BUILDING OPTIMIZATION- AN INTEGRATED APPROACH TO THE DESIGN OF TALL BUILDINGS

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ABSTRACT

There has been much research done on building optimization that deal with the issues within specific individual fields, such as architecture, structural engineering, and construction engineering. However, in practical application these issues must be addressed in a much more holistic manner as building design is becoming much more inclusive. A balance must be made that addresses the constructability and scheduling concerns of the contractor, the enclosure and spatial concerns of the architect, and finally the load-carrying concerns of the structural engineer. What if these issues were considered altogether and integrated more fully into building optimization? These issues and concerns would indubitably result in compromise solutions and tradeoffs that would have to be taken into account. This research will not only investigate and utilize current optimization techniques for the conceptual design of tall buildings, but also introduce a new metric in the dynamic analysis of high rise structures.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering

This is dedicated to all those who helped me
make it through this year. I would not have
made it this far without my family and most
of all, my Lord and Savior Jesus Christ.

To Mom and Jess
I LOVE YOU

ACKNOWLEDGMENTS

I would like to first take the time to thank my good friend and advisor Dr. McGee for all of his support and guidance throughout my first year as a graduate student. Thanks for helping me develop the new relative and elasticity measures for tall building analysis. Your encouragement and advice won't be forgotten as I embark on the next stage of my academic career.

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PREFACE

In theory, there has been much research on the topic of structural optimization; however, additional investigation should be done on its practical application. In addition, there arises a need to examine how structural optimization can be integrated into a more inclusive form of optimization which not only considers the structural engineer's concerns regarding building design, but also considers the concerns of other participants in the design process, such as the owner, architect, mechanical engineer, and also the electrical engineer. Where the structural engineer is mainly concerned with deflection and load-carrying capacities of the building, these other parties are interested in income revenue, enclosure and spatial conditions, heating, ventilating, air conditioning, and lighting (Grierson, 2002). Hence, there arises a need to formulate multiple criteria in determining an optimal building based on various disciplines. In taking a multi-objective/multi-disciplinary approach to building design, what results is an overall more efficient and optimal design.

The overarching goal of this research was to not only investigate and utilize current optimization techniques for tall buildings, but also develop a new metric in the dynamic analysis of high rise structures. The first chapter will introduce the general idea of structural optimization along with its current applications and will examine several issues that primarily focus on advancing building optimization from a structural standpoint. Optimization techniques will be discussed along with current advances in the field of tall building optimization. The next chapter will introduce the idea of *inclusive* optimization and will examine the effect on the design of a multi story office building when considering other contributors in the design process. Chapter 3 will discuss the interface between structure and architecture in tall building design and will examine how they relate through a case study of the John Hancock Center. Chapter 4 discusses the general optimization problem and will introduce the *governing multi-objective problem* for tall buildings. Chapter 5 will present the results of a dynamic analysis program of a 40-story building developed by the author and will introduce the idea of *relative* and *elasticity* measures in tall buildings. The final chapter will present overall final thoughts and recommend matters which deserve further research.

CHAPTER 1 STRUCTURAL OPTIMIZATION

> "If you find that you're spending almost all your time on theory, start turning some attention to practical things; it will improve your theories. If you find that you're spending almost all your time on practice, start turning some attention to theoretical things; it will improve your practice."
>
> -Donald Knuth

1.1 Introduction

The general objective of structural, or shape, optimization is to find a shape in either two or three dimensional space that is "the best" in a certain sense, while at the same time satisfying certain requirements or constraints. In structural building design, these constraints are usually governed by maximum allowable deflection, stress, weight, etc. This chapter will first examine the practical utility of shape optimization for relatively basic structural systems and will then extend the idea to the optimization of much more complex structural systems, such as tall buildings. The chapter will end with an investigation of two types of form-finding techniques that have been used in the past.

1.2 Practical Applications of Structural Optimization

When considering and formulating a structural optimization problem, there are four main factors that must be considered:

- uncertainty level
- design variables and parameters
- problem formulation
- optimizing tool

These factors are tabulated below with a particular structural optimization problem defined in italics characterized as a *probabilistic* optimization of a *structure* under *static* loading made of *reinforced concrete* with a *minimum cost single* objective under *multiple constraints* using *mathematical programming.*

Uncertainty Level	Variable and Parameters			Formulation			Algorithm Code
	Geometry	Loading	Material	Objective	Limit States	Constraints	
Deterministic	Section Member *Structure*	*Static*	Steel *RC* /PC /PPC Composite	*Single* Multiple	Single *Multiple*	SLS • Stress • Deflection • Cracking • Fatigue • Buckling •*Local damage*	*MP* OC
Probabilistic	Struct.Layout ComplexSyst.	Dynamic	Elastic *Elastic-Plastic* Str.- Hard. Str.- Soft.	Performance Economy • Weight • *Cost* CostParameter •Relative costs •Expected life	*SLS* *ULS* Other	ULS • *Collapse* • Ductility • Instability	GA

Table 1 Structural Optimization Factors

(Cohn et al, 1994)

In Cohn's 1994 paper, *Application of Structural Optimization*, a 501-example catalog of practical structural optimization problems was compiled, which provided new insights into the present state-of-the practice at that time. Various methods of finding solutions to optimization problems were utilized for each example, which included mathematical programming (MP), the optimality criteria (OC), and genetic algorithms (GA). The major structural types that Cohn focused on were relatively basic in nature and included the following: plane trusses, beams, columns, shafts, plane frames, arches, space trusses, plates and shells (see Tables 2-4).

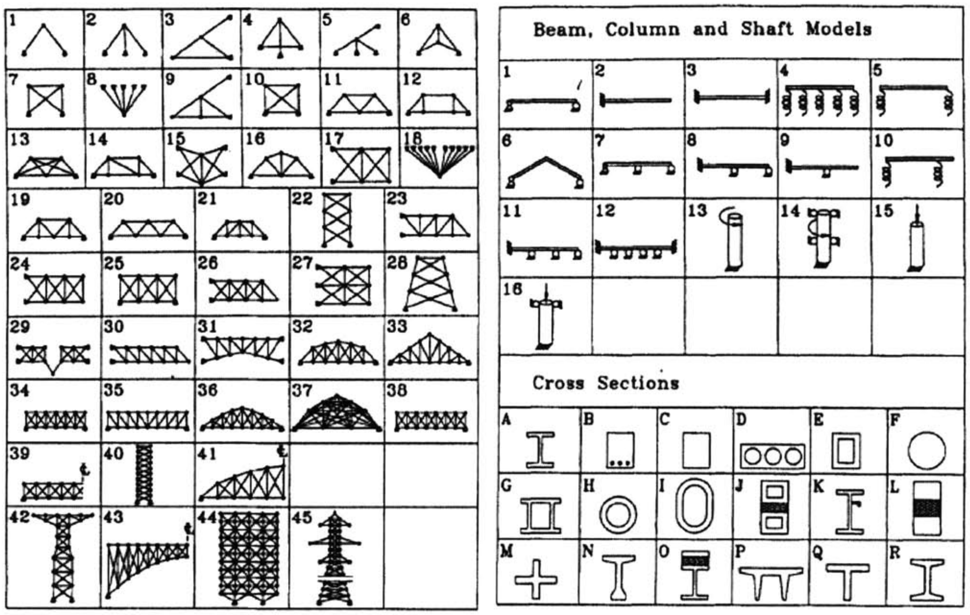


Table 2a, b Plane Trusses and Beams, Columns, and Shafts, respectively

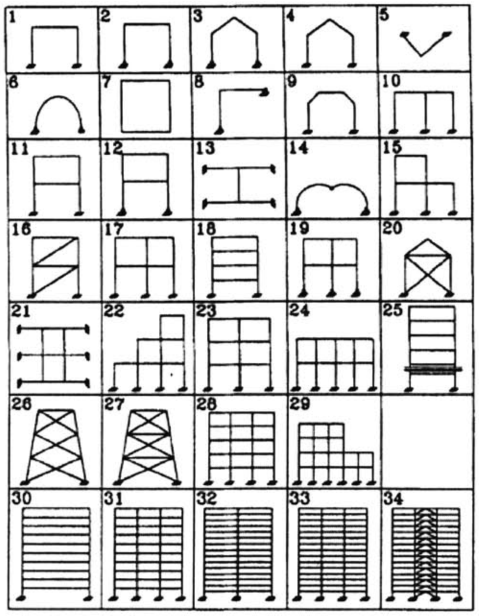


Table 3 Plane Frames and Arches

(Cohn et al, 1994)

The initial goal of Cohn's investigation was to gain factual evidence of the range of practical structural optimization currently in use at the time and understand the possible reasons for its limited and slow implementation. His second goal was to encourage the use of design optimization from a structural perspective rather than a mathematical one, particularly when dealing with problem identification. He noticed that the gap between theory and practice lied within the priority mathematical optimization had over structural optimization at the time. One important conclusion made by Cohn was the realization that optimization could become more appealing to practicing designers if more physical examples of its application were made available, particularly for realistic structures, loading conditions, and limit states. (Cohn, 1994)

1.3 Structural Optimization for Tall Buildings

Cohn's observation of the apparent gap between theory and practice in 1994 must have been shared by many others in the field. In fact, taking structural optimization theory to practical design has still proven a formidable challenge for engineers. However, progress has been made on developing a much more realistic tool for practical applications, as optimal member sizing algorithms for high rise structures have been created, which replace the traditional trial and error design approach that tends to be computationally expensive. These new strategies not only obtain the most economical element sizes of a tall structure, but also ensure minimal impact on floor area use.

A new approach to tall building design has been developed at the Hong Kong University of Science and Technology, which resulted in the creation of a highly integrated computer system called OPTIMA. Capable of not only working with existing structural analysis software while at the same time producing optimal element sizes that satisfy wind-induced serviceability criteria, OPTIMA also considers cost factors associated with structural materials, usable floor area, architectural aesthetics, quality of living space and comfort, and construction methods.

When designing any tall building, the creation of the lateral stability system is usually the first and most challenging task for the structural engineer. Normally, several preliminary schemes for the structure are considered and evaluated. After that, the final scheme is selected and the majority of the structural engineer's effort is spent sizing members to satisfy certain safety requirements. The typical optimal sizing formulation, taken from Chan's 2004 paper, *Advances in Structural Optimization of Tall Buildings in Hong Kong,* for a basic high rise structure can be summarized as follows:

$$\text{Minimize } \mathrm{Cost}(A_{i_s}, B_{i_c}, D_{i_c}, t_{i_w}) = \sum_{i_s=1}^{N_s} w_{i_s} A_{i_s} + \sum_{i_c=1}^{N_c} w_{i_c} B_{i_c} D_{i_c} + \sum_{i_w=1}^{N_w} w_{i_w} t_{i_w}$$

Subject to:

$$\frac{\delta_l^{top}}{H} \le d_l^U \qquad (l = 1, 2, \ldots, N_l) \qquad \text{- Top drift constraints}$$

$$d_j = \frac{(\delta_j - \delta_{j-1})}{h_j} \le d_j^U \qquad (j = 1, 2, \ldots, N_j) \qquad \text{- Interstorey drift constraints}$$

$$\ddot{\delta}_l \le a_l^U \qquad (l = 1, 2, \ldots, N_a) \qquad \text{- Wind induced acceleration constraints}$$

$$\sigma_p \le \sigma_p^U \qquad (p = 1, 2, \ldots, N_p) \qquad \text{- Element strength constraints}$$

$$A_{i_s}^L \le A_{i_s} \le A_{i_s}^U \qquad (i_s = 1, 2, \ldots, N_s) \qquad \text{- Steel element sizing constraints}$$

$$B_{i_c}^L \le B_{i_c} \le B_{i_c}^U \qquad (i_c = 1, 2, \ldots, N_c) \qquad \text{- Concrete element width sizing constraints}$$

$$D_{i_c}^L \le D_{i_c} \le D_{i_c}^U \qquad (i_c = 1, 2, \ldots, N_c) \qquad \text{- Concrete element depth sizing constraints}$$

$$t_{i_w}^L \le t_{i_w} \le t_{i_w}^U \qquad (i_w = 1, 2, \ldots, N_w) \qquad \text{- Concrete wall thickness sizing constraints}$$

(Chan, 2004)

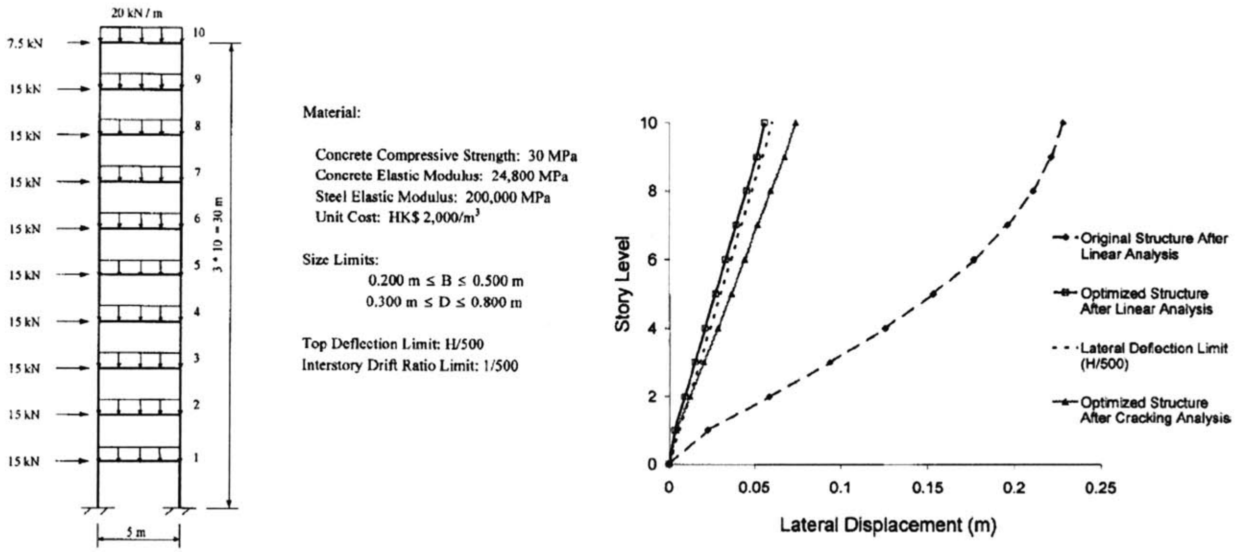
where the governing constraints are *top drift*, *interstory drift*, *acceleration*, *element strength*, and *element/wall sizing*.

While the handling of a vast number of design variables and constraints for large-scale structures poses a major issue, the ability for optimization algorithms to be generally applicable to various types of building structures poses as another. Usually, the optimality criteria (OC) approach is utilized for the design of tall buildings as it tends to be suitable for managing many design variables with relatively few active lateral stiffness design constraints. The OC approach, however, doesn't always produce the global optimum design. As a result, advances in research has produced a hybrid method, called the OC-GA method, which incorporates the optimality criteria and genetic algorithms (GA), as GA's generally present better global behavior than the OC. For this reason, the combination of the two approaches has been developed in order to produce a more holistic and computationally efficient optimization procedure. (Chan, 2004)

As stated previously, when considering building design optimization from a structural engineer's standpoint, maximum allowable deflection and maximum allowable weight are critical design constraints. Furthermore, when considering the design of tall buildings, in particular those made of concrete, the designer must also constrain interstory drift in the structure. Concrete cracking is the major cause of this phenomenon as it typically leads to reduced lateral stiffness. This issue was taken into account by Chan in his optimization of a ten-story, single bay frame under a given gravity and lateral load.

In his work in 2006, Chan employed a meticulous optimality criterion which minimized the cost of a high-rise reinforced concrete structure under top and multiple interstory drift constraints in conjunction with member sizing requirements. Chan not only used a probability-based approach to identify cracked members, but also utilized two iterative methods to analyze the lateral deflection of the building, which were the direct stiffness reduction method and the load increment method.

In order to begin the optimization process, an initial set of member sizes had to be given. After that, newer member sizes were formed based on the strength requirements. Next, the deflection and lateral drift constraints were checked for satisfaction using an iterative process. Finally, a convergence of structural cost was ensured. The design example used by Chan is illustrated in Figure 1 with results of the deflected profiles for linear elastic multiple interstory drift constrained optimal design. In this work, Chan concluded that the optimized structure under multiple linear elastic drift constraints underestimated the lateral deformation up to about 25%, resulting in inadequate design when compared to nonlinear concrete cracking analysis. (Chan, 2006)



Material:

Concrete Compressive Strength: 30 MPa
Concrete Elastic Modulus: 24,800 MPa
Steel Elastic Modulus: 200,000 MPa
Unit Cost: HK$ 2,000/m^3

Size Limits:
$0.200 \text{ m} \leq B \leq 0.500 \text{ m}$
$0.300 \text{ m} \leq D \leq 0.800 \text{ m}$

Top Deflection Limit: H/500
Interstory Drift Ratio Limit: 1/500

Figure 1a, b Ten-story single-bay frame and Lateral Displacement Profile, respectively (Chan, 2006)

In Chan's earlier research in 2001, he studied the idea of optimizing the lateral stiffness of a tall building through the use of hybrid materials, in this case concrete and steel. The least cost objective was obtained through an optimality criteria approach. Once the structural form of the lateral stiffness system was realized, the best steel and concrete sizes were obtained, which of course satisfied all serviceability lateral stiffness and practical sizing requirements. To quantify the effectiveness of this idea, the optimization technique was applied to the preliminary design of an 88-storey building in Hong Kong.

To achieve this rigorous task, Chan first had to formulate the optimal design problem which consisted of assigning the steel and concrete sizing variables, creating the objective function, and setting the stiffness design constraints. The final task was by far the most demanding of the three as two types of serviceability performance constraints were considered in the high-rise building design. The constraints were concerned with static wind drift and wind-induced vibrations.

While discussing the lateral deflections under static equivalent wind loads, Chan explained in detail the two kinds of lateral deflections that must be considered. These two types, which were briefly discussed in his two previously mentioned papers, are the overall building drift ratio and the interstory drift ratio. The lateral displacement values were obtained by the principle of virtual work.

When approached with the problem of wind-induced vibration, Chan used the common approach of limiting the natural periods to suppress its effects. The fundamental circular frequency of vibration for an undamped structure was found using the Rayeigh method, which can be summarized as follows:

$$\frac{1}{2}\omega^2\phi^{\mathrm{T}}M\phi \text{ (kinetic energy)} = \frac{1}{2}\phi^{\mathrm{T}}F \text{ (work done by inertia forces)}$$

$$\Rightarrow \omega^2 = \frac{\phi^{\mathrm{T}}F}{\phi^{\mathrm{T}}M\phi} = \frac{\phi^{\mathrm{T}}K\phi}{\phi^{\mathrm{T}}M\phi} = \frac{K^*}{M^*} \qquad (1\text{-}1)$$

(Chan, 2001)

where M and M* are the mass matrix and generalized mass, K and K* are the stiffness matrix and generalized stiffness, and ϕ is the computed mode shape of the structure under the inertial force F.

Since the natural period is inversely related to the circular frequency, one can limit the natural period by increasing the circular frequency, which is achieved by increasing the structure stiffness. This entire concept is explained in greater detail in Chan's 2001 paper.

After the optimal design problem was devised, the optimality criteria (OC) method was utilized to solve the problem. In traditional optimization theory, the needed optimality criteria can be indirectly obtained by converting the constrained problem into an unconstrained Lagrangian function and then solving for the stationary condition of the new function. With the omission of the sizing constraints, Chan's Langrangian function was formed as shown in Eq. (1-2), which can briefly be explained as the first bracketed portion describing structure cost and the second bracketed portion describing the design constraints multiplied by the corresponding Lagrange multipliers.

$$
\begin{aligned}
L(A_{i_s}, B_{i_c}, D_{i_c}, B_{i_w}, \lambda_s) = & \left[\sum_{i_s=1}^{N_s}(w_{i_s} \cdot A_{i_s}) + \sum_{i_c=1}^{N_c}(w_{i_c} \cdot B_{i_c} D_{i_c}) + \sum_{i_w=1}^{N_w}(w_{i_w} \cdot B_{i_w})\right] \\
& + \sum_{j=1}^{N_g} \lambda_j \left[\sum_{i_s=1}^{N_s}\left(\frac{e_{i_s j}}{A_{i_s}} + E'_{i_c j}\right) + \sum_{i_c=1}^{N_c}\left(\frac{e_{0i_c j}}{B_{i_c} D_{i_c}} + \frac{e_{1i_c j}}{B_{i_c} D_{i_c}^3} + \frac{e_{2i_c j}}{B_{i_c}^3 D_{i_c}}\right)\right. \\
& \left. + \sum_{i_w=1}^{N_w}\left(\frac{e_{0i_w j}}{B_{i_w}} + \frac{e_{1i_w j}}{B_{i_w}^3}\right)\right] \qquad (1\text{-}2)
\end{aligned}
$$

(Chan, 2001)

This optimization strategy was applied to an 88-storey tower in Hong Kong that consisted of a mixed use of structural steel and reinforced concrete. It included a central reinforced concrete core wall that was linked to eight exterior composite mega-columns by the use of three levels of steel outriggers. This optimization routine contained two objectives,

- minimize the structural material cost
- minimize the overall cost

in which the overall cost included material cost and cost associated with floor area occupied by vertical elements. A couple views and a typical floor plan of the structure is shown in Figure 3. (Chan, 2001)

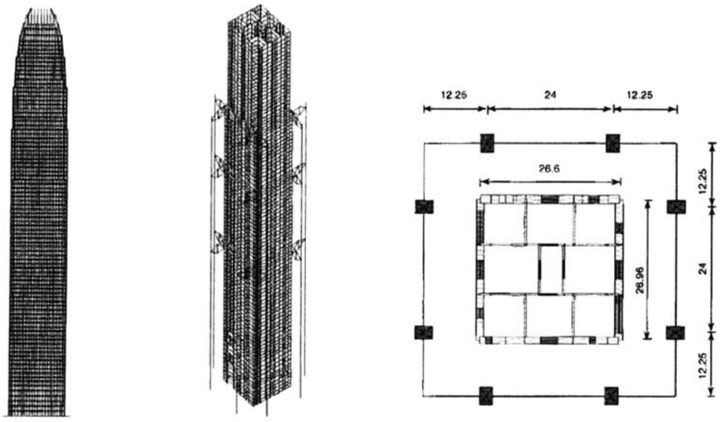


Figure 2 Front, side, and plan view of the 88-story tower in Hong Kong

(Chan, 2001)

1.4 Structural Design using Genetic Algorithms and Evolutionary Computation

The concept of genetic algorithms (GA) has also been used in building design optimization. In his work, Pezeshk not only explained the general strategy of GA's, but also how it is implemented in the design of structural steel structures. He describes the core characteristics of GA's, stating how they are generally based on the principles of survival of the fittest and adaptation. The advantages of applying GA's to the design of structures were also discussed in the introduction.

Pezeshk also mention the processes in which all GA's consist, which include coding and decoding design variables into strings, evaluating the fitness of each solution string, and applying genetic operators to generate the next generation of solution strings. These genetic operators can be broken down into three categories:

- reproduction
- crossover
- mutation

The objective of the reproductive operator is to ensure the survival of the information stored in strings with good fitness. Crossover is a procedure where a chosen parent string is broken into segments and interchanged with segments of another parent string. Finally, mutation allows for diversity within a solution population by introducing random changes into the design population.

In his work he formulated the basic structural optimization problem, which deals with the minimization of structural cost. To comprehend this work, one must first understand The Fundamental Theorem of Genetic Algorithms which basically says,

"short, low order schemata are given exponentially increasing or decreasing numbers of samples depending on a schema's average fitness"

Mathematically, this statement can be written as:

$$m(H,t+1) \geq m(H,t) \times \frac{f(H)}{f_{avg}}\left[1 - p_c \frac{\delta(H)}{L-1} - O(H)p_m\right] \tag{1-3}$$

(Pezeshk et al, 2002)

where m(H,t+1) and m(H,t) are the number of schema H in generation t+1 and t, respectively, f(H) is the average fitness value of strings that include schema H, f_{avg} is the average fitness value of the whole population, δ(H) is the length of schema H, L is the total length of the string, O(H) is the order of schema H, and p_c and p_m are the probabilities of crossover and mutation, respectively. These ideas are explained more fully in Pezeshk 2002 paper, *State of the Art on the Use of Genetic Algorithms in Design of Steel Structures*. (Pezeshk et al, 2002)

Kicinger also researched evolutionary design approaches for steel structures. In his work, multi-objective topological design of optimum steel structural systems in high-rise structures was investigated using an Evolutionary Computation (EC) approach. Analogous to GA's, an evolutionary algorithm is simply a search and optimize process in which a population of designs undergo a series of gradual changes. Because this approach is directed by a measure of perceived performance defined by the objective function(s), one of the most important concerns of EC is the adequate choice of performance evaluation functions, as these functions provide feedback about suitability of each design. In addition, this feedback is used to improve the subsequent design.

Obviously in most structural problems, an evaluation function based on one criterion usually isn't sufficient; thus, multiple evaluation functions are needed. Kicinger's research examines a two-stage multiobjective topological design process in which an evolutionary algorithm produces a conceptual design and the sizing of structural members is configured using a structural analysis program called SODA. The multiobjective evolutionary optimization experiments were conducted using a design tool called Emergent Designer. To develop each design generation, this tool used representations of steel structural systems such as bracings, beams, and supports. The actual genome that was manipulated by an evolutionary algorithm was encoded as a string of integer values (see Figs. 4 and 5).

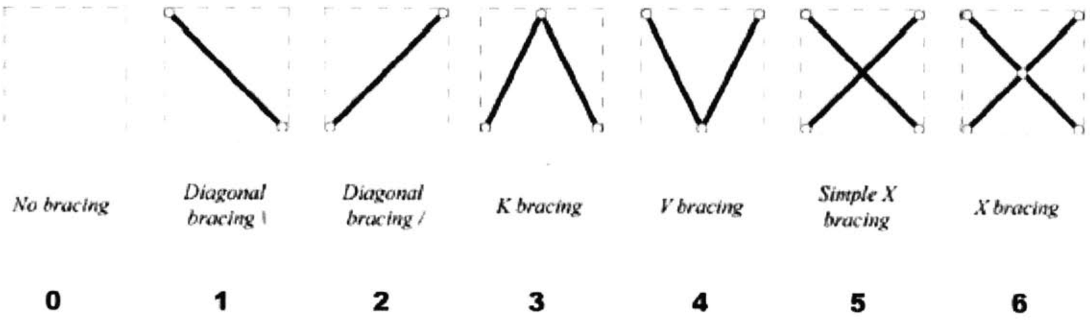


Figure 3 Phenotypic, symbolic, and genotypic values of attributes representing wind bracing (Kicenger et al, 2004)

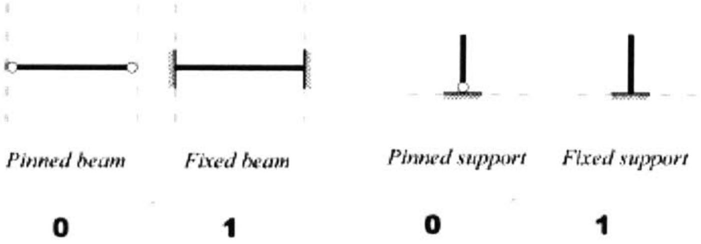


Figure 4 Phenotypic, symbolic, and genotypic values of attributes representing beams and supports, respectively

(Kicinger et al, 2004)

The goal of this study was to examine how the topologies change when the total weight and the maximum horizontal displacement of the structural system was varied. (Kicinger et al, 2004)

Balling investigated structural optimization by subdividing the concept into three subproblems:

- size
- shape
- topology optimization

Size optimization is concerned only with the dimensions of the cross sectional areas and the properties of each structural member. These design variables must be discrete since members are usually manufactured in distinct shapes and sizes. Shape optimization deals with the configuration, or pattern, of the structure in which the coordinates of joints are treated as continuous design variables. Lastly, topology optimization allows members or joints to be removed from the design altogether and may also optimize connection or support type as mentioned previously. This class of optimization is naturally discrete. The unique aspect of this work is that it not only simultaneously optimizes size, shape, and topology of trusses and frames, but also simultaneously finds several optimum and near-optimum in a single iteration. In the end, the designer is given a choice of different topological optimum solutions in which to choose.

In his bridge example, Balling et al develop ten different solutions that would minimize total material volume of a truss bridge. Interestingly, the results produced traditional bridge designs such as the cantilever truss, suspension bridge, cable-stayed bridge, and the Warren truss; however, it also produced unconventional and rather unexpected designs such as Topologies 8, 9, and 10 shown in Figure 5.

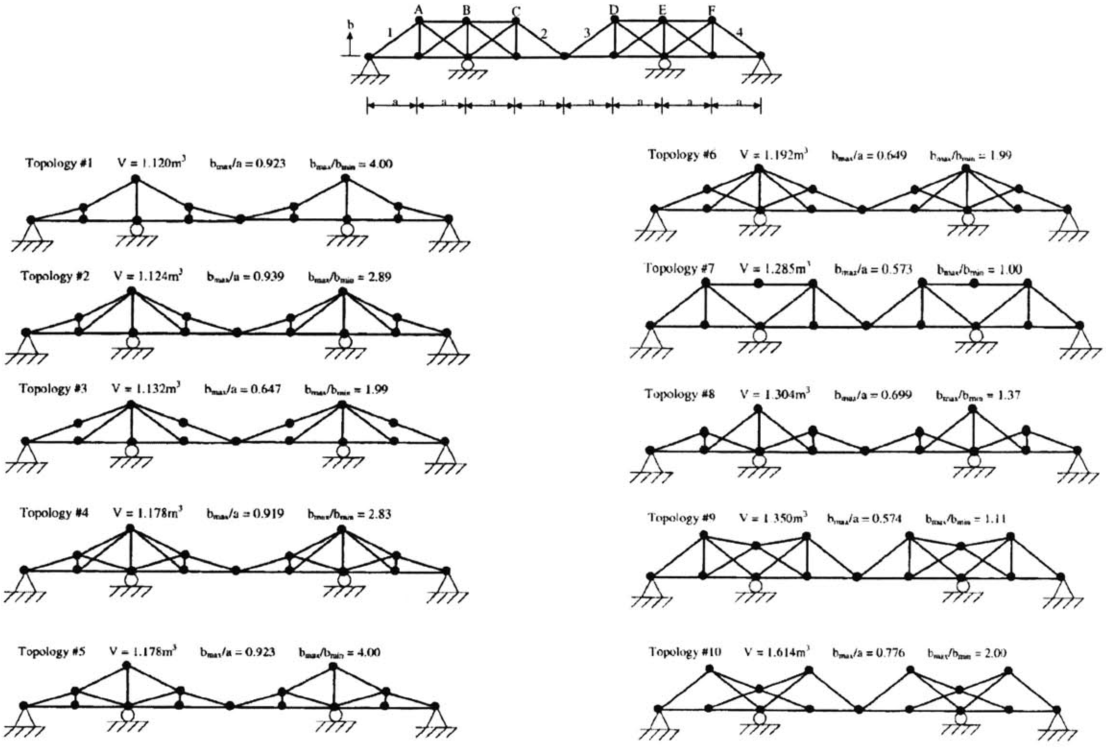


Figure 5 Optimum Bridge Typologies

(Balling et al, 2006)

Also included in his work was the investigation of a 4-story, 3-bay frame. In this case the genetic algorithm found 83 feasible designs that minimized material volume; however, it could not find a feasible unbraced design. It was realized that all competitive topologies braced the interior bay rather than the exterior bays. One of the optimum designs is shown below along with the base case frame. (Balling et al, 2006)

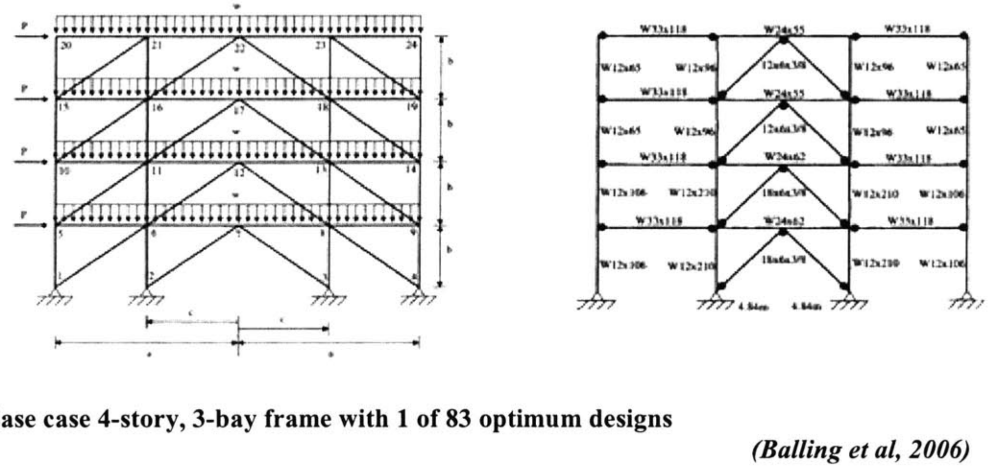


Figure 6 Base case 4-story, 3-bay frame with 1 of 83 optimum designs

(Balling et al, 2006)

CHAPTER 2 INCLUSIVE OPTIMIZATION

"You can please *some* of the people *all* of the time. You can please *all* of the people *some* of the time. However, you can never please *all* of the people *all* of the time."

-Unknown

2.1 Introduction

The main objective of inclusive building optimization is to create the most optimal building from the perspective of various members of the design process, which include but not limited to the owner, architect, and engineers. This chapter will present an inclusive optimization approach applied to the design of a multi-story office building.

2.2 Muilti-Story Office Building Design

It has been argued that the most difficult stage of any design process is the initial conceptual phase since this stage is typically vaguely defined and lacks a structured solution strategy. For this reason, most designers limit there design ideas before continuing the design process, which essentially eliminates other possible solutions that could have been better in the long run. Grierson's work focuses on compromise solutions that should be considered when dealing with optimization. He uses the Pareto optimization approach to handle trade-offs that arise between competing objective criteria. Grierson justifies the use of nondominated optimization to identify a range of conceptual design solutions by claiming that the relative importance of each conflicting criteria are unknown at the initial design stage. As a result, no design is dominated by any other feasible design solution. This optimization approach can be stated as follows:

$$\text{Minimize: } \{\text{ObjectiveCriteria}_1, \ \ldots, \ \text{ObjectiveCriteria}_m\}$$
$$\text{Subject to: Explicit Constraints}$$
$$\text{Implicit Constraints}$$

(Grierson, 2002)

where the m competing ObjectiveCriteria are functions of the variable for the design problem; the Explicit Constraints impose explicit restrictions on the design variable values; and the Implicit Constraints impose inherent restrictions on the design in that they limit the availability of variable values.

In his study, Grierson considered architectural, structural, mechanical, and electrical requirements in addition to land and construction cost, energy and maintenance costs, and the quality of occupied space for a given building project. Hence, the design objective criteria were to minimize capital cost, minimize operating cost, and maximize income revenue.

Architectural and engineering assumptions had to be made in order to formulate the optimization problem. A few of these assumptions were:

- the column lines were regularly spaced in two orthogonal-plan directions
- the building plan footprint and floor-to-ceiling clearance height are identical for all stories
- windows were installed at a fixed distance above the floor and extended to the ceiling
- designs with larger spans and more window area for the same floor area had higher lease rates
- the structural system, floor system, exterior cladding, and windows were variable (see Table 5)
- the mechanical system included HVAC and elevator system
- the building electrical systems power the HVAC, elevator, and lighting systems

Base-10 index	Structural system	Floor system	Cladding type	Window type	Window ratio	Number of bays (a,b)	Bay width (a,b) (m)
0	Steel frame	Two-way flat plate	Precast concrete	Standard glass	0.25	3	4.5
1	Concrete frame	Two-way flat slab	Tilt-up concrete panel	Insulated glass	0.30	4	5.0
2	Concreate frame and shearwall	Two-way slab and beam	Solid brick	Standard HA	0.35	5	5.5
3	Steel frame and bracing	Waffle slab	Metal siding panel	Insulated HA	0.40	6	6.0
4		Steel joist and beam	Stucco wall		0.45	7	6.5
5		Composite beam and slab	Glazing panel		0.50	8	7.0
6		Composite deck and slab			0.55	9	7.5
7		Composite beam, deck, and slab			0.60	10	8.0
8					0.65		8.5
9					0.70		9.0
10					0.75		9.5
11					0.80		10.0
12					0.85		10.5
13					0.90		11.0
14					0.95		11.5
15					1.00		12.0

Note: HA=heat absorbing glass (tinted); window ratio=ratio of actual window area to maximum possible window area on building perimeter; number of bays (a,b)=number of column bays along building width a and length b (8 choices in each direction); bay width (a,b)=span distance between columns along building width a and length b (16 choices in each direction).

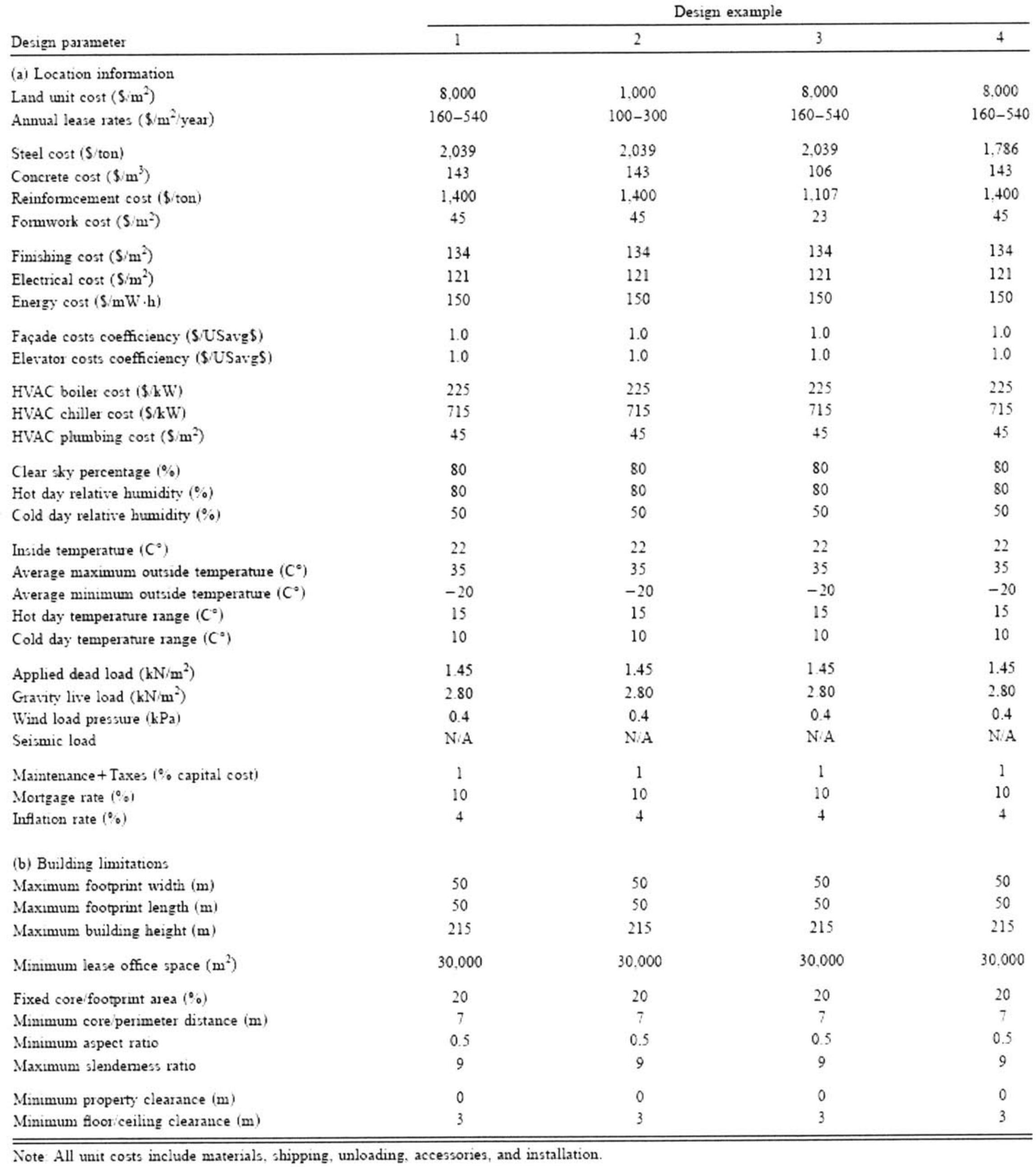
Table 4 Primary variable values for office building conceptual design (Grierson, 2002)

This Pareto optimization problem was solved using a multicriteria genetic algorithm (MGA) approach, in which the computational steps are similar to those of a simple genetic algorithm. The primary design variables were converted to their binary equivalents as shown in the Table 6, and the initial population of conceptual designs was defined by a randomly generated set of binary bit-strings. The first and subsequent generations of the search were based on designs that complied with the explicit and implicit constraints to ensure that each design generated was indeed feasible.

	Base-2 Value								
Base-10 index	Structural system	Floor system	Cladding type	Window type	Window ratio	Number of bays (a)	Number of bays (b)	Bay width (a)	Bay width (b)
0	00	000	000	00	0000	000	000	0000	0000
1	01	001	001	01	0001	001	001	0001	0001
2	10	010	010	10	0010	010	010	0010	0010
3	11	011	011	11	0011	011	011	0011	0011
4		100	100		0100	100	100	0100	0100
5		101	101		0101	101	101	0101	0101
6		110			0110	110	110	0110	0110
7		111			0111	111	111	0111	0111
8					1000			1000	1000
9					1001			1001	1001
10					1010			1010	1010
11					1011			1011	1011
12					1100			1100	1100
13					1101			1101	1101
14					1110			1110	1110
15					1111			1111	1111

Table 5 Binary representation of primary design variable values (Grierson et al, 2002)

Governing parameters for typical office buildings were needed to begin the analysis, which broadly define building location and limitations. These parameters specified location information and building limitations as listed in Table 7. Notice that four design scenarios are investigated in this study.

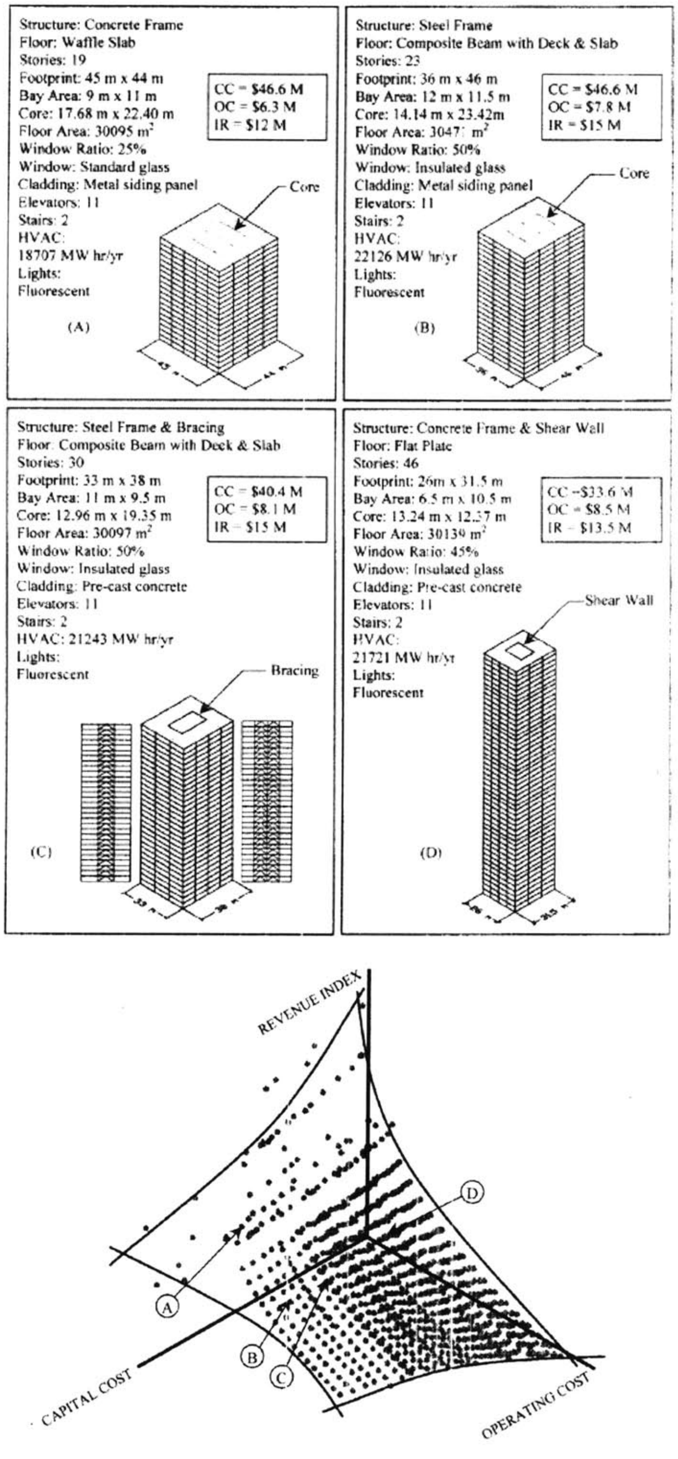


Design parameter	Design example 1	Design example 2	Design example 3	Design example 4
(a) Location information				
Land unit cost ($/m^2)	8,000	1,000	8,000	8,000
Annual lease rates ($/m^2/year)	160–540	100–300	160–540	160–540
Steel cost ($/ton)	2,039	2,039	2,039	1,786
Concrete cost ($/m^3)	143	143	106	143
Reinformcement cost ($/ton)	1,400	1,400	1,107	1,400
Formwork cost ($/m^2)	45	45	23	45
Finishing cost ($/m^2)	134	134	134	134
Electrical cost ($/m^2)	121	121	121	121
Energy cost ($/mW·h)	150	150	150	150
Façade costs coefficiency ($/USavg$)	1.0	1.0	1.0	1.0
Elevator costs coefficiency ($/USavg$)	1.0	1.0	1.0	1.0
HVAC boiler cost ($/kW)	225	225	225	225
HVAC chiller cost ($/kW)	715	715	715	715
HVAC plumbing cost ($/m^2)	45	45	45	45
Clear sky percentage (%)	80	80	80	80
Hot day relative humidity (%)	80	80	80	80
Cold day relative humidity (%)	50	50	50	50
Inside temperature (C°)	22	22	22	22
Average maximum outside temperatue (C°)	35	35	35	35
Average minimum outside temperatue (C°)	−20	−20	−20	−20
Hot day temperature range (C°)	15	15	15	15
Cold day temperature range (C°)	10	10	10	10
Applied dead load (kN/m^2)	1.45	1.45	1.45	1.45
Gravity live load (kN/m^2)	2.80	2.80	2.80	2.80
Wind load pressure (kPa)	0.4	0.4	0.4	0.4
Seismic load	N/A	N/A	N/A	N/A
Maintenance+Taxes (% capital cost)	1	1	1	1
Mortgage rate (%)	10	10	10	10
Inflation rate (%)	4	4	4	4
(b) Building limitations				
Maximum footprint width (m)	50	50	50	50
Maximum footprint length (m)	50	50	50	50
Maximum building height (m)	215	215	215	215
Minimum lease office space (m^2)	30,000	30,000	30,000	30,000
Fixed core/footprint area (%)	20	20	20	20
Minimum core/perimeter distance (m)	7	7	7	7
Minimum aspect ratio	0.5	0.5	0.5	0.5
Maximum slenderness ratio	9	9	9	9
Minimum property clearance (m)	0	0	0	0
Minimum floor/ceiling clearance (m)	3	3	3	3

Note: All unit costs include materials, shipping, unloading, accessories, and installation.

Table 6 Four design scenarios with governing parameters for a typical office building design
(Grierson et al, 2002)

Representative Pareto designs were presented based on these parameters and are shown below along with their location on the optimal cost-revenue trade-off surface for design example 1.



Structure: Concrete Frame
Floor: Waffle Slab
Stories: 19
Footprint: 45 m x 44 m
Bay Area: 9 m x 11 m
Core: 17.68 m x 22.40 m
Floor Area: 30095 m^2
Window Ratio: 25%
Window: Standard glass
Cladding: Metal siding panel
Elevators: 11
Stairs: 2
HVAC:
18707 MW hr/yr
Lights:
Fluorescent

CC = \$46.6 M
OC = \$6.3 M
IR = \$12 M

Structure: Steel Frame
Floor: Composite Beam with Deck & Slab
Stories: 23
Footprint: 36 m x 46 m
Bay Area: 12 m x 11.5 m
Core: 14.14 m x 23.42m
Floor Area: 30471 m^2
Window Ratio: 50%
Window: Insulated glass
Cladding: Metal siding panel
Elevators: 11
Stairs: 2
HVAC:
22126 MW hr/yr
Lights:
Fluorescent

CC = \$46.6 M
OC = \$7.8 M
IR = \$15 M

Structure: Steel Frame & Bracing
Floor: Composite Beam with Deck & Slab
Stories: 30
Footprint: 33 m x 38 m
Bay Area: 11 m x 9.5 m
Core: 12.96 m x 19.35 m
Floor Area: 30097 m^2
Window Ratio: 50%
Window: Insulated glass
Cladding: Pre-cast concrete
Elevators: 11
Stairs: 2
HVAC: 21243 MW hr/yr
Lights:
Fluorescent

CC = \$40.4 M
OC = \$8.1 M
IR = \$15 M

Structure: Concrete Frame & Shear Wall
Floor: Flat Plate
Stories: 46
Footprint: 26m x 31.5 m
Bay Area: 6.5 m x 10.5 m
Core: 13.24 m x 12.37 m
Floor Area: 30139 m^2
Window Ratio: 45%
Window: Insulated glass
Cladding: Pre-cast concrete
Elevators: 11
Stairs: 2
HVAC:
21721 MW hr/yr
Lights:
Fluorescent

CC = \$33.6 M
OC = \$8.5 M
IR = \$13.5 M

Figure 7a, b Representative Pareto designs and optimal cost-revenue tradeoff surface, respectively (Grierson et al, 2002)

Although relatively rough estimates and general assumptions were made in this analysis, the results can be used as a guide as it balances the concerns of various parties involved in the design, which generally include the financial concerns of the owner, the enclosure and spatial concerns of the architect, the load-carrying concerns of the structural engineer, and finally the HVAC, elevator, and lighting concerns of the mechanical and electrical engineers. (Grierson et al, 2002)

CHAPTER 3 STUCTURE AND ARCHITECTURE

"...[structure] is to the architect what the lawyer is to the accused, a necessary evil."
-Mario Salvadori

3.1 Introduction

The interface between structure and architecture has been examined by scholars and practicing professionals for decades. Structure has always had a decisive influence on architecture and is usually the cause of conflict between the architect and structural engineer. Even the most average architects are good artists. A talented architect, however, must be a generalist who is knowledgeable not only in space distribution, but also in construction techniques, electrical systems, mechanical systems, real estate, finance, human behavior, and social conduct. It has been stated that the architect must know about so many professions that he is sometimes said to know nothing about everything. Pragmatism and technical expertise, however, are qualities in which the gifted engineer must possess as he is a specialist in specific aspects of the design process, and this area of expertise is the only field in which the engineer is concerned. Currently, there are structural engineers who only specialize in concrete or steel blast design and others who only specialize in earthquake design. It comes as no surprise that engineers are said to know everything about nothing.

(Salvadori, 1980)

This chapter will discuss the interface between structure and architecture, specifically in the design of tall buildings. A case study on the John Hancock Center in Chicago, Illinois will be presented in an attempt to reveal the mindset of both the architect and structural engineer when evaluating the success of a tall building.

3.2 The Structural-Architectural Link

There are many components that make up the design of tall buildings, and much research has been done to find the optimum design of these building components. Typically these components, which include columns, bracing, floor construction, skin, and mechanical systems are examined separately rather than as they relate to the building system as a whole. This method of design can be quite inefficient since there is a definite relationship among these components. Consequently, a change in one component or building system will generally result in changes in many others. For example, a deviation in the floor depth will change the building height, and therefore the overall structural, architectural, and mechanical costs of the building. Consider also the design of the core, which is dictated by vertical transportation of people and services, as well as the position of public spaces. Furthermore, the entire structural system affects the appearance and configuration of the building.

The interface between structure and architecture is without a doubt extremely complex. When structure is expressed, it should not only be structurally correct but also elegant and appealing. Structure should merge with architectural form without becoming over dominant; in addition, it should maintain a sense of "honesty". Through intimate collaboration, the structural engineer and architect are assumed to be capable of producing a design that not only satisfies the serviceability concerns of the engineer, but also fulfills the functional requirements of the client and aesthetic desires of the architect. Because every building is typically unique, there is always a need for innovative structural systems; therefore, the relationship between architect and engineer is critical. It is not to be believed that this relationship implies that the two professions become one, but rather the contrary. There should exist, however, a link between the two professions in order to help them better relate. When considering this link, one must first discover a common ground shared by the two. This common ground can be found in the concept of structural art.

Structural art embodies three basic principles: efficiency, economy, and elegance. Efficiency and economy alone are insufficient as they have proven to produce too many unattractive structures; hence, there is a need for an additional principle, which is the latter. The idea of an elegant structure is clearly compatible with the ideals of architecture and is believed to be the connection between the two professions. (CTAH *a*, 1995)

3.3 The John Hancock Center

It is a general rule of thumb that in the design of tall buildings, the need for lateral resistance to wind and seismic loads prevails throughout the structural design process. Consequently, this need greatly impacts the architectural planning along with the selection of material and structural systems. Therefore, if this matter is addressed early during the conceptual design stage of the design process better decisions on building form and planning are probable, inevitably leading to optimal conditions. When examining the interrelationship between aesthetics and structural form, an interesting case study is the John Hancock Center in Chicago, Illinois. This section will examine the efficacy of the building from the vantage point of both the architect and structural engineer by examining specific issues pertinent to each profession. First, a brief overview of the building will be presented for context.

The John Hancock Center is a 100-story mixed-use building consisting of approximately 93,000 m^2 of office and apartment space in addition to a combined total of 75,000 m^2 of parking and commercial space. The tower tapers from a ground floor plan approximately 50 by 80 m to a roof plan of about 30 by 50 m at an elevation of 344 m.

Initially, the sight was envisioned to contain, twin buildings, one commercial and the other residential; but, due to environmental concerns, this plan was eliminated and the single building design was adopted. Given that apartment usage requires relatively shallow depth from windows to core in order to provide views and natural light while office usage allows more depth, a natural result of these requirements could have been a tiered building. Instead, with the help of engineers at the Illinois Institute of Technology, Skidmore Owings and Merrill developed a tapered building with the largest feasible apartment on the forty-sixth floor and the largest office floor on the ground level. This angle of the taper was designed to not only meet the requirements of the developer, but also allow for a continuous structure to be used on the façade in order to create a tapered tube.

The structural system is made up of columns and spandrel beams along with X-bracing that all work together to form the exterior tube. The most extraordinary feature is undoubtedly the fully exposed X-bracing on the façade. These diagonal cross braces called for a challenging geometric regulation on the building as the bracing from each face had to intersect at a common point on the corners so that wind shear could be transferred directly from face to face by the bracing. The X-bracing is continuous along each face and is connected to the columns, which allows load to be transferred from bracing to columns and vice versa. Beams are present at the levels where X-bracing intersects corner columns so that the bracing could redistribute gravity loading among the columns. Because the gravity loading in the diagonals causes them to always be in compression during wind loading, simpler connections are achievable.

The exposed structure of the John Hancock Center appears thin and light; nonetheless, it retains a look of strength and stability. The elegant balance of power and lightness through the uncovering of its structural system makes the tower aesthetically remarkable.

This next section will first assess the John Hancock Center through the lens of an architect; afterwards, the tower will be examined through the scope of a structural engineer. Some assessments presented here are subjective and were attained through documented research. (CTAH *b*, 1995)

3.3.1 Architectural Perspective

Building form and aesthetics may be viewed from an architectural perspective in terms of the following traits:

- Plan View
- Elevation
- External Appearance
- Balance and Simplicity
- Proportion and Scale
- Relationship of Spaces
- Visual Impact
- Style
- Ornamentation and Décor

This list of characteristics is not complete but rather serves as a fundamental basis in which a building's aesthetics and form can be evaluated. Additional research can be performed that examine these along with other possible traits in further detail to provide a more complete evaluation.

3.3.1.1 Plan View

Although the plan view constantly varies with height, the basic rectangular concept is simple. The building's taper was adjusted to meet the requirements of the developer. Since the taper acts as a structural tube, large open spaces are available inside of the building. The apartment space begins about mid-height on the 46th floor as this was agreed to be the largest feasible floor that fits the building's program. The office and commercial space are on the building's lower levels.

3.3.1.2 Elevation

The architectural appearance achieved yet slightly dominated by the structure, which evokes a sense of strength and stability through the use of horizontal, vertical, and diagonal members.

3.3.1.3 External Appearance

This building seems to have a technological rather than architectural façade, as the structure is made highly apparent and no emphasis is placed on having a vivid and jovial color scheme.

3.3.1.4 Balance and Simplicity

The mass of the building is balanced while the architectural expression is quite straightforward.

3.3.1.5 Proportion and Scale

With respect to its surroundings, the building is quite large; however, the Xb bracing separates the building into smaller more plausible sections while the visible flooring help scale the building down to a more tolerable human level. Interestingly, the overall proportions of the building are well balanced as the moderate slope provides an elegant beauty to the buildings form. This beauty would be lost if the building was a tall perpendicular box.

3.3.1.6 Relationship of Space

A vertical linear relationship of spaces exists in the following upward order: commercial, offices, and residential apartments.

3.3.1.7 Visual Impact

The tapered form is stabilized through the diagonal braces on each of the facades as they connect the entire structure to the ground, thus suggesting a feeling of safety. The structural members are organized in a skeletal form as the building provides a contrast to its setting due to its massive size and overall dimensions.

3.3.1.8 Style

The tapered shape and X bracing gives the building a unique structurally-expressed style. Because the bracing inevitably obstructs the outside views at certain locations, the structural scheme is not enthusiastically accepted by some of the building's occupants; however, the gain in the structuralist architectural expression of the building far outweighs the sacrifice of some of its users.

3.3.1.9 Ornamentation and Décor

The aesthetic of this building lacks pretentious beauty and accentuates the structural appearance instead. With the exception of the travertine sheathing at the bottom, no other attempt was made to cover the external structure.

3.3.2 Structural Perspective

Building form and aesthetics may be considered from a structural viewpoint in terms of the following traits:

- Shape and Size
- Dimensions
- Strength and Stability
- Stiffness
- Efficiency and Economy
- Simplicity and Clarity
- Lightness and Thinness

Similar to the previous section, a brief evaluation will be presented as a basis for assessing the merit of the design but this time from the viewpoint of the structural engineer. Again, it should be stated that this list is not exhaustive and supplementary research can be performed that evaluate these and other traits in further detail.

3.3.2.1 Shape and Size

The structure is formed primarily by the taper and the X-bracing located on the building's exterior, thus giving the structure a skeletal shape. The ratio of the height to footprint dimension of the building is within the acceptable range. Furthermore, the rigid structural tube system makes the high slenderness ratio quite tolerable.

3.3.2.2 Dimensions

The ground floor is approximately 50 by 80 m and the clear span from central core is 18 m. The building is tapered to a dimension of about 30 by 50 m at the roof while the exterior clear span reduces to about 9 m. These large spans would most likely be infeasible without the external X bracing system.

3.3.2.3 Strength and Stability

As previously mentioned the tapered form and X bracing provide strength and stability to the structural system. The stability of the system is reflected through the use of structural redundancy created by the diagonals and the external columns. These columns and diagonal members connect all the sides and corners of the building to provide further stability to the system.

3.3.2.4 Stiffness

The structural system has adequate resistance to excessive deformations under loads that can potentially cause discomfort to occupants at the higher floors. The system also provides sufficient resistance to prevent excessive damage to the nonstructural elements as the X braced tube provides plenty of rigidity to the system.

3.3.2.5 Efficiency and Economy

Typically in multi-use high rise buildings, a usual solution is to place a thin building on top of a broader one allowing for the apartments to be above the offices and commercial space below. This type of approach is cost-ineffective when compared to a tapered-tube approach as the latter allows a continuous optimum structure to be used that would closely follow the flow of stresses for both gravity and wind loads. In addition, the diagonal added to the structures exterior increases the efficiency of the building, which results in a much more economical solution.

3.3.2.6 Simplicity and Clarity

The building has simple and clear connections as visible steel elements plainly show the direction of forces and also reveals the structural logic of the building's form. In addition, the joint detailing and fabrication was straightforward making the members simple to erect on site.

3.3.2.7 Lightness and Thinness

The building makes use of 145 kg/m^2 steel, which is a relatively small amount of material compared to a similar building its size. The sizes of the exterior members of the structure are proportioned to the building shape, thus giving the building a sense of thinness. This lightness and thinness result in a visual effect that the literature calls structural elegance. (CTAH *a*, 1995)

3.3.3 Conclusion of Case Study Analysis

It can be seen through this case study that both the architect and engineer have fundamentally different perspectives on what qualities an effective building should possess. However, there is typically a common degree of elegance that both professions usually agree should be present within the building's form.

The next chapter will introduce the general optimization problem and will utilize a basic multi-objective optimization technique for the potential design of a high rise structure, which considers the aforementioned engineering and architectural issues addressed within the past three chapters.

CHAPTER 4 THE GENERAL OPTIMIZATION PROBLEM

"If you optimize everything, you will always be unhappy."

-Donald Knuth

4.1 Introduction

All optimization problems share a common structure, which typically includes a cost-related objective to be minimized, or an achievement objective to be maximized. These objectives are usually controlled by constraints that limit the range of possible design specifications that could be utilized and can either be linear or nonlinear in nature. Linear programs are decision models that contain both a linear objective function and linear constraints, which can be easily solved by modern computers. Nonlinear programs, however, are decision models that contain nonlinear objective functions, nonlinear constraints, or both. These types of programs are not as straightforward in solving as nonlinear programs and require careful investigation in order to determine their solution.

This chapter will first present the common form of the optimization problem through examples of basic nonlinear program models that deal with issues related to the current research. After that, a brief discussion on multi-objective optimization will be presented. Finally, the chapter will end with a brief description of a useful linear multi-objective optimization approach that can be utilized in the conceptual design of high rise structures.

4.2 Designing a High Rise Building for Cost

The Problem:

A city developer has decided to build a high rise building on a large downtown site. The developer requires that the building provide at least 1,000,000 square feet of leasing space due to estimated future demand. For simplicity, let's say the footprint of the building is square.

Assume that a consultant has found a formula for the cost of construction and this consultant discovers that the foundation cost is proportional to the footprint area multiplied by the number of floors raised to the (1/4)th power. He also realizes that the building cost is directly proportional to the product of floor area and the number of floors raised to the (3/2) power, that is,

$$Foundation\ \ Cost = Ax^2 z^{1/4} \qquad\qquad Building\ \ Cost = Bx^2 z^{3/2} \quad \text{(4-1a, b)}$$

which means that the total cost, C, is

$$Total\ Cost = C = Ax^2 z^{3/2} + Bx^2 z^{3/2} \qquad \text{(4-2)}$$

where,

x= the length in feet of the side of the building
z= the number of floors of the building

with A and B as proportionality factors. The developer has to determine the footprint and number of stories for his building to minimize cost and the 1,000,000 square foot space requirement is satisfied.

Optimization Model Formulation:

This optimization problem has a single nonlinear objective, which is,

Minimize $Ax^2z^{3/2} + Bx^2z^{3/2}$ *(cost)*

and a single nonlinear constraint, which is

Subject to: $x^2z \geq 1{,}000{,}000$ *(space requirement)*

In this case, since the building will not be built larger than needed, the single constraint becomes an equality constraint.

4.3 Designing a Building for Space

The Problem:

This same developer realizes that he may have over-estimated future demand and decides to eliminate his space requirement. Instead, he decides to give his building a much more peculiar shape in order to attract more potential clients. As a result, he approaches an architectural firm to aid in developing a more unusual shape for his building. For simplicity, let's say that the architectural firm decides to come up with the concept of a tent-like building, which is not highly unusual but will be considered so for this illustration. Furthermore, the building is vertically symmetric with straight sides one half the length of the site and one base dimension spanning the entire length of the site. Given that the site has a certain square area, the challenge for the firm is to select the height of the building such that the volume inside is maximum in order to create a highly flexible space.

Optimization Model Formulation:

A diagram of the fundamental shape of the building is shown in Figure 8. The basic approach is to let the unknown height of the building be represented by *h* and the cross-sectional base of the building be represented by *b*.

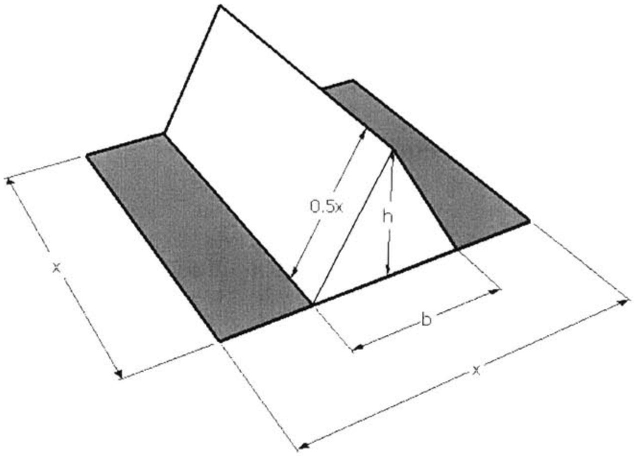


Figure 8 Basic concept of the tent-like building scheme

As a result, the volume inside of the building is the cross sectional area of the building, which is *(½)bh*, multiplied by the length of the building, x. Therefore the nonlinear objective function is,

$$\text{Maximize } Z = \frac{1}{2}bhx$$

and the single constraint for the problem is based on the Pythagorean Theorem, which constrains the base and height of the building with respect to the building side as follows,

$$\text{Subject to: } (0.5b)^2 + h^2 = (0.5x)^2$$

Both of the examples were greatly simplified; however, the point of both examples was to illustrate to entirely different objectives encountered in building design. As you can see, both the objective function and the single constraint for both of these examples are nonlinear. For these particular nonlinear problems, conventional methods exist that can find the optimum solution. In fact, for relatively small nonlinear optimization problems there are quite a few techniques that are capable of finding optimum solutions-some of which include dynamic programming, unconstrained optimization, calculus with substitution, Lagrange multipliers, and the gradient search methods. For the sake of brevity, these methods will not be discussed; but, one technique for optimization of numerous objectives will be explained at the end of the chapter. Next, a discussion on multi-objective optimization using linear programming will be discussed.

4.4 Optimization of Multi-objectives

As previously mentioned, in the design and construction of a high-rise building, there are typically multiple goals that strive to be obtained during the process. In fact, for many engineering management problems, more than one objective is generally encountered. More often than not, these objectives conflict as various interested parties have contradictory goals. Multi-objective programming handles optimization problems with two or more objective functions and differs from the single-objective problem as it doesn't seek a best overall solution, but rather quantifies the degree of conflict, or tradeoff, among objectives. Stated differently, the aim is to find the set of solutions, known as the noninferior set, for which no other better solutions can be found to exist.

Quite a few optimization techniques have already been developed to capture explicitly the tradeoffs that may exist between incompatible and perhaps disproportionate objectives. This next section will first introduce the idea of *noninferiority*. After that, a brief explanation of a useful multi-objective optimization technique for generating the noninferior set of solutions will be discussed.

4.4.1 Noninferiority and the Noninferior Set

Single-objective programs seek to find the single feasible solution or solutions that provide the optimal value of the single objective function. For programs having multiple objectives, the solution that optimizes any one objective generally will not optimize any other. In fact, for any extremely challenging decision-making problem, there is typically a significant degree of conflict between objectives. These conflicting objectives may sometimes contain different units of measure as well. In this case, such objective functions are called *noncommensurate.* Consider a structural design problem in which the engineer wishes to not only maximize strength but also minimize weight or cost. Obviously the strength objective is at odds with the weight or cost objective. In addition, the unit of measure for strength is unlike the unit of measure for weight or cost.

Because a strategy that is optimal with respect to one objective may likely be clearly inferior for another, a concept must be introduced that measures solutions against multiple, conflicting, and noncommensurate objectives. This concept is known as *noninferiority*, and can be defined as follows:

A solution to a problem having multiple and conflicting objectives is noninferior if there exist no other feasible solution with better performance with respect to any one objective, without having worse performance in at least one other objective.

Therefore, the purpose of this type of analysis is to create the *noninferior set* , which are all solutions that are noninferior. This is also sometimes called the *Pareto frontier*, which was seen in Figure 8 of Chapter 2 for the office building design. It should be noted that the determination of noninferiority gets progressively more complex as problems grow in both the number of constraints and the number of objectives. In the following section a method for producing the noninferior set will be summarized, which is called the weighting method.

4.4.2 Weighting Method

Recognized as being the oldest and probably most frequently used multi-objective solution technique, the weighting method can be performed as follows:

1. Specify the objectives, decision variables, and constraint equations.
2. Solve *n* linear programs, each having a different objective function.
3. Combine all objective functions into a single-objective function by multiplying each objective function by a weight and adding them together such that

   $$\text{Maximize} Z = \lfloor Z_1, Z_2, Z_3, \ldots, Z_p \rfloor$$

   takes the form

   $$\text{Maximize} Z(w_1, w_2, w_3, \ldots w_p) = w_1 Z_1 + w_2 Z_2 + w_3 Z_3 + \ldots + w_p Z_p$$

   which is known as the *grand* objective. For minimization objectives, simply multiply the *grand* objective function by -1 to change its sense to a maximization objective.
4. Solve a series of linear programs using the grand objective while methodically varying the weights on the individual objectives.

   It should be duly noted that this method seems to be applicable only for programs with linear objectives and constraints. Unfortunately, objective functions and constraints are nonlinear in most engineering-related management problems. As a result, a method of linear approximation known as *piecewise approximation* can be adopted in order to transform certain nonlinear objective functions and constraints into linear functions.

4.4.3 The Governing Multi-Objective Problem

Now that a brief introduction of the optimization problem has been explained, consider the scenario of the design of a high rise building that must fulfill the objectives of multiple interested parties (owner, architect, engineer, contractor, etc.) under a given amount of parameters similar to but not limited to those encountered in the office building design in Chapter 2 (see Table 7). In this scenario, however, imagine that some objectives are more important, or more heavily weighted, than others and it is assumed that this hierarchy of objectives is known. Therefore, the *governing multi-objective problem* can be stated as follows:

$$\text{Maximize} \quad Z = w_1 Z_1(x_1, x_2, \ldots, x_n) + w_2 Z_2(x_1, x_2, \ldots, x_n) + w_3 Z_3(x_1, x_2, \ldots, x_n) + \ldots + w_p Z_p(x_1, x_2, \ldots, x_n)$$

$$\begin{aligned} \text{Subject to:} \quad & g_1(x_1, x_2, \ldots, x_n) \leq b_1 \\ & g_2(x_1, x_2, \ldots, x_n) \leq b_2 \\ & \ldots \\ & \ldots \\ & \ldots \\ & g_m(x_1, x_2, \ldots, x_n) \leq b_m \\ & x_j \geq 0 \, \forall_j \quad (\mathit{for\ all\ j}) \end{aligned}$$

(ReVelle et al, 2004)

where **Z** is the grand objective while $Z_1(x_1, x_2, \ldots, x_n)$, $Z_2(x_1, x_2, \ldots, x_n), \ldots$, and $Z_p(x_1, x_2, \ldots, x_n)$, are the *p* individual objectives as a function of certain governing parameters of the structure. It should be duly noted that this technique assumes that the parameters listed in Table 7 along with possible others can be defined in such a way that certain basic structural parameters, such as story height, total height, maximum deflection, and mass distribution can be specified with the intention that a subsequent dynamic analysis could be conducted. Further research is recommended to examine the feasibility of this assumption.

CHAPTER 5 TALL BUILDING STRUCTURAL ANALYSIS

"The technical man must not be lost in his own technology. He must be able to appreciate life; and life is art, drama, music, and most importantly, people.

-Fazlur Khan

5.1 Introduction

For this chapter we assume that the *governing optimization problem* was solved for a specific high rise structure so that the optimum structural system was a 40-story braced frame as shown in the Figure 10. The following investigation includes a dynamic analysis of a multi-degree of freedom braced frame. The idea of *relative* and *elasticity* measures in tall buildings will also be introduced.

5.2 Dynamic analysis of the multi-degree of freedom system

The following input parameters were used for the dynamic analysis, which are assumed to be derived from the solution to the *governing multi-objective problem*:

$n=40$

$H= 160$ m

$h= 4$ m

$m_j=1000.05882 - j/7 \quad (j=1\ldots n)$

$u_{max}=0.027$ m

where n is the number of stories, H is the total height of the building, h is the story height, m_j is the mass of the j^{th} floor, and u_{max} is the maximum deflection, or maximum drift. Notice that in this assumed solution to the *governing multi-objective problem* the mass varies with height. The 40 story braced frame system was simplified into a multi-degree of freedom system containing 40 masses.

The governing equation of motion for this system is defined as follows:

$$M\ddot{u}+C\dot{u}+Ku=P \tag{5-1}$$

where **M**, **C**, **K**, and **P** are the mass, damping, stiffness, and force matrix, respectively. In this problem, the force matrix is created by a triangular horizontal wind load applied at each story. The wind load is assumed to reach a maximum value of 14.59 kN/m at the top story with a forcing frequency of 1.5π rad/sec. The structure was assumed to contain about 5% damping.

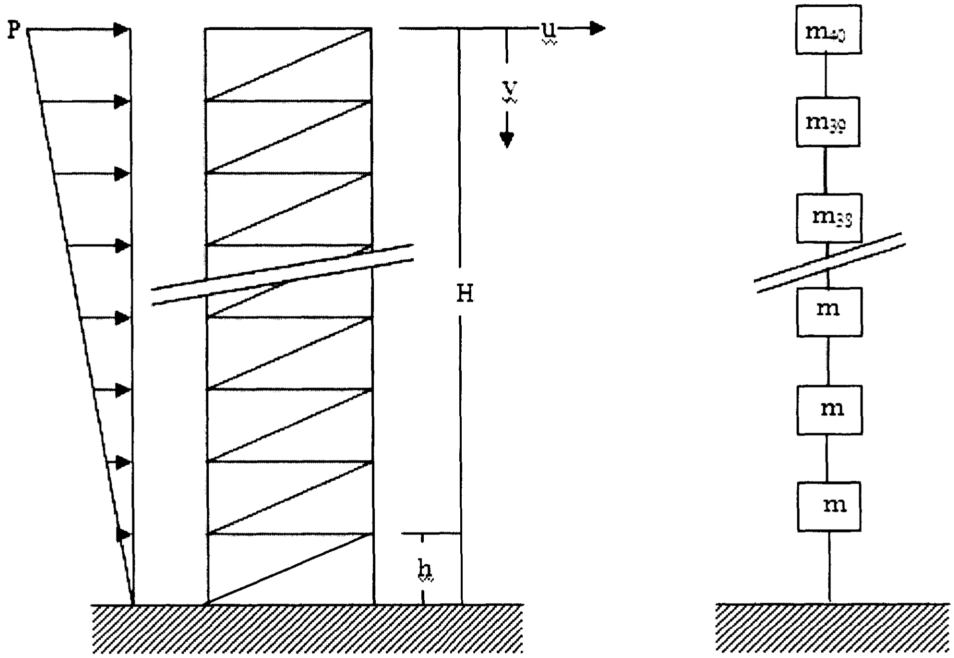


Figure 9 40-story braced frame modeled as a multi-degree of freedom system

In order to begin a dynamic analysis on this multi-degree of freedom system a mode shape had to first be specified. Because the system represents a high rise building, modeling the structure solely as a discrete shear beam is inaccurate. As a result, a generalized approach was adopted that estimates the deflection of a family of cantilevers based on their shear and bending characteristics (Stafford Smith et al, 1981). This method was utilized to determine a reasonable estimate of the modal profile of the deflected 40 story braced frame.

After the mode shape was specified, the governing equation of motion was solved using a slightly modified version of Connor's approach (Connor, 2003). It was observed that two sets of stiffness, damping, and natural frequency parameters were found that satisfy the maximum displacement, u_{max}, criterion. The first set contains a natural frequency of about 6.49 rad/sec (0.97 sec) while the second set has a natural frequency of about 1.46 rad/sec (4.3 sec). The second solution strategy gives a natural period which agrees with the generally accepted formula for estimating the natural period for tall buildings. This formula states that the natural period is equal to about one-tenth of the number of stories of the building; therefore, a 40 story building would have a natural period of about 4 seconds.

Both sets of solution strategies are presented in this section; however, it was decided that the most feasible solution would be the second solution set since it requires less stiffness, which means it would be less expensive to implement. In addition, the nodal accelerations of the floors for the first solution strategy were far beyond the 0.02*g* comfort limit for a typical building (Connor, 2003). Consequently, the following section will utilize the second solution strategy to introduce a new technique in dynamic analysis of tall buildings.

5.2.1 Maximum Deflected Shape

Figure 11 is the maximum displacement profile for the braced frame. This displacement profile was estimated using the generalized equation developed by Stafford Smith (Stafford Smith et al, 1981), which considers both bending and shear effects of the system. In order to apply this equation, a few assumptions needed to be made on the member properties of the system as a first guess approximation of the displacement profile of the 40 story braced frame system. The frame is considered to be a simple beam-to-column connection; hence, there is no rigid frame action. The member properties are as follows:

Area of the columns, $A_c = 0.074\ m^2$

Area of the diagonals, $A_d = 0.0093\ m^2$

Modulus of elasticity, $E = 2.07 \times 10^8$ kPa (for all members)

Flexural rigidity of the uncoupled vertical elements, $EI = 0.1296E$

Flexural rigidity of the fully composite section, $EI_g = 129.6E$

Racking shear rigidity of the coupled structure, GA = 0.0361E and the general deflection equation can be stated as,

$$u = \frac{pH^4}{EI_g}\left[\frac{11}{120} - \frac{1}{8}\left(\frac{y}{H}\right) + \frac{1}{24}\left(\frac{y}{H}\right)^4 - \frac{1}{120}\left(\frac{y}{H}\right)^5 + \frac{1}{(k^2-1)(k\alpha H)^2}\left\{\frac{1}{3} - \frac{1}{2}\left(\frac{y}{H}\right)^2 + \frac{1}{6}\left(\frac{y}{H}\right)^3 - \frac{1-\left(\frac{y}{H}\right)}{(k\alpha H)^2} + \frac{\cosh k\alpha(H-y) + \left(\frac{1}{k\alpha H} - \frac{k\alpha H}{2}\right)(\sinh k\alpha H - \sinh k\alpha y) - 1}{(k\alpha H)^2 \cosh k\alpha H}\right\}\right] \tag{5-2}$$

where *p* is the intensity at the top of the triangularly distributed load, *k* is the ratio of the fully composite inertia, I_g, to the sectional area inertia $\Sigma A_i c_i^2$ and, α^2 is the ratio of the racking shear rigidity of the coupled structure to the flexural rigidity of the uncoupled vertical elements. Note that c_i is the distance from the centroid of wall i to the common centroid of the wall sectional areas. In this structure, *k* is 1.0005, and α is 0.5278. (Stafford Smith et al, 1981)

For the general deflection equation above, notice that the height is measured from the top of the building (see Fig. 10). Observe that the maximum deflection at the top of the building (y = 0 m) is about 0.027 m, which is the specified maximum deflection.

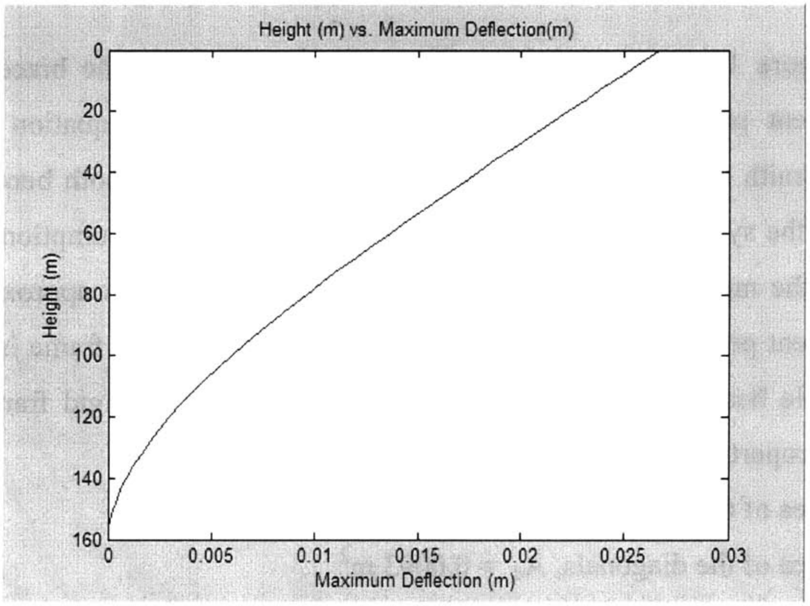


Figure 10 Height vs. Maximum Deflected Shape

This maximum deflection profile was taken as the desired mode shape of the 40 story braced frame and a dynamic analysis was conducted to obtain required stiffness and damping values for each story of the structure. This technique is slightly different from Connor's approach in which he considers an *s* factor to account for shear and bending deformation (Connor, 2003). The current study also considers both shear and bending deformation of the structure and defines a nonlinear mode shape. Furthermore, the damping was proportioned to the element stiffness. As previously mentioned, two sets of stiffness and damping values were acquired that satisfy the maximum deflection criterion. The two sets of required stiffness and damping parameters along with the nodal response values are presented in the following section.

5.2.2 First Solution Strategy

This solution strategy requires a natural frequency value of about 6.49 rad/sec and requires a greater amount of stiffness than the second strategy as will be seen.

5.2.2.1 Required Stiffness and Damping

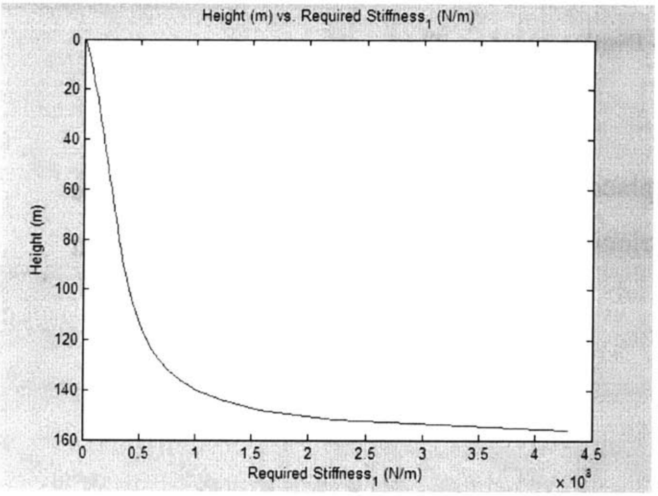


Figure 11 Height vs. Required Stiffness

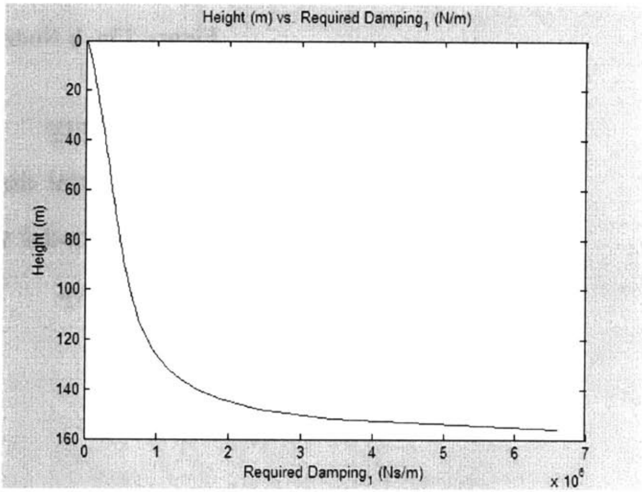


Figure 12 Height vs. Required Damping

5.2.2.2 Nodal Displacement

This plot contains 40 sinusoidal lines that give the total displacement of each node vs. time. The first figure below plots the response over a 10 second period and the second figure plots the response over a 30 second period. Data was recorded at one half second intervals. Notice that as time passes the response grows until it reaches the limiting u_{max} value for the 40th node. This peak nodal displacement occurs after about 8 seconds.

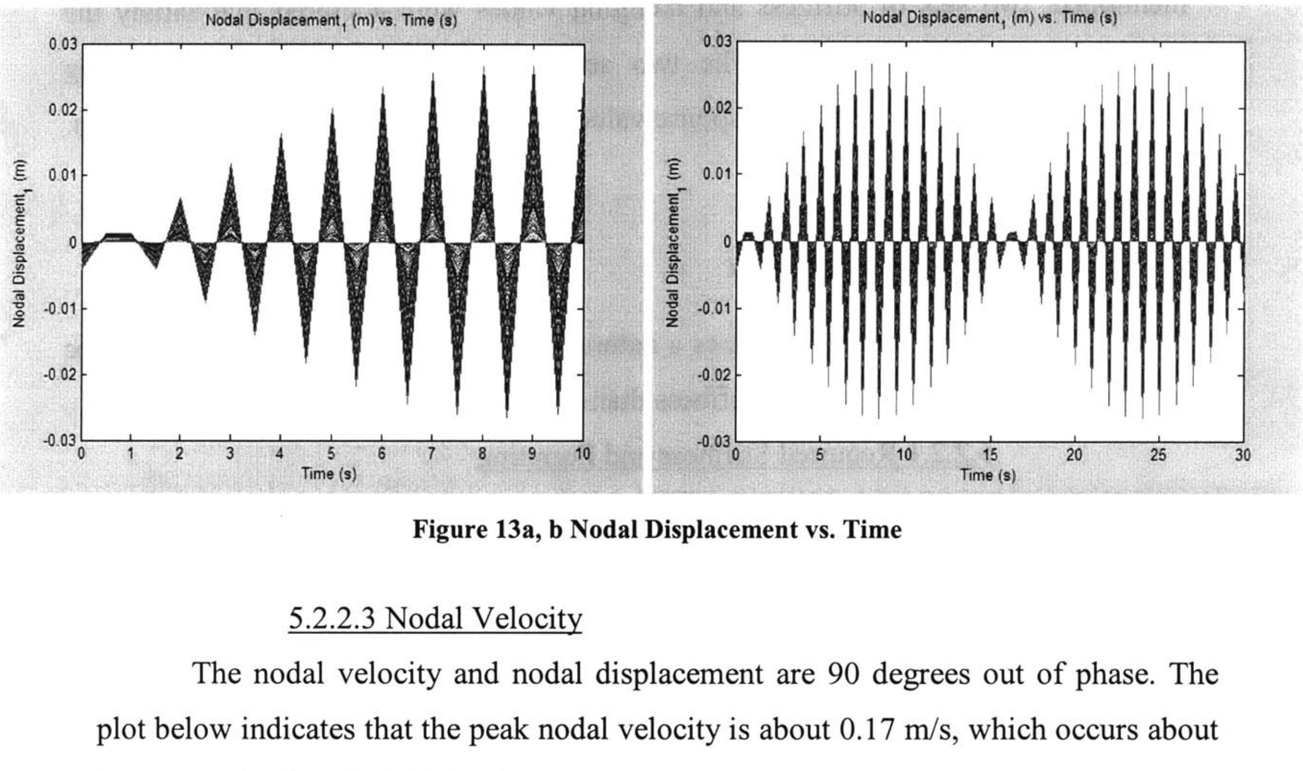


Figure 13a, b Nodal Displacement vs. Time

5.2.2.3 Nodal Velocity

The nodal velocity and nodal displacement are 90 degrees out of phase. The plot below indicates that the peak nodal velocity is about 0.17 m/s, which occurs about 16.5 seconds after the initial velocity.

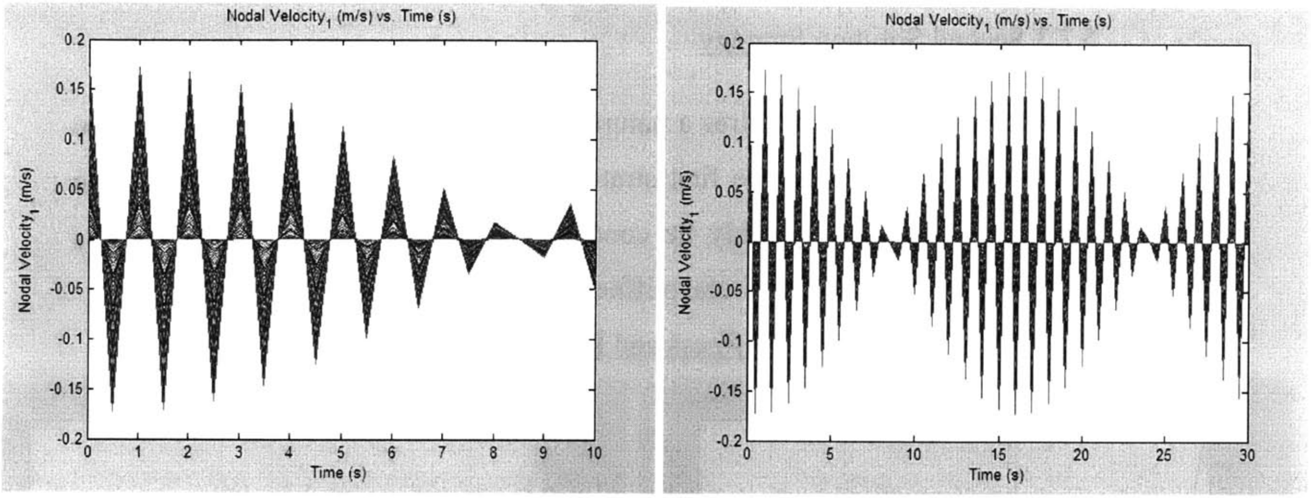


Figure 14a, b Nodal Velocity vs. Time

5.2.2.4 Nodal Acceleration

The nodal acceleration is in phase with the nodal displacement. Notice that the peak nodal acceleration reaches a value of about 1.12 m/s^2, or 0.11*g*, which exceeds the maximum comfort level (0.02*g*).

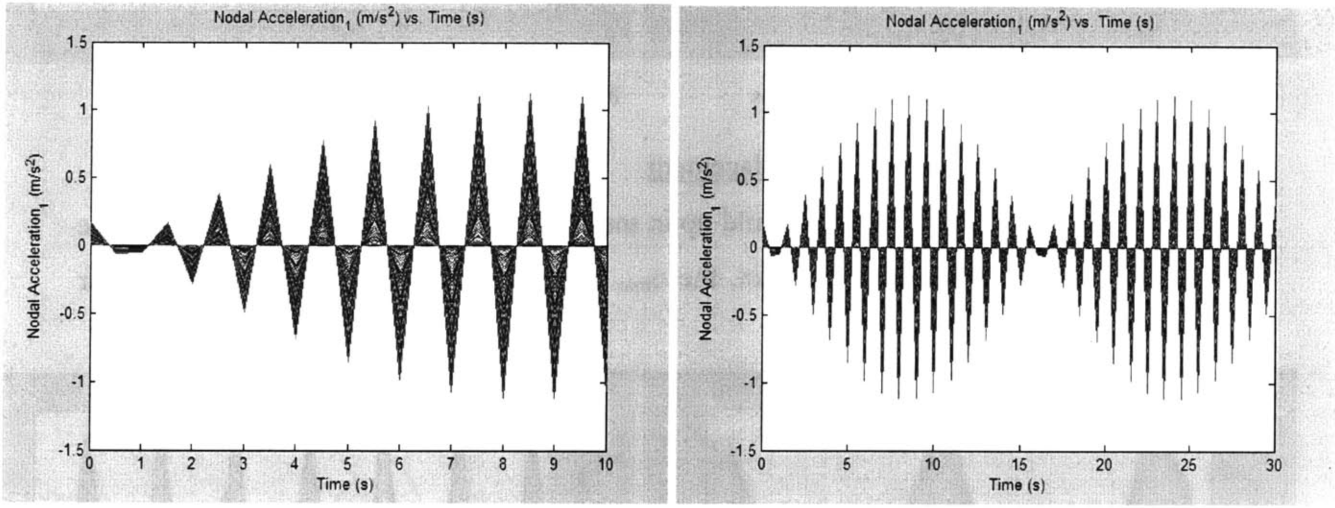


Figure 15a, b Nodal Acceleration vs. Time

5.2.3 Second Solution Strategy

This solution strategy requires a natural frequency value of about 1.46 rad/sec and requires less stiffness than the first strategy. The required damping remains the same; therefore, it could reasonably be concluded that this strategy would be less expensive than the first in terms of total stiffness and damping cost.

5.2.3.1 Required Stiffness and Damping

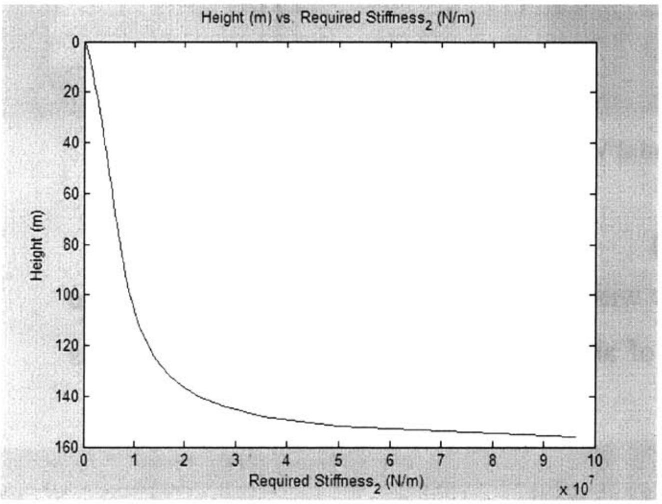


Figure 16 Height vs. Required Stiffness

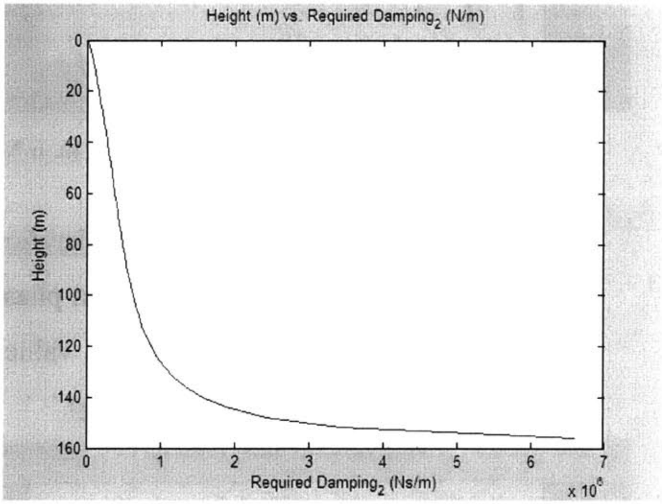


Figure 17 Height vs. Required Damping

5.2.3.2 Nodal Displacement

Observe that there is no build up in maximum nodal displacement through time for the second solution set. In fact, the u_{max} value for the 40th node is attained after about 1 second.

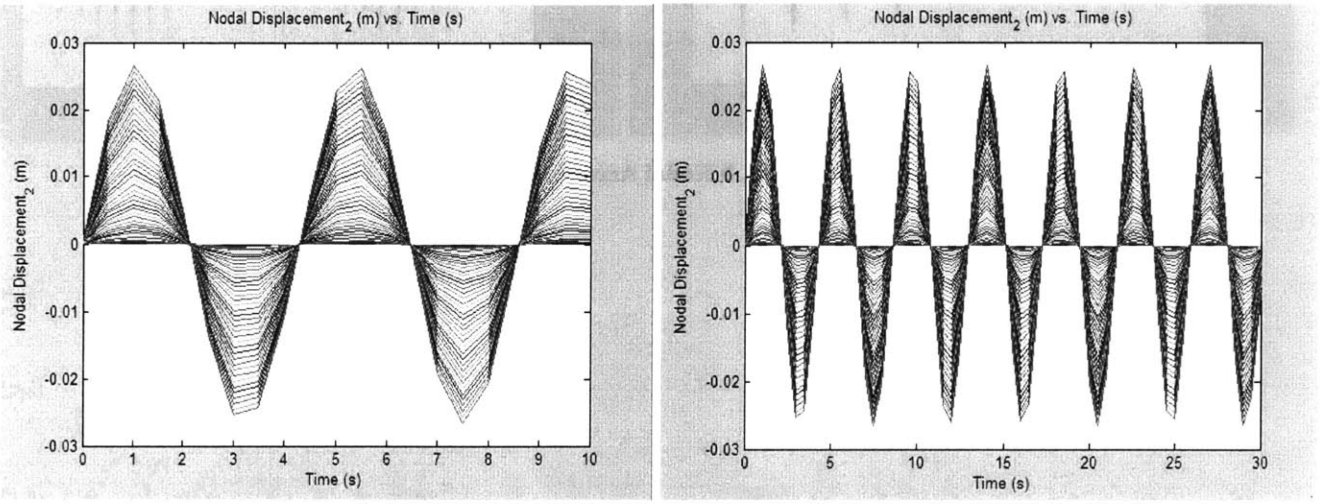


Figure 18a, b Nodal Displacement vs. Time

5.2.3.3 Nodal Velocity

The peak nodal velocity for the second strategy is about 0.04 m/s, which occurs about 2 seconds after the initial velocity.

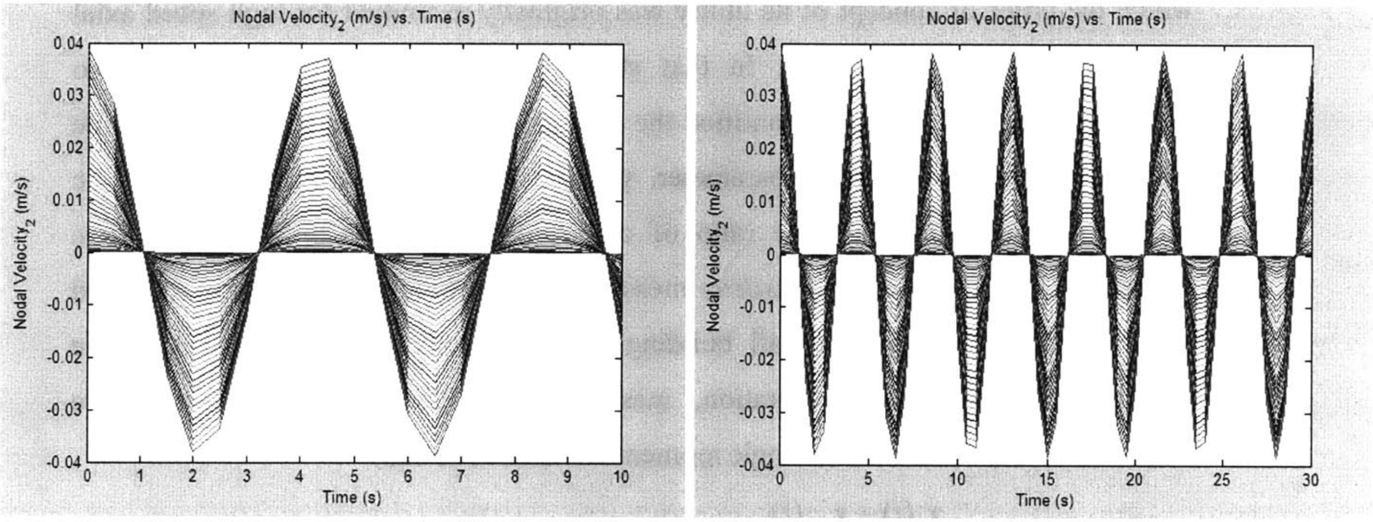


Figure 19a, b Nodal Velocity vs. Time

5.2.3.4 Nodal Acceleration

The maximum peak acceleration for the second solution strategy is about 0.057 m/s^2, or 0.01*g*, which is less than the maximum comfort level (0.02*g*). This ma

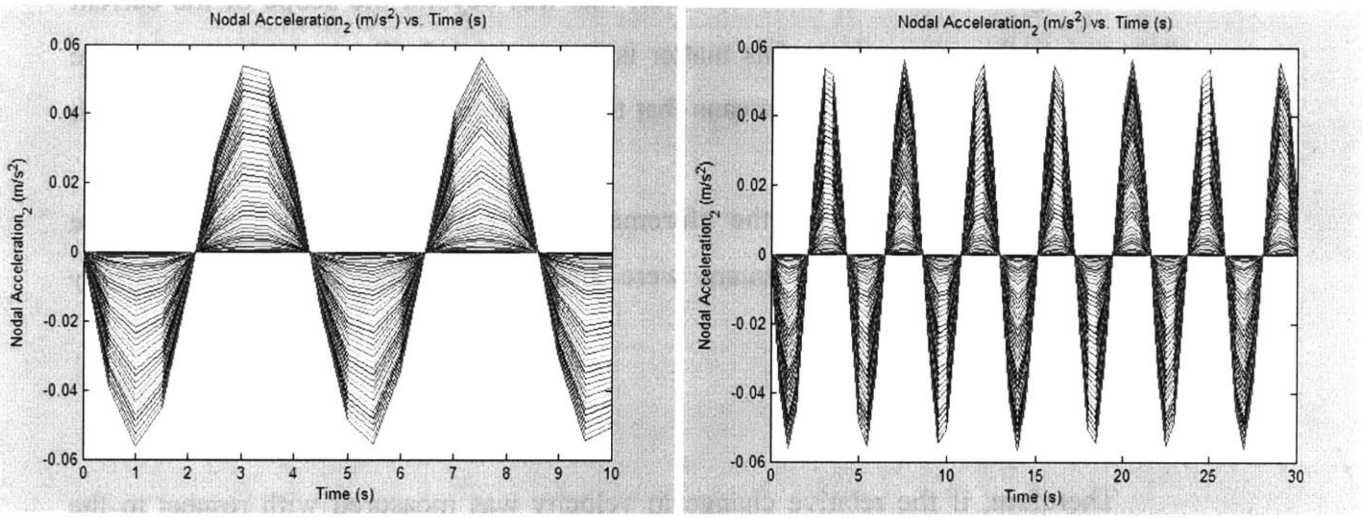


Figure 20a, b Nodal Acceleration vs. Time

5.3 Relativity and Elasticity

A new technique for analyzing the characteristics of multi-degree of freedom systems was developed. This technique employs the idea of *relativity* and *elasticity* in which the proof of concept of its utility was originally examined for high speed axial compressors (Coleman, 2006). In that study Coleman and McGee created two measures. The first measure quantified the change of a parameter with respect to the average change of that same parameter, which is called a *relative* measure. The second measure quantified the ratio of one *relative* measure to another *relative* measure, which is called an *elasticity* measure. This technique was slightly modified for the dynamic analysis of tall buildings. In this study, relative changes in the displacement, velocity, acceleration, mass, stiffness, damping, and force were measured across each node at single moments in time such that,

$$rel^*(x_i) = \frac{x_i(t) - x_{i-1}(t)}{\left(\dfrac{x_i(t) + x_{i-1}(t)}{2}\right)} \tag{5-3}$$

where x_i is the desired parameter of/on the i^{th} floor at a certain instance in time, t.

These relative changes in each parameter can also be measured for a particular node at single moments in time; however, this was beyond the scope of the current study and further research on this matter is recommended. The asterisk (*) over the relative and elasticity measures means that the parameters were measured across each node at single moments in time.

The relative changes of the aforementioned parameters with respect to the relative change in the displacement were also quantified such that the *elasticity* measure can be defined as,

$$E_u^*(x_i) = \frac{rel^*(x_i)}{rel^*(u_i)} \tag{5-4}$$

Therefore, if the relative change in velocity was measured with respect to the relative change in displacement, this measure would be called a "velocity-displacement" elasticity measure. All relative and elasticity measures are plotted against height. Since all elasticity values are measured with respect to displacement, the "displacement-displacement" elasticity was not calculated since by definition this would be a trivial measure as the relative change in one parameter with respect to the relative change in that same parameter is one. The results of the study are presented in the following section.

5.3.1 Relative and Elasticity Measures

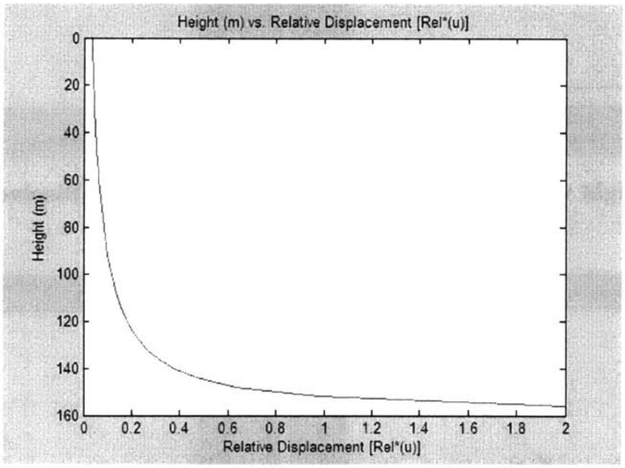


Figure 21 Height vs. Relative Displacement

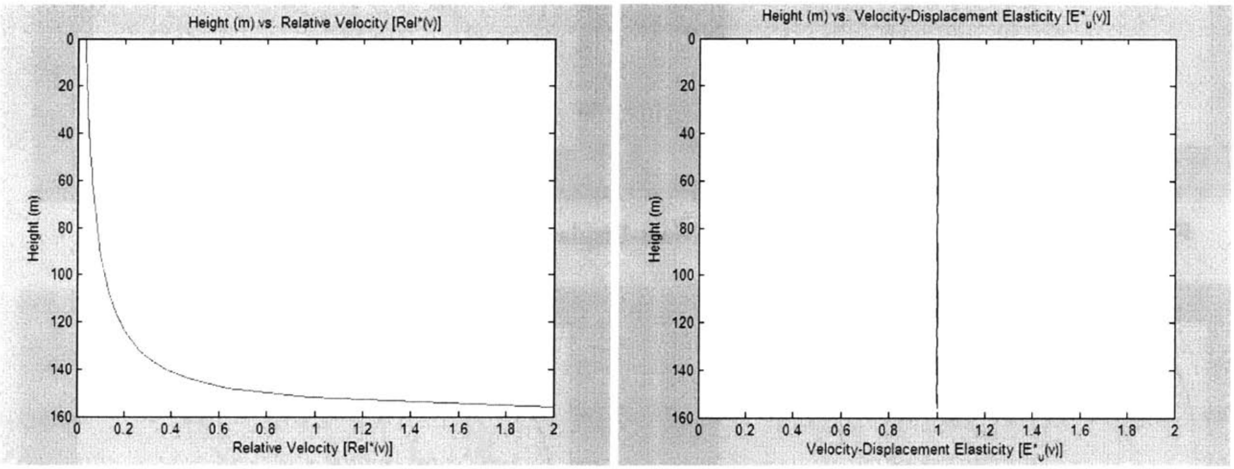


Figure 22a, b Height vs. Relative Velocity and Velocity-Displacement Elasticity, respectively

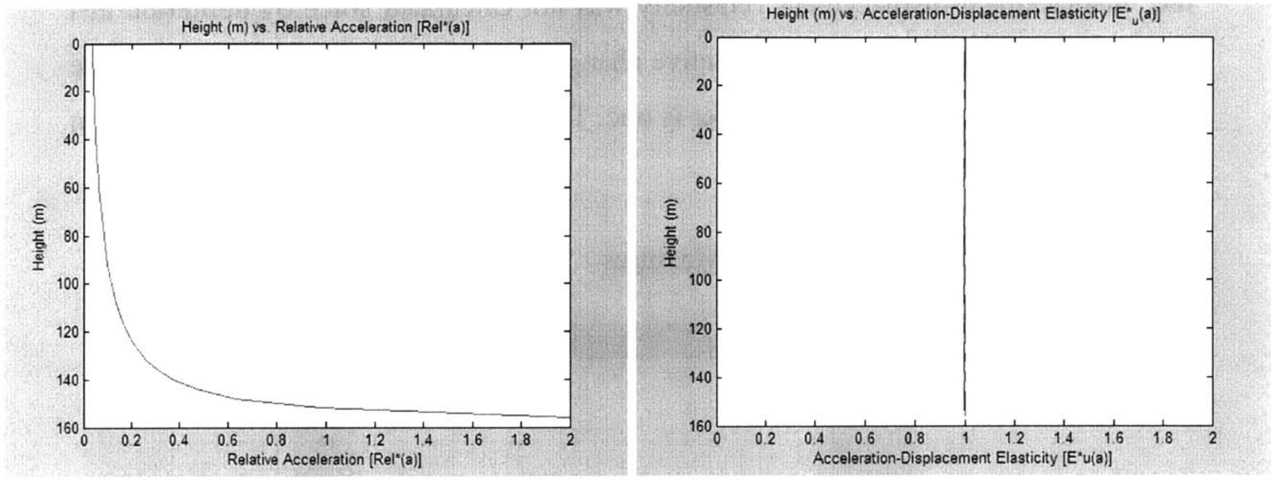


Figure 23a, b Height vs. Relative Acceleration and Acceleration-Displacement Elasticity, respectively

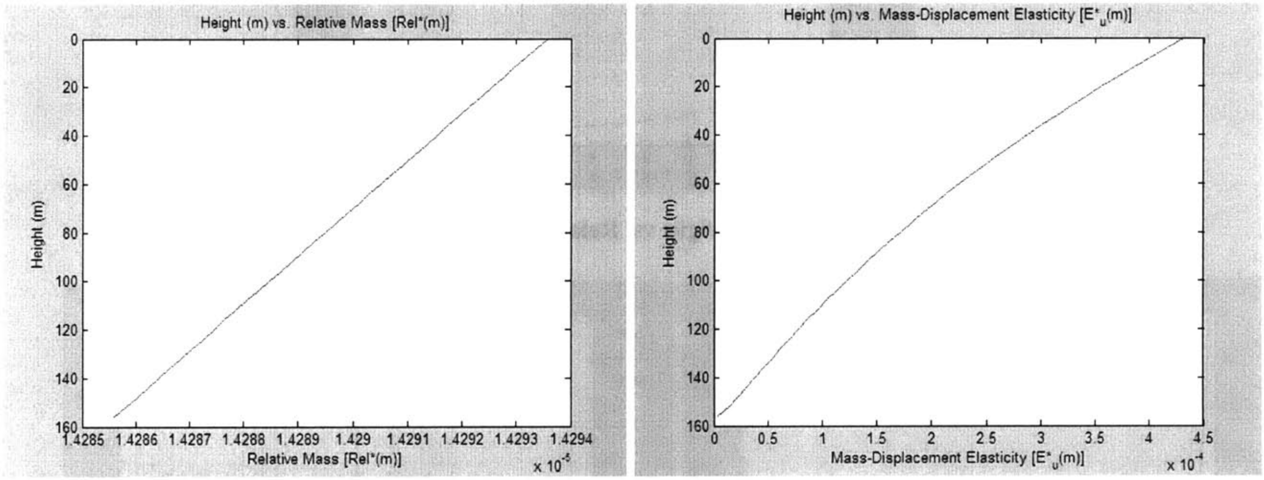


Figure 24a, b Height vs. Relative Mass and Mass-Displacement Elasticity, respectively

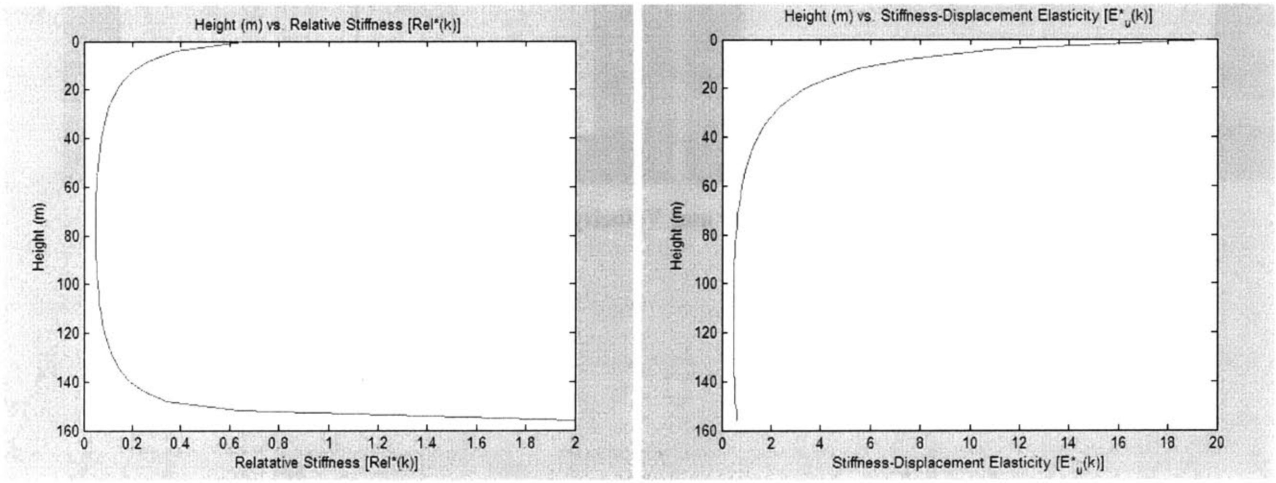


Figure 25a, b Height vs. Relative Stiffness and Stiffness-Displacement Elasticity, respectively

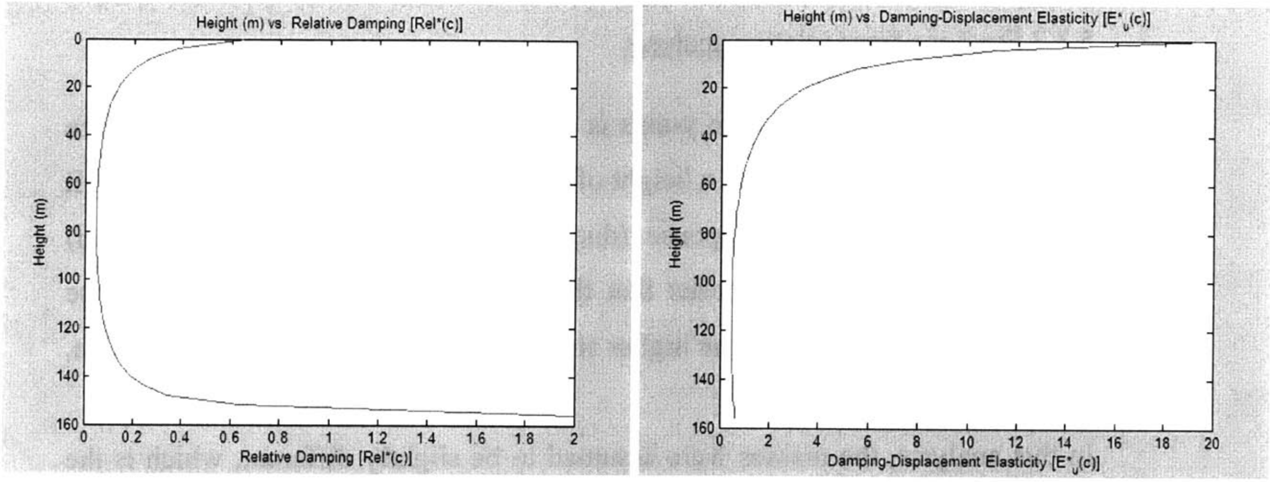


Figure 26a, b Height vs. Relative Damping and Damping-Displacement Elasticity, respectively

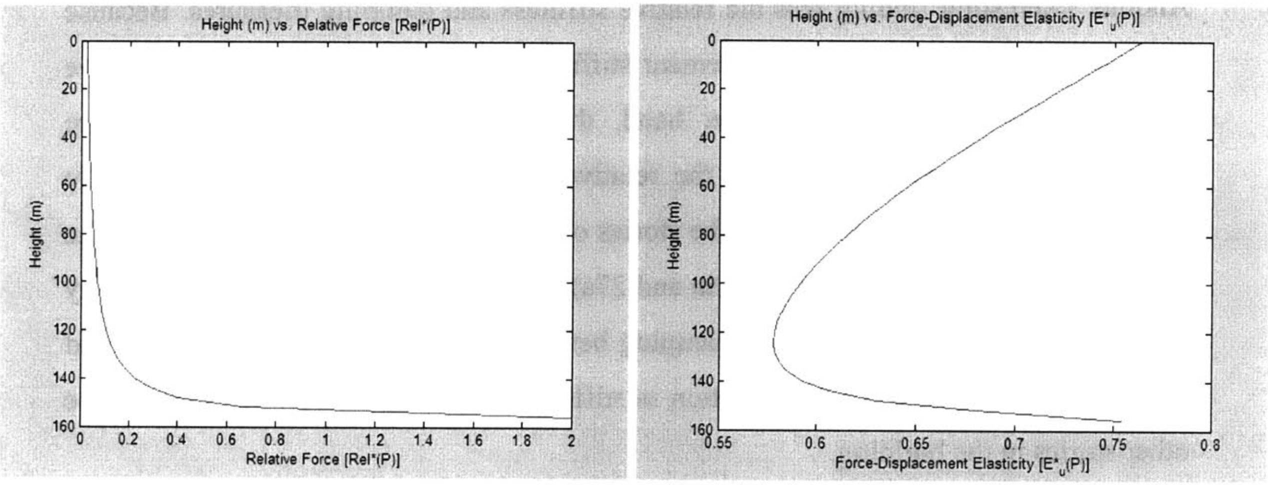


Figure 27a, b Height vs. Relative Force and Force-Displacement Elasticity, respectively

After examining the findings of the current analysis, several conclusions were made regarding the relative and elasticity measure. It should be duly noted that both the relative and elasticity measures are measured across each story of the building at various instances in time. It was found that both measures were time invariant; thus, both measures can be characterized by one single moment in time. The next sections will first discuss the findings of the relative measures and afterward discuss the findings of the elasticity measures.

5.3.2 Findings from relative analysis

It should be restated that the y-axis is measured from the top of the structure down towards the ground; therefore, a height of 0 m indicates the top of the building. It was observed that the relative response (displacement, velocity, and acceleration) decreases with elevation, which means that there is a greater variation in response between the lower stories than for the higher stories of the building (see Figs. 22, 23a, and 24a).

In this analysis, the masses were assumed to be slightly different, which is the reason why the relative mass is practically zero between all stories (see Fig. 25a). Another interesting finding was the relative stiffness and damping measures. Because the damping was proportioned to element stiffness, it is no surprise that their relative measures are similar; on the other hand, the characteristic of the measures are noteworthy. The results show that the relative stiffness and damping measures are relatively constant through most of the stories of the building with the exception of the lower and higher stories (see Figs. 26a and 27a). This suggests that there is a relatively large variation in the stiffness and damping between a small portion of the lower and higher stories compared to the variation in stiffness and damping between most of the other stories in the building.

Recall the force on the structure was a triangular wind load acting horizontally. Notice that the relative force characteristic is similar to the characteristic of the relative response, which suggests that there could possibly be a proportionality factor that relates the relative force to the relative response for each floor (see Fig. 28a). This proportionality factor is the elasticity measure and will be discussed in the following section.

5.3.3 Findings from elasticity analysis

The results of the elasticity analysis have also been presented. As previously mentioned, since the elasticity was measured with respect to displacement, the "displacement-displacement" elasticity is a trivial measure and was not considered in the analysis. In fact, it was realized that the elasticity was also one for the other two responses (velocity and acceleration) when taken with respect to displacement (see Fig 23b and 24b). Therefore, it can be concluded that there is a constant one to one relationship between the relative measures of all three response values along the entire structure.

There is not, however, a constant one to one relationship between the relative measures of the other parameters across each story and the relative response across each story. It was observed that the mass-displacement elasticity was nearly zero, which is due to the fact that there is very little change in mass across each story (see Fig. 25b). There may be a significant difference in the findings if there were a major difference in mass for each story. Further research on this matter is recommended.

Other results show that the stiffness-displacement elasticity is relatively constant throughout the entire building until a sudden increase occurs around 30 feet from the top of the structure. As expected, the damping-displacement elasticity was in agreement with the stiffness-displacement elasticity results (see Figs. 26b and 27b). The force-displacement elasticity was quite interesting as it suggested that the relative force between each story is related to the relative displacement between each story by a proportionality factor that decreased until it reached an elevation of about 30 m from the ground and then increased along the rest of the structure.(see Fig. 28b).

5.4 Summary of findings from Tall Building Analysis

In this investigation, two solution strategies were developed that limit the maximum deflection of a 40-story braced frame. It was decided that the second solution would be more desirable in terms of cost since it requires less stiffness, which means it would be less expensive to implement.

In addition, this investigation indicated that a relative analysis may be quite useful in examining the response, mass, stiffness, damping, and force in a multi-degree of freedom system while an elasticity analysis may also be worthwhile when investigating these same issues, with the exception of the response. Further research on this matter is suggested.

CHAPTER 6 CONCLUSION

6.1 Brief summary of study and future work

It can be argued that much progress has been made in the application of structural optimization since Cohn's reflection on the topic in 1994. With that in mind, there is still much more work that needs to be done in designing a building that performs at its optimal level from the vantage point of not only the structural engineer, but also others involved in the design, such as the owner, architect, and other engineers. When considering others involved, aforementioned issues arise that are usually neglected by the structural engineer.

The present study discussed current advances in the field of structural optimization which are now being applied to much more complex systems, such as high-rise structures. The notion of the importance of *inclusive* optimization was stressed while a basic technique for multi-objective optimization was utilized so that multiple interests could be considered in the conceptual design stage of tall buildings. Two interests in particular, the architect and engineer, was examined. Finally, this research not only conducted a dynamic analysis of a 40-story braced frame, but also introduced two potentially useful measures in the analysis of tall buildings.

Further research on the implementation of the *governing multi-objective problem* for tall buildings is suggested along with further study of the *relative* and *elasticity* measures. In striving toward the optimal building other possible approaches should be considered- two of which have been suggested in the following section.

6.2 Alternate approaches

Other issues such as thermal design and control (Wright et al, 2001), and thermal comfort and sustainability (Nicol et al, 2002) along with alternate building materials and envelope design (Caldas et al, 2003) must be addressed in order to make a building more efficient overall. Progress has been made that allow structural and architectural design aspects to become simultaneously optimized using genetic algorithms (Rafiq et al, 2003). In addition, research on building performance optimization has been done within specific fields, such as automatic resizing techniques (Chan et al, 1995), elastic and inelastic drift performance (Chan et al, 2004), energy consumption (Raman, 2001), general daylighting (O'Connor et al, 1997), daylighting within a smart façade system (Park et al, 2003), and advanced daylighting systems integrated with typical interior layouts (Hu, 2003).

A careful study should be conducted that further addresses these issues in order to produce a more efficient building. This task can be achieved in a variety of approaches with the overarching goal of eventually obtaining "the optimal building". This section discusses two possible means of achieving this goal.

6.2.1 Approach 1

The current research investigation has shown that although significant progress has been made in the application of structural optimization to tall high rise buildings, specifically in nonlinear lateral stiffness design, there is still much to be learned about the building performance under other loading conditions. After the tragedy of 9/11, designers had to consider the effect of abnormal loading conditions that were not typically considered before, such as the effect of an enormous impact load on a high rise structure. The research proposed here intends to investigate the drift performance and optimization of tall buildings that have undergone significant impact. To simulate the effect of impact the lateral bracing system will be removed at certain sections of the structure. After that, a subsequent evaluation of the building's drift capacity will be performed and optimal member sizing will be identified based on the new bracing system configuration. To achieve this task, a case study should be done on buildings that have experienced such types of impact loads, such as The World Trade Center Towers. In addition, a technique for obtaining the optimal solution must be employed. Additional research must be done to identify the most suitable technique.

6.2.2 Approach 2

It can be claimed that in the long-run, the operability of the building is the most important measure in evaluating building performance, as energy consumption over the life of the building is the greatest contributor to cost. Knowing this, it may be more beneficial to examine techniques that either minimize energy use, maximize energy efficiency, or both. The proposed research will study how these techniques compare and examine what measures must be taken to reduce the cost of the building in the long-run. To achieve this task, an extensive background study must be conducted to not only identify these measures, but also more accurately evaluate their effect on general building performance. A strategy for evaluating energy consumption will have to be created and case studies will also need to be performed for practical application.

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