the design and analysis routines.

In the following subsections each of the major components of the method are described.

3.1 Design Vectors

The term "design vector" is used to describe the list of member sizes employed at any stage of the process. It is the vector that is progressively refined from the initial to the final design. In the manual, i.e., interactive option, a member is selected or changed by pointing to an item on a displayed list of conventional designations (W18x40, W36x300, etc.) and then pointing to the member on a line diagram of the frame. The properties of that section, which are in the system database, are assigned to that member by the program.

At any stage of the process, three design vectors are stored: the "previous", "current", and "next" vectors. The current vector lists the members whose properties are being used at the current stage of the program in all calculations. The new trial design suggested by the computer or interactively by the user is stored as the next vector. This multiple, progressively updated, record enables the designer to recover a design if a subsequent review of the new trial design produces less satisfactory results than the current one.

3.2 Design Equations

One aim is to make these design tools applicable to a wide range of structural design codes. This is a difficult task since at present there is no uniform format for codes. It is for this reason that the scope of the elastic analysis based procedures has been limited to codes employing the limit states design philosophy. The format of the design equations in this type of code can be given rather generally as:

$$\frac{\text{calculated load effect at factored loads, } (S_i)}{\text{estimated resistance to factored load effect, } (R_i)} \leq 1 \qquad (1)$$

To achieve a degree of code independence the design procedure has been implemented in the following way: 1) The user is afforded full control over the specification of load and resistance factors. 2) In cases in which different codes specify different formulas for the calculation of resistance to a given load effect, for example, to direct compression, several commonly used formulas are included in the program to give the designer a choice. 3) To accommodate the use of interaction equations commonly found in codes, the scheme described below has been used to define design equations that combine different load effects.

It is possible to define equations of the following type:

$$g = \sum_{i=1}^{7} \delta_i C_i \left(\frac{S_i}{R_i}\right)^{e_i} \leq \bar{g} \qquad (2)$$

in which δ_i is 1 or 0 depending on whether the i^{th} load effect is active or inactive, C_i is a coefficient, e_i is an exponent, g is a function of the load effects and member resistance, and $\bar{g}$ is the limit imposed on the design equation (usually unity). In cases in which a structural member is subjected to two or more load effects that cause direct stresses in the same direction, structural specifications prescribe so-called "interaction equations" for design. This type of equation can be defined by activating the corresponding load effects in eqn. 2 [1]. However, to accommodate the definition of interaction equations that consider the stability of individual members it is necessary to modify eqn. 2 since the bending terms in such equations need to include

both an amplification factor and an equivalent moment factor.

Figure 2 shows the menu page used for the interactive definition of the design equations. The equation displayed is an interaction equation for compression and bending. The load effects that are active are indicated by a double line box. This and the design equations to be considered in the subsequent examples are taken from Ref. [5].

3.3 Load Combinations

To verify a limit state it is generally necessary to check the adequacy of the structure for more than one load combination. The load combinations to be considered in the example to follow are those given in Ref. [5].

3.4 Analysis

The object of the analysis is to calculate the internal member forces and moments due to the applied loads. The applied loads can be either the specified service loads or factored loads, depending on the limit state under consideration. Most modern specification contain provisions for the use of first- or second-order analysis to estimate the response of the structure. The difference in the application of specification clauses in these two cases is often restricted to the consideration of stability effects. For example, if the second-order effects are taken into account directly in the analysis, the Canadian Limit States Design Specification allows the use of effective length factors and uniform bending coefficients calculated on the assumption that sideway is prevented.

Conventional stiffness method procedures are employed to calulate member forces when a first-order elastic analysis is requested. To solve for the structural response for the second and subsequent load combinations, advantage is taken of the already decomposed structure stiffness matrix from the first load combination.

The column effective length factors required when the design is based on first-order elastic analysis are computed by performing a separate elastic critical load analysis of planar bents in the structure. The reference loads used in the elastic critical load analysis of the example to be presented correspond to specified gravity loads. The effective length factors are calculated from the member axial loads at the elastic critical load [1].

For second-order analysis either iterative or incremental procedures can be employed to solve the finite element equilibrium equation. The iterative procedures provide a more accurate approach to equilibrium at the expense of computational effort. Although the incremental procedures are approximate, it has been found that for steel frames of regular geometry and loading, results accurate for design can be obtained even if steps of 10 to 20% of the applied loads are specified. Unless otherwise specified, the incremental predictor-corrector method [3] will be used in all subsequent analyses which consider elastic second-order effects.

3.5 Design Evaluation

There are two basic ways to evaluate a design. One is based on the overall behavior of the structure and the other concentrates on the performance of individual members. Several tools have been implemented which, in combination with engineering judgment, enable the designer to decide when a trial design is adequate.

To aid in the evaluation of a design based on overall behavior, the tools implemented include the display of the deflected shape of the structure, force and

and moment diagrams, and plots of the total or story lateral drift.

The performance of individual members is evaluated through the design equations. The objective is to identify those members that are either over- or under-designed. The graphical technique use for this purpose identifies those members for which the left hand side of the design equations give values between two limits specified by the designer. Figure 3 shows an image displayed for this purpose. The information in the upper right of the figure shows that the maximum value for the left hand side of the equation under consideration is 1.195. In this illustration the designer is looking for those members for which the design equation is violated, i.e., those members for which the value of the left hand side of the design equation is greater than 1.0. As an aid to detecting such conditions, the members which possess values in this – or any other – specified range are shown in dashed lines on the displayed image of the frame.

3.6 Re-Design

If the design evaluation process indicates that only a few members require modification it is probably best to select new trial sections based on judgment. The selection of new sections can then be performed interactively by replacing the current section by another of the 210 standard sections in the database. When a substantial number of members requires modification, the use of this "manual" approach becomes impractical and the automatic procedure is indicated.

The automatic re-design procedure suggests to the designer a new design vector for which the design equations are satisfied. The term "suggest" is used because the designer can modify the selected sections if a suggested section is impractical or if it violates functional requirements, such as a rule that the column depth at a given level not be greater than the depth of the columns at lower levels. A search procedure has been implemented to select from the the available sections the one that meets the design equations and any user specified depth limit [1]. When the designer is satisfied with the new trial list of sections, the vectors are updated.

4. EXAMPLE

The fictitious nonsymmetric three-dimensional frame shown in Fig. 4 has been selected to demonstrate the application of the strength design procedure. A plan view of the structure, its material properties, and the specified service loads are shown in Fig. 4b. The bents spanning in the E-W direction are identified by a letter, while those spanning in the N-S direction are identified by a number.

The structure is designed for three possible load combinations, gravity loads acting alone and gravity loads plus the full wind load acting in either the West-East or the South-North directions.

In this example live load reduction provisions are not explicitly considered. To compensate for this, the live load specified in Fig. 4b is less than the value one would normally specify for a structure of this type. In addition, placement of the live load in the most unfavorable locations (pattern loading) for individual members has not been considered.

Two alternative designs are obtained for the structure. The first, Design I, is based on the use of three dimensional second-order elastic analysis. The second design, Design II, is obtained by using three dimensional first-order elastic analysis and sidesway based effective length factors to compensate for the neglected second-order effects.

The design equations used in this example are those specified in the Canadian Limits States Design Specification. The load factors and the load combinations

considered are also taken from Ref. [5]. Following conventional practice, the members in the structure are grouped to satisfy certain symmetry and functional requirements. The most critical member in a group governs the design of all the members in that group. A total of 64 members groups is used. Member groups 1-34 are beams, and the remainder are columns. Details of the grouping arrangement can be found in Ref. [1]. For the initial trial design, all columns were arbitrarily defined as W14x90 and the beams as W18x50. An upper limit of 61.0 cm is specified for the beams depths, while a maximum depth of 35.6 cm is prescribed for the columns. In both cases a minimum depth of 15.2 cm is designated. The distance between floors is 3.65 m.

The final sections obtained by the two design procedures are given in Table 1. By considering the second-order effects directly in the analysis, one attains a steel frame weight about 6% less than that obtained with the conventional elastic design procedure.

A comparison of the two designs shows that the beam sections in Design I are generally heavier than their counterparts in Design II. This is due to the consideration of second-order moments in the first design. The column sections, however, are generally smaller in Design I because inclusion of the second-order moments in their design does not completely offset the reduction in columns sizes achieved by assuming effective length factors of unity. The ratio of total beam weight in Design I to that of Design II is 1.08, and the analogous ratio for columns is 0.80.

As an extension to this example and an illustration of the capabilities of this system for full nonlinear (geometric and material) analysis Designs I and II have been analyzed to collapse for each of the load combinations considered. A full report of the results can be found in Reference [1]. In summary, all the collapse load factors computed exceed the minimum required. For instance, the collapse load factors for the most critical combined load case (wind + gravity) are 1.51 and 1.59 for Designs I and II, respectively.

5. SUMMARY

This paper has presented an approach to the interactive limit states design of steel frames. Computerized design aids are provided that enable an engineer to systematically and efficiently go through the iterative process typical of structural design. At all times the engineer has the option to override the suggestions made by the computer. The application of these tools to the design of one three-dimensional structure shows a 6% saving of steel through consideration of second order effects in the analysis.

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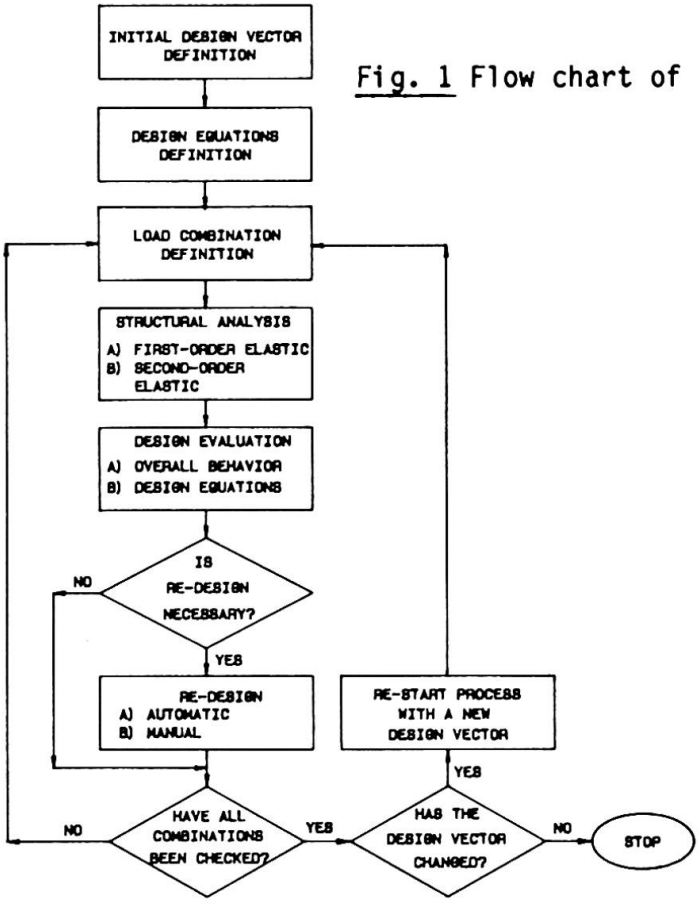

Fig. 1 Flow chart of design procedures.

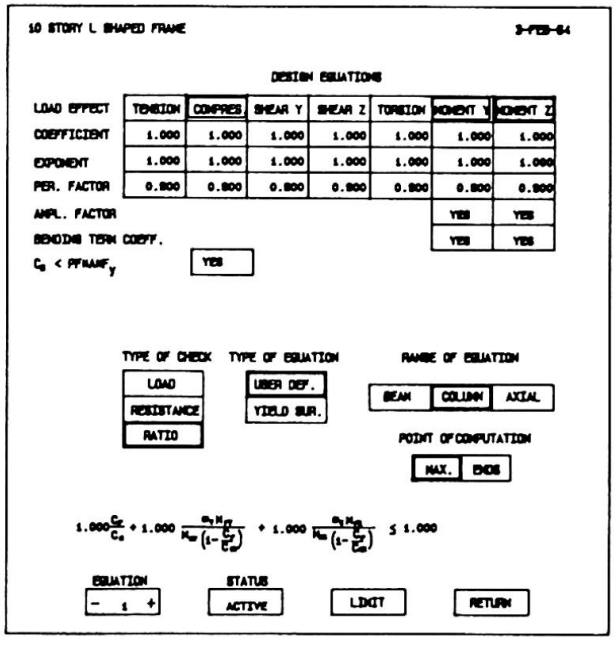

Fig. 2 Definition of design equations.

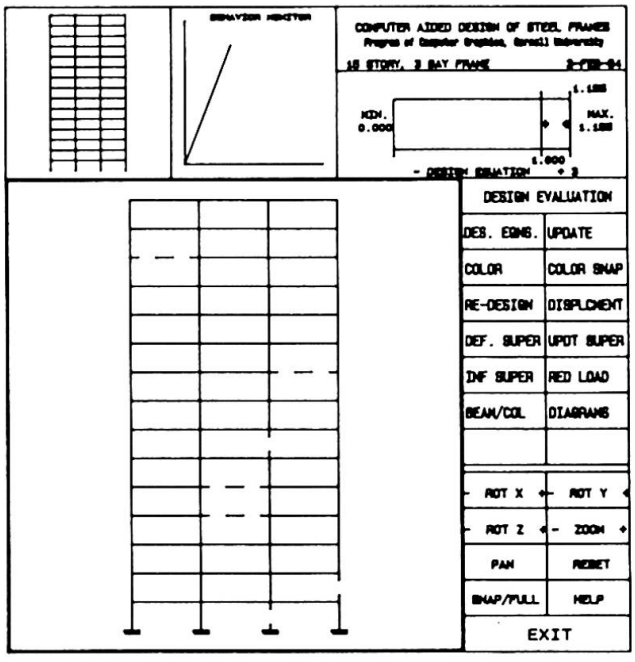

Fig. 3 Identification of overstressed members.

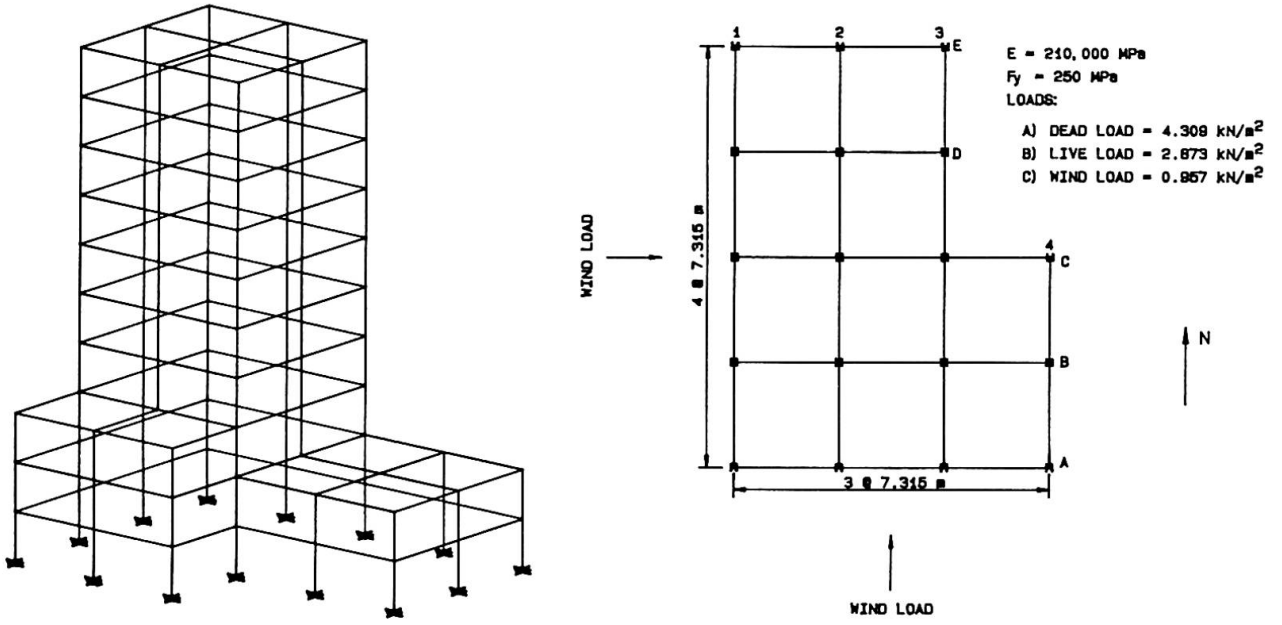

Fig. 4 a) Simplified isometric view of example structure, b) Dimension, material properties, and specified loads.

DESIGN I				DESIGN II			
1	W16X 26	33	W14X 22	1	W14X 22	33	W12X 22
2	W16X 26	34	W12X 22	2	W16X 26	34	W12X 22
3	W16X 26	35	W12X 72	3	W14X 22	35	W14X 90
4	W14X 22	36	W14X 109	4	W12X 22	36	W14X 132
5	W12X 22	37	W8 X 24	5	W12X 19	37	W10X 33
6	W18X 40	38	W12X 65	6	W18X 40	38	W12X 87
7	W21X 44	39	W12X 87	7	W18X 40	39	W14X 109
8	W18X 40	40	W14X 43	8	W18X 40	40	W12X 53
9	W18X 35	41	W14X 43	9	W18X 35	41	W12X 53
10	W16X 31	42	W12X 72	10	W14X 30	42	W14X 90
11	W18X 35	43	W10X 39	11	W18X 35	43	W10X 49
12	W16X 26	44	W10X 49	12	W16X 26	44	W12X 72
13	W16X 26	45	W12X 40	13	W14X 22	45	W10X 49
14	W14X 22	46	W8 X 35	14	W12X 22	46	W10X 49
15	W12X 22	47	W14X 109	15	W12X 19	47	W14X 132
16	W14X 30	48	W14X 176	16	W14X 30	48	W14X 211
17	W12X 22	49	W10X 39	17	W12X 19	49	W14X 48
18	W16X 26	50	W12X 79	18	W16X 26	50	W14X 90
19	W16X 26	51	W14X 145	19	W16X 26	51	W14X 176
20	W16X 26	52	W14X 38	20	W12X 26	52	W14X 48
21	W14X 22	53	W12X 72	21	W12X 22	53	W14X 90
22	W12X 22	54	W14X 109	22	W12X 19	54	W14X 145
23	W21X 50	55	W10X 49	23	W18X 40	55	W12X 58
24	W21X 50	56	W12X 79	24	W21X 44	56	W14X 90
25	W21X 44	57	W10X 33	25	W18X 40	57	W12X 40
26	W18X 40	58	W12X 45	26	W18X 35	58	W8 X 48
27	W18X 35	59	W12X 26	27	W16X 31	59	W10X 39
28	W18X 40	60	W10X 49	28	W18X 35	60	W12X 65
29	W18X 40	61	W12X 53	29	W18X 35	61	W12X 65
30	W16X 26	62	W8 X 40	30	W12X 26	62	W10X 49
31	W14X 22	63	W10X 49	31	W12X 22	63	W12X 65
32	W12X 22	64	W8 X 48	32	W12X 19	64	W12X 65
89900 kg				95345 kg			

Table 1 Final sections and total weight obtained by Design I and Design II.