DISPLACEMENT CONTROL IN A GENERAL PURPOSE BUILDING DESIGN FRAMEWORK

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ABSTRACT

The goal of the displacement and drift control procedure presented in this paper is to systematically and automatically alter the size of various members in the structure in order to limit specified joint displacements caused by one or more loadings. The procedure will systematically determine the most appropriate members to change, update these members, re-calculate displacements or drifts, either through a complete structural analysis or an approximate method. At the center of this procedure is the ability for the engineer to specify geometric and additional design constraints and parameters which allow the designer to better control the overall design.

A sensitivity analysis procedure will be presented which determines the displacement changes in the structure with respect to the change in weight or area of the members. The sensitivity analysis determines which members are updated in a given cycle in order to satisfy the constrained displacements. Several two and three-dimensional frame structures will be presented to illustrate the procedure and the effects of various design parameters on the final design of the structure to satisfy specified displacement constraints.

KEY WORDS

Displacement control, constraints, design parameters, sensitivity, drift

INTRODUCTION

Structural design is often controlled by displacement limitations. Engineers often rely on rules-of-thumb to guide them in the necessary design changes to satisfy these displacement limitations. However, these guidelines are highly problem dependent and can not be easily codified for a general purpose design system. Clearly, the need exists for a system to assist the engineer in the drift control decision making process which will also allow the engineer to consider architectural and other design constraints.

The goal of the displacement and drift control procedure presented in this paper is to systematically and automatically alter the size of various members in the structure in order to limit specified joint displacements caused by one or more loadings. The procedure will systematically determine the most appropriate members to change, update these members, re-calculate displacements or drifts, either through a complete structural analysis or an approximate method which will also be presented. The process will then iterate until all of

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the constraints have been satisfied or an iteration limit has been reached. At the center of this procedure is the ability for the engineer to specify geometric and additional design constraints and parameters which allow the designer to better control the overall design. Furthermore, the procedure recognizes the difference between a physical member and an analytical member when selecting members to change.

SENSITIVITY ANALYSIS PROCEDURE

At the center of this procedure is the selection of the members to change in order to satisfy the displacement constraints. In this paper, a sensitivity analysis procedure is presented which determines the displacement changes in the structure with respect to the change in weight or area of the members. The sensitivity analysis determines which members are updated in a given cycle in order to satisfy the constrained displacements. The essence of the sensitivity analysis in this procedure involves the calculation of a sensitivity coefficient for each member of a structure subjected to structural loadings and displacement constraints. The sensitivity coefficient will determine the sensitivity of a displacement constraint to the change in the size of a particular member. The member with the most sensitive sensitivity coefficient is defined herein as the member that, when updated in size, most greatly decreases the constrained displacements while minimizing the structural weight increase. Weight increase minimization may be viewed as a means of limiting the structural cost. However, the weight may not be the only variable governing structural cost. For example, available steel sections, and not the member weight, may be the controlling factor for the member selection process. The designer, through the use of several parameters, can also control this member selection process characteristic.

The sensitivity coefficient definition used for this study is based on the work of Nha (1998) and Manicharajah (2000). A unit loading is placed at the constrained joint in the direction specified by the user. The member strain energy is then calculated as shown below:

$$\alpha_{ij} = \{u^{ij}\}^T * [K^i] * \{u^i\}$$

where

i = member i
j = location of constraint
K^i = member i local stiffness matrix
u^{ij} = local displacement vector of member i due to unit load applied at joint j
u^i = local displacement vector of member i due to real loading

The summation of all member strain energy terms is equal to the displacement at the constraint location associated with the real loading. The goal of the sensitivity analysis developed by Maham (2003) is to determine how a change in a member size will affect a constrained displacement. In order to achieve this effect, the procedure calculates each member’s contribution to the constrained displacement with the initial properties and with the member properties of the next available profile that can be chosen. The procedure assumes member size changes do not significantly alter the structure’s stiffness and, therefore, result in small force and displacement changes. This approximation allows for the calculation of a member's contribution to a constrained displacement after resizing without performing a reanalysis of the structure. The estimated change in the constrained displacement can then be obtained by subtracting the member's contribution to the displacement before and after resizing. The change in the strain energy, $\Delta\alpha_{ij}$, for a given member is shown below:

$$\Delta\alpha_{ij} = -\{u^{ij}\}^T * [\Delta K^i] * \{u^i\}$$

where the change in stiffness is determined by subtracting the initial stiffness and the stiffness after the member's size has been changed.

A member's sensitivity coefficient is defined as the ratio of the change in strain energy due to change in the member's weight due to member size increase. The sensitivity coefficient, γ_{ij} , is thus found by dividing the change in strain energy by the change in weight, Δw^i, due the change in a member's size and is given by the following equation:

$$\gamma_{ij} = \frac{-\{u^{ij}\}^T * [\Delta K^i] * \{u^i\}}{\Delta w^i}$$

An overview of the displacement control procedure is shown below in Figure 1.

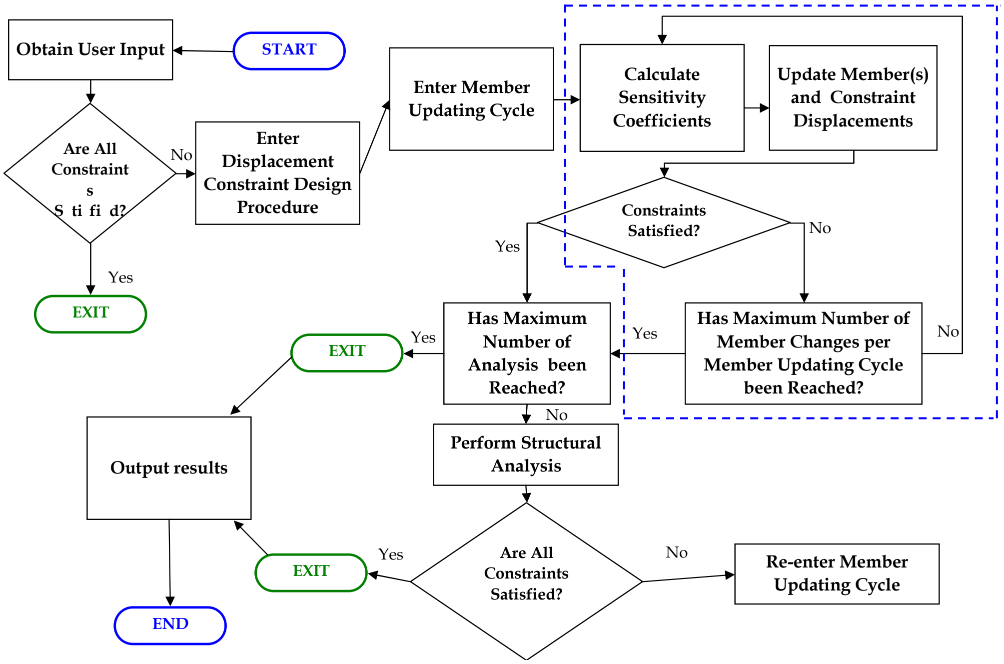

Figure 1: Overview of Displacement Constraint Procedure

PARAMETERS IMPLEMENTED TO CONTROL PROCEDURE

As with any iterative procedure, a number of parameters are needed to effectively control the procedure. These parameters are briefly described below:

- Define members that may be updated during a member update cycle. In some structures, the engineer can not allow all members to be changed. In other instances, the engineer may know from experience which members are more likely to be changed and the procedure can be accelerated when a subset of the members must be checked for updating.
- Define the maximum number of members that may be changed during a member updating cycle.
- Define the maximum number of static analyses that can be performed during execution of the procedure.
- Specify one of two cases for selecting the members to update: Case 1 – update the most sensitive member for all displacement constraints; Case 2 – update the most sensitive member for each displacement constraint.

The Displacement Control Procedure was implemented into GTSTRUDL (2005). GTSTRUDL is a general purpose analysis and design tool which has a number of other features which are useful for controlling design. Member constraints and physical member definition are two of these features which are illustrated in the following examples.

EXAMPLE 1

The first example illustrates the use of the drift control procedure to control the displacements of the braced steel plane frame shown in Figure 2. The frame was subjected to a horizontal displacement constraint of 0.4 inches (10.16 mm) at the top right joint. The columns were each defined as Physical Members – the two three story columns were required to be the same size over the three stories. Only one member was changed per iteration of the procedure. All beams were initially specified as W10x15 while the columns were initially specified as W6x20 and the braces as 4x4x3/8 single leg angles.

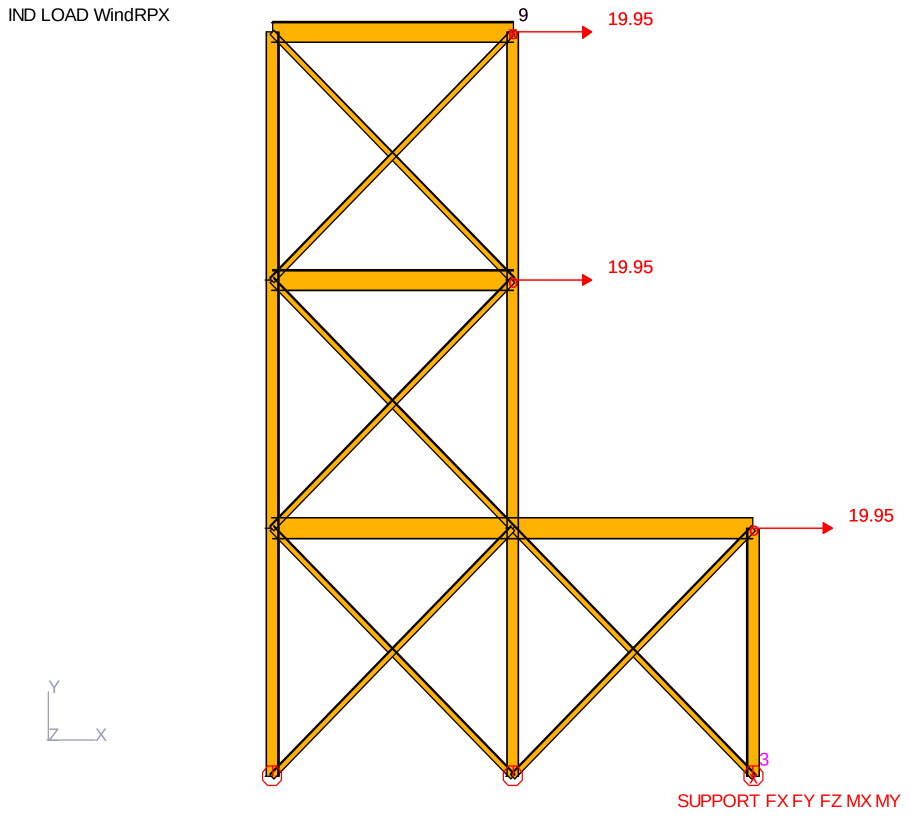

Figure 2: Braced Plane Frame Example Subjected to Joint Constraint at Top Right Joint – Joint 9

The initial and final sizes of the members which changed during the displacement control procedure are shown in Table 1. Also shown in Table 1 is the number of changes performed on each member.

Table 1: Initial and Final Profiles for Members Changed in Example 1

Member	**# Times changed**	**Initial Profile**	**Final Profile**
19	13	4x4x3/8	4x4x3/4
13	5	4x4x3/8	5x5x3/8
1	1	W6x20	W8x21
2	1	W6x20	W8x21
3	1	W6x20	W8x21

The final displacement at joint 9 after the changes shown in Table 1 was 0.393 inches (9.98 mm). Due to the specification of each column as a Physical Member, all three analytical members in the first column were changed to be the same size.

EXAMPLE 2

The second example is a rigid steel plane frame shown in Figure 3. All beams were initially specified as W18x35 and all columns were specified as W14x53. The displacement was constrained at the top left joint, joint 31 in Figure 2, to be 2.0 inches (50.8 mm). The initial displacement at joint 31 due to the loadings shown below was found to be 2.15 inches (54.61 mm). Two cases were investigated using this example to demonstrate the value of specifying Member Constraints. The first case did not include any constraints on the size of the members while the second case included the constraints shown below:

- The nominal depth of the columns was constrained to be between 14 (355.6mm), W14's, and 16 inches (406.4 mm), W16's.
- The nominal depth of the beams was constrained to be 18 inches (457.2 mm), W18's.

In order to understand the motivation for these two cases, one must understand the selection process once a member is determined to be the most sensitive and requires updating in order to satisfy the displacement constraint. When determining the next available section profile, the procedure moves to the section in the profile table with the next largest cross-sectional area. Depending on the profiles in the profile table and the behaviour of the structure, the search for a suitable profile may require a large number of selections from the profile table. For this example, the beams were found to the most sensitive. When determining the beam's next available section profile, the procedure moved to the next section in the table which ordered the cross-sections based on cross sectional area. Although the cross sectional area of the beam increased, the strong axis moment of inertia decreased. The procedure then continued through the table until an acceptable profile was found which caused a decrease in the displacement. In order to allow the user to better control the process and to also end up with a more usable design, Member Constraints were imposed in the second case for this example.

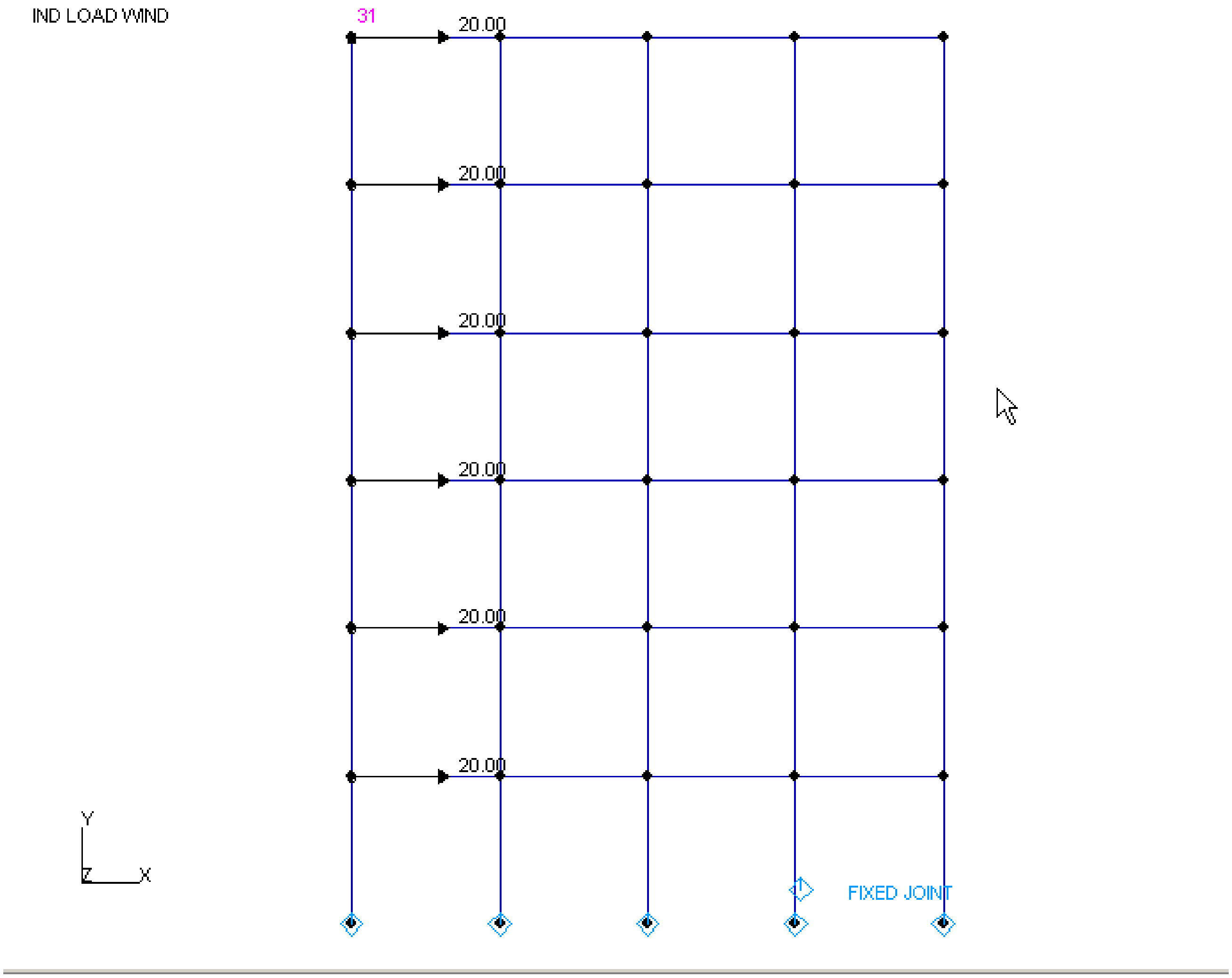

Figure 3: Rigid Plane Frame Example Subjected to Joint Constraint at Top Left Joint – Joint 31

While both variations produced members which satisfied the displacement constraint, the second variation found suitable members with a fewer number of table selections. In addition, the Member Constraints allow the engineer to control the design in order to satisfy other geometric or constructability issues.

EXAMPLE 3

The third example is a five story braced steel space frame structure shown in Figure 4.

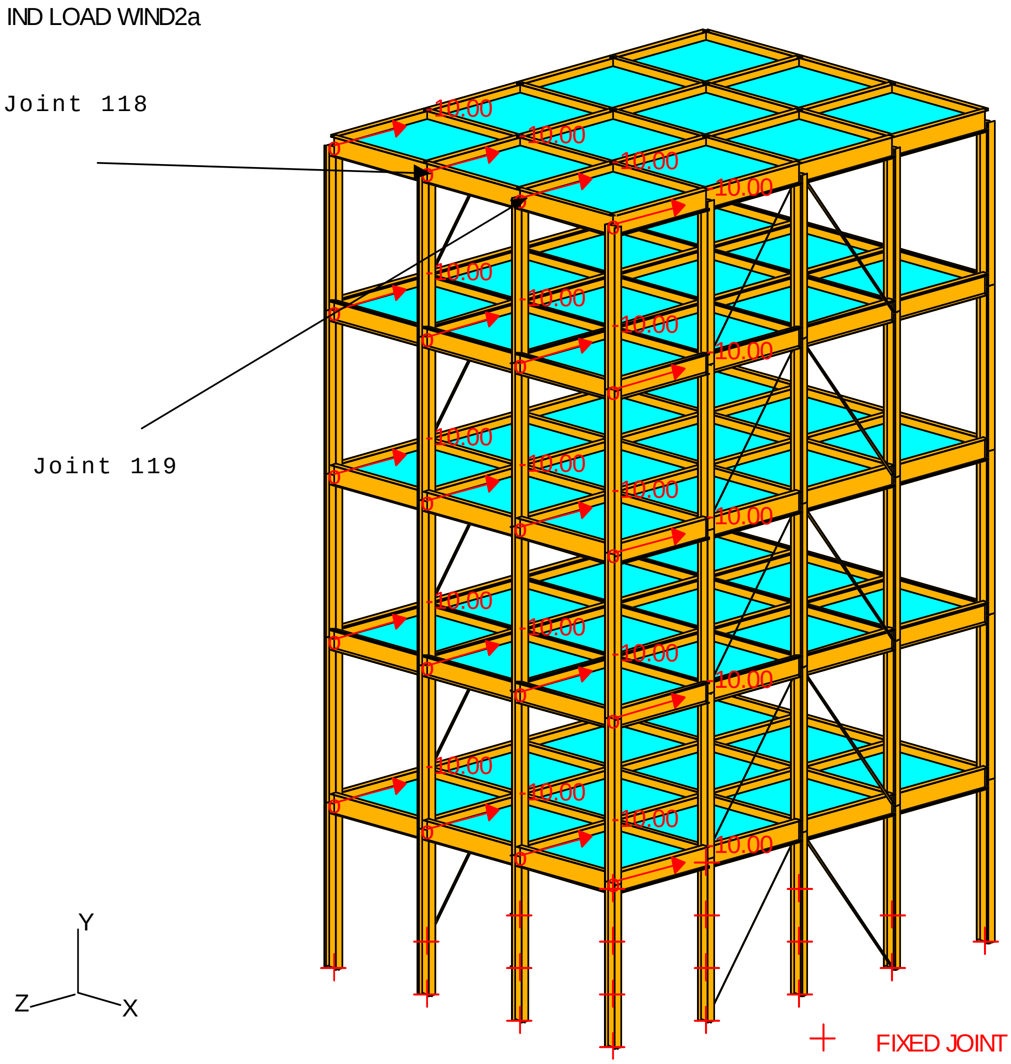

Figure 4: Five Story Braced Space Frame Example

Initially, all beams in the X-direction were W18x35 and all beams in the Z-direction were W18x50. The columns had initial section profiles of W14x53 and the braces were initially single 1x1x1/4 angles. A z-displacement constraint of 2.0 inches (50.8 mm) was initially imposed at joint 119. The z-displacement at joint 119 was 2.64 inches (67.05mm) based on the initial profiles for the members.

Two cases were executed for this example. The first case specified the following parameters for the displacement control procedure:

- Only the braces were allowed to be changed (they were previously found to be the most sensitive members)

- Ten members were allowed to be changed for each iteration in order to reduce the number of analyses
- The most sensitive member was updated for all displacement constraints

The displacement control procedure based on the first case satisfied the specified constraint at joint 119 and resulted in a displacement of 1.987 inches (50.47mm). However, since a unit load is applied at the joint with the specified constraint, unsymmetrical results and an unsymmetrical design resulted. The displacement at joint 118 was 2.069 inches (52.55mm).

In order to remedy this procedure, the second case imposed a constraint at joint 118 also. The first two parameters from the first case were retained in the second case. The last parameter was changed as shown below:

- The most sensitive member for each displacement constraint was updated

The results from the displacement control procedure based on the second case produced a symmetrical structure with the z-displacement at joints 118 and 119 equal to 1.982 inches (50.34 mm).

CONCLUSIONS

The Displacement Control Design procedure presented in this study is an effective technique for limiting joint displacements in a structural system by systematically altering member sizes. The ability to specify Member Constraints provides a useful tool to control the member selection process and to produce a more realistic design. Furthermore, the Physical Member updating capabilities allow for consideration of realistic design requirements when altering member sizes.

REFERENCES

GTSTRUDL (2005), *GTSTRUDL Reference Manuals*, Computer Aided Structural Engineering Center, Georgia Tech, Atlanta, GA.

Maham, A. S. (2003). *Displacement and Interstory Drift Design in GTSTRUDL.* M.S. Thesis, School of Civil and Environmental Engineering, Georgia Tech, Atlanta, GA

Manickarajah, D., Xie, Y. and Steven, G. (2000), “Optimum Design of Frames with Multiple Constraints Using an Evolutionary Method”, *Computers and Structures 74*, pp. 731-741.

Nha, C., Xie, Y. and Steven, G. (1998), “An Evolutionary Structural Optimization Method for Sizing Problems with Discrete Design Variables”, *Computers and Structures 68*, pp. 419-431.