OPTIMIZATION-BASED COMPUTER-AIDED DESIGN OF EARTHQUAKE RESISTANT STEEL STRUCTURES

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SUMMARY

This paper describes steps and options available for casting a practical design problem into a mathematical format for the optimization-based, computer-aided design of earthquake resistant steel structures. A critical review of the present DELIGHT.STRUCT system is made, and identification of its favorable attributes and shortcomings is given. Finally, a summary of current and anticipated development at the University of California, Berkeley is presented.

INTRODUCTION

Optimization-based computer-aided structural design may be viewed as a two-stage process. First, a designer has to deal with the conceptual task of recasting a structural design problem into a mathematical formulation that captures its practical nature. A suitable solution procedure is then employed to solve the optimization problem.

While wide attention has been given to the latter stage, less effort has been expended in the area of problem formulation. Thus, the purpose of this paper is to review the mathematical formulation procedure utilized in DELIGHT.STRUCT(Refs. 3,7,8) and its predecessors(Refs. 4,5,6) for the aseismic design of planar steel frames. Experience gained to date has been via investigations of the seismic behavior of moment-resistant (elastic, localized nonlinearities and general nonlinear), base isolated, and friction-braced frames(Refs. 4,5,6,7,8).

BACKGROUND TO DELIGHT AND DELIGHT.STRUCT

DELIGHT is an interactive computer system that was developed to provide engineers from various disciplines with a working environment in which optimization techniques could be applied to engineering design. Its extensive capabilities are outlined in reference 1. DELIGHT.STRUCT is a union of the DELIGHT system and an optimal structural design package called STRUCT. It is capable of dealing with statically and dynamically loaded structures whose response may be linear or nonlinear(Ref. 3).

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DESIGN PHILOSOPHY AND METHOD

Currently accepted seismic design philosophy has been well documented(Ref. 2). The limit states design method is particularly amenable to the methodology of an automated design system because it forces the designer to start by identifying all the ways in which a structure may fail to fulfill its intended purpose. Determination of acceptable levels of safety against violation of each limit state is then estimated before a designer proceeds to work through a design in a step-by-step manner until all the aforementioned requirements have been satisfied.

Optimization-based design requires the extra step of recasting the limit states and design objectives into a mathematical statement. By allowing the computer to take care of the subsequent calculations, the designer should be freed to concentrate on the more creative aspects of the design problem. Hence, for example, during convergence to a satisfactory solution, the designer may either interactively complement these calculations with his/her intuitive knowledge or allow automatic information feedback via the optimization algorithm. A balance in use of these two options will in practice be most efficient in leading to a good design.

FORMULATION OF THE OPTIMIZATION PROBLEM

Once a designer has a clear understanding of the design problem he or she can proceed to list mathematical statements for the design objectives and constraints. An optimization algorithm is then specified to solve the mathematical design problem. During the optimization process, the algorithm will call on a simulator to evaluate the cost function and constraint performances. The following sections briefly describe these stages when the process is applied to the aseismic design of steel frames.

Limit States.

Constraints are divided into three general classes of limit states: serviceability, damageability and ultimate strength. Recommendations from the Uniform Building Code(Ref. 10) have been used to set the constraint boundaries so that final designs contain an acceptable level of safety.

Serviceability.

This limit state corresponds to the frame's response to dead and live service loading. In summary:

$|$ column end moments $|$ < 0.6 * column yield moments.
$|$ column axial force $|$ < 0.5 * axial yield or buckling force.
$|$ girder end moments $|$ < 0.6 * girder yield moments.
$|$ girder midspan deflection under live load $|$ < [1/240] * span.
$|$ brace force $|$ < 0.5 * brace yield or buckling force.

Damageability.

This limit state is associated with the frame's response to combined dead plus live gravity loads in addition to a scaled earthquake ground motion of intensity equivalent to that expected to occur several times during the structure's lifetime. Damage is defined as element yielding. The functional constraints on element response are:

max over time ¦ column end moments ¦ < column yield moments.
max over time ¦ girder end moments ¦ < girder yield moments.
max over time ¦ shear element force ¦ < shear yield force.
max over time ¦ dissipator force ¦ < dissipator yield force.
max over time ¦ brace force ¦ < brace yield or buckling force.

Moreover, non-structural damage should be limited. As this will be related to interstory drifts and floor accelerations, the following two functional constraints are also enforced.

max over time ¦ absolute floor accel ¦ < 0.5 * gravity accel.
max over time ¦ story drift ¦ < 1/200.

Ultimate Strength.

The design philosophy adopted accepts major structural damage possibly beyond repair in the event of a severe earthquake. Collapse is nevertheless prohibited. Large displacements at the top of the frame are used as a measure of the possibility of collapse. Thus, "Sway", defined as the maximum relative horizontal displacement at the top of the frame divided by the frame height, is limited as follows:

max over time ¦ frame sway ¦ < Sway.

This parameter has been set to 0.01. Structural damage will also be closely related to the amount of inelastic deformation. A single cycle at a high ductility range may cause damage equivalent to that of many cycles at a lower ductility range. The following constraint on inelastic energy dissipation under monotonic loading has been adopted(Ref. 7):

Ed < Ey * [mu -1] * [1-S] * [2 + S*[mu - 1]]

where Ed = inelastic dissipated energy, Ey = elastic strain energy at yield, mu = allowable ductility factor and S = strain hardening ratio. The beam and column ductility factors have been set to 6 and 3, respectively, and the strain hardening ratio has been assumed to be 0.05.

Objective Functions.

The objective function has been considered to be the weighted sum of the following terms reflecting performance and cost:

1 Volume of structural elements.
2 Moderate earthquake : Sum of squares of minimum story drifts.
3 Severe earthquake : Input energy at frame base.
4 Severe earthquake : Inelastically dissipated energy.
5 Severe earthquake : Energy dissipated by the columns.

Algorithms.

The DELIGHT environment supports optimization algorithms capable of solving linear and nonlinear constrained and unconstrained problems. The main objections in using unconstrained methods for engineering and related problems are well outlined in Nye(Ref. 1). Consequently, the combined Phase I - Phase II method of feasible directions due to Polak et al.(Ref. 11) has recently been used. Although this algorithm may only be expected to converge linearly to a local minimum, it does guarantee an improved design with each iteration. A further strength lies in its ability to accommodate conventional (time independent) functional (time dependent) and box (restrictions on the maximum and minimum allowable section sizes) constraints.

Constraint Evaluation.

The ANSR(Ref. 12) structural simulator has been used to supply response values to software routines for constraint evaluation. Frames are modelled as 2-dimensional and the basic ANSR element types available include beam, column, and truss member behavior. Empirical relations(Ref. 7) may be utilized to extend this range to model shear-beams, natural rubber support bearings and special energy absorbing devices.

Modelling features.

The capabilities of DELIGHT.STRUCT allow elements to be subjectively grouped so that they possess equal properties. Repetition of elements is related to economical construction. Furthermore, the calculation required at each iteration in the feasible directions algorithm will be approximately proportional to the total number of design variables, because partial derivatives of active nonlinear constraints are presently calculated with a forward finite difference scheme. However, section sizes chosen within each group will be bounded by the most critical constraint within the group. Hence, grouping should retain flexibility in the optimal design while simultaneously keeping the problem practical in terms of element repetition and required calculation. The optimization problem is further simplified by reducing the number of unknowns in each element to a single variable. For example, the section moment of inertia is chosen as the primary unknown for beam and column elements. Parameters of secondary importance such as cross sectional area and radius of gyration are obtained from Walker's empirical relationships for wide flange steel sections(Ref. 9).

IDENTIFICATION OF PROBLEM AREAS

The following list summarizes the authors' opinions of attributes and shortcomings of the present system.

a) Although the method of feasible directions assures an improved design with each iteration, the algorithm cannot guarantee convergence to a global minimum. It is therefore essential that the designer be prepared to find a starting design that is close to the anticipated optimal design. Nevertheless, interactive repositioning of the design vector may still be necessary to get the required convergence. Furthermore, the designer should not always expect a substantial improvement in the cost function. Rather, with a good initial design a small improvement may be obtained with, for example, a redistribution of element sizes.

b) Coefficients in the weighted-sum objective function have to be chosen so the final combination reflects a balance in tradeoffs among competing structural performance attributes. Their optimal choice is a major task in itself and is still a subjective decision. Moreover, this approach retains the limitation of hiding the changing importance of each term's contribution to the overall cost as one proceeds through the design process. Consequently, only single term objective functions have been considered to date.

c) When the optimization problem has been formulated, the earthquake loading input and structural modelling parameters are the components of the problem subject to the most uncertainty. The present environment uses a single scaled earthquake record for both the damageability and ultimate strength limit states. Guidelines suggest that the frequency content of the single record should be representative of an ensemble of such records expected to occur at a site. The record should neither contain localized frequency bands of low amplitude motion or envelope all peak response values in the ensemble(Ref. 14).

d) The ANSR simulator uses Rayleigh damping to model a phenomenon that still isn't well understood. Viscous damping is assumed in the elastic range. The nonlinear analyses employ a combination of viscous plus hysteretic damping. Calculations so far indicate that constraint performance is sensitive to the choice of specified damping ratio.

e) In reality, the effect of a single constraint's failure on the overall integrity of a structure will be related to both the constraint's type and coupling to other constraint performances. Even for small frames, this relationship may be extremely complex and probably will never be completely understood. Mahin and Bertero(Ref. 13) also indicate that while peak story drift and floor acceleration frame response parameters are commonly used as an approximate measure of non-structural damage in frames for which non-structural components are not expected to significantly contribute to the response, there is in fact very little reliable data available to make such interpretations more than qualitative. In specifying the boundary between satisfactory and unsatisfactory constraint performance, the designer will be guided by code clauses and technical references for some constraints, and his or her intuition for others. Moreover, designers commonly assert that they cannot express everything they know about a good design in a mathematical formulation. On the basis of these comments and observations of missing information, modelling deficiences, and uncontrollable variations, it is reasonable to contend that a mathematical formulation will often fall short of describing the real design problem. Therefore, the presently used design approach of forcing all constraints to have less than some preset probability of failure or response performance would seem unjustifiably rigid. A more rational method would only require the designer to specify "Ballpark" estimates of acceptable bounds on response quantities or failure probabilities for constraint performances. He or she could then proceed to find a balanced optimal design by trading off various active constraints and terms in the objective function.

CURRENT AND ANTICIPATED WORK

The software of DELIGHT.STRUCT has recently been extended to permit optimal design under multiple ground motions. This should alleviate the problem of the frequency content of a single ground motion misguiding the final design. It also enables constraints to be described in a probabalistic form. Moreover, since various objective function terms are coupled to the frame response, they can also be considered to be probabalistic. However, the design procedure is still based on the conditional situation of all three limit states having occurred during the structure's lifetime. Work should be initiated to develop a method capable of taking into account the temporal nature of ground motions that correspond to each of the limit states.

It is anticipated that the presently used feasible directions algorithm may be replaced by the recently developed 3 phase multi-objective feasible directions algorithm due to Nye(Ref. 1). In this algorithm, constraints are categorized as being either hard or soft. Hard constraints are those that the designer gives priority to the algorithm satisfying. They might represent a physical boundary such as volume not being permitted to exceed an upper bound. Soft constraints are those in which a moderate violation is tolerable if these violations can be simultaneously traded off against one another or against performance objectives during an optimization run. The importance of a constraint violation is a subjective matter in which the designer assigns good and bad values of constraint performance. These might typically be related to an exceedance probability over the lifetime of the structure or perhaps a code clause whose purpose is to provide a general guide for good design. Good and bad values are also specified for all terms in the objective function. Finally, it is essential that extensive computer graphics be developed to support the user interaction demanded by the design algorithm.

CONCLUDING REMARKS

This paper has reviewed a design procedure that is amenable to an automated design environment. It is philosophically attractive because it demands that a designer start the process by writing down all the information he or she knows about the structure and its desired seismic response. This conceptual task will be constrained by both the flexibility of the optimization algorithm and the ability of the designer.

The authors contend that this approach to design is a step in the right direction and note that the DELIGHT.STRUCT system should be closer to becoming a practical engineering tool after the anticipated program of development has been implemented.

REFERENCES

1. W.T. Nye, " DELIGHT : An Interactive System for Optimization-Based Engineering Design." UCB/ERL M83/33 Univ of Cal, Berkeley, Ca, May, 1983.
2. Recommended Lateral Force Requirements and Commentary, Seismology Committee, Structural Engineers Association of California, San Fransisco, Calif, 1975.
3. R.J. Balling, K.S. Pister, E. Polak," DELIGHT.STRUCT: A Computer Aided Design Environment for Structural Engineering." Report No UCB/EERC 81/79, Earthquake Engineering Research Center, Univ of Cal, Berkeley, 1981.
4. D. Ray, K.S. Pister, E. Polak, " Sensitivity Analysis for Hysteretic Damping Systems : Theory and Applications.", Computer Methods in Applied Mech. and Eng., No 14, 1978, pp. 179-208.
5. M.A. Bhatti, V. Ciampi, J.M. Kelly, K.S. Pister,"An Earthquake Isolation System for Steam Generators in Nuclear Power Plants.", Nuclear Eng. and Design., No 73, 1982, pp 229-252.
6. M.A. Bhatti, "Optimal Design of Localized Nonlinear Systems with Dual Performance Criteria under Earthquake Excitations." Report No EERC 79/15,Earthquake Eng. Research Center, Univ of Cal, Berkeley, Ca, July 1979.
7. R.J. Balling,V. Ciampi,K.S. Pister, and E. Polak." Optimal Design of Seismic-Resistant Planar Steel Frames.", Report No EERC 81-20, Earthquake Eng. Research Center, Univ of Cal, Berkeley, Ca, December 1981.
8. M.A. Austin, K.S. Pister, "Optimal Design of Friction-braced Frames under Seismic Loading." Report no UCB/EERC-83/10, Earthquake Engineering Research Center, Univ of Cal, Berkeley, June 1983.
9. N.D. Walker, "Automated Design of Earthquake Resistant Multistory Steel Building Frames", Report No 77-12,Earthquake Engineering Research Center, Univ of Cal, Berkeley, Ca, May 1977.
10. Uniform Building Code, International Conference of Building Officials, Whittier, Ca, 1979 Edition.
11. E. Polak,R. Trahan,D.Q. Mayne, " Combined Phase I - Phase II Methods of Feasible Directions. " Mathematical Programming, Vol 17, No 1, pp 32-61, 1979.
12. D.P. Mondkar, G.H. Powell, " ANSR-I General Purpose program for Analysis of Nonlinear Structural Response." Report No EERC 75-37, Earthquake Engineering Research Center, Univ of Cal, Berkeley, Ca, December 1975.
13. S.A. Mahin, V.V. Bertero, " Prediction of Nonlinear Seismic Building Behavior. " Journal of Technical Councils of ASCE, TC1, November,1978.
14. H. Seed,C. Ugas,J. Lysmer,"Site-Dependent Spectra for Earthquake-Resistant Design.", No EERC 74-12, Univ of Cal, Berkeley, Ca, 1974.