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The Application of Genetic Algorithm To The Optimization Of Outrigger Braced High Rise Buildings

Tharwat A. Sakr
Department of Structural Engineering, Faculty of Engineering, Zagazig University, Zagazig, Egypt.

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ABSTRACT

Outrigger braced systems are commonly used in high rise building to reduce the top drift and base moments in cores and shear walls. The system of core/shear wall outrigger systems are efficiently used in high rise buildings up to 60 story height as reported. In this paper, the optimum location of the outrigger girders across the height of the building is investigated. The design variables incorporated are the location of different outrigger girders while the lateral drift and the base moment are the main objective functions. The genetic algorithm technique is used in optimization for which a framework for the application of binary coded genetic algorithm with two-point cross over is developed and used to solve the defined problem. The simplified method presented by *Wu and Lee (2003)* is adapted for the analysis of outrigger system. The findings of the optimization procedure are verified through a comparison with a study of the effect of outrigger position on the used objective functions and the proposed system is also used for further parametric study.

Keywords
High rise, Outrigger, Optimization, Genetic Algorithm.

1. INTRODUCTION

The control of top drift and base moment in the core of a tall building structure under lateral loads has become the main concern in structural design of tall buildings. As outriggers have considerable contribution on the reduction of these two main parameters, outrigger braced systems are now commonly used in high rise buildings to improve their resistance to lateral loads resulting from wind and earthquakes. They consist of one or more rigid girders (outriggers) connecting the inner core or shear wall to the outer columns. The function of outriggers is obtained by mobilizing the axial strength and stiffness of exterior columns to resist part of the overturning moment produced by lateral loading (*Nair (1998)*). The system had been reported to be very effective in increasing the structural flexural stiffness (*Zhang et al (2007))* and to be efficient particularly for buildings up to 60 stories height (*Namara, (2005)*) or even more (*Ahsan Kareem et al* (*1999*)). This fact attracted too many studies to derive methods of analysis, find the optimum positions of outriggers and investigate the contribution of such system on the enhancement of the performance of buildings. Stafford smith and Salim introduced an approximate method for solving symmetrical outrigger systems subject to uniformly distributed load and triangular loads *(Stafford smith and Coull (1991)). Hoenderkamp, and Snijder (2003)* used stiffness-based procedure for the analysis of braced frame buildings with internal braced frame and outer façade riggers in both ends. Optimization of the location of façade riggers in drift bases lead to the reduction of the top drift by 24.48% at optimum location for the case of uniform lateral load. Specifying the optimum locations of such girders that hopefully lead to the uppermost reduction in drifts or moments are of very high importance. Obtaining a closed form solution for the optimization of outriggers is a complicated and difficult task and instead, numerical methods are frequently applied (*Wu and Li(2003)*). *Stafford Smith and Salim (1984)* performed multiple regression analysis to develop formulae for optimum levels of outrigger for drift reduction. Limitations exist in assumptions but it is suitable for preliminary design and it had been applied to up to 4 levels of outriggers. The evaluation of structural performance of outrigger-braced frame-core structures and the optimum location of the outriggers was investigated by *Wu and Li (2003)*. The influences of the locations of outriggers and the variations of structural element stiffness on the base moment in core, top drift and fundamental vibration period of such tall building structures were also analyzed. Optimum location of outriggers for systems with equally spaced up to four level outrigger systems was also investigated. The optimum location of the outrigger and the parameters affecting its position were also investigated (*Zeidabadi1 Et al (2004)*). The results showed that the behavior of the structure can be significantly influenced by the location of the outrigger. It was also indicated that in most ordinary cases the best location of outriggers to minimize top drift is somewhere between 0·4 to 0·6 of the height of the structure. Increasing the rigidity of outriggers to very high vales which results in high restraining moments leading to weak story have been studies by *ZHANG et al (2007)* by deriving equations for the optimum location of outrigger for min. top deflection and mutation moment. They concluded that optimization analysis based on actual rigidity is very important and that infinite rigidity assumption affects the results. Other systems considered as “virtual” outriggers for tall buildings instead of conventional outriggers as belt trusses and basements had been also discussed by *Nair (1998).*

The area of structural optimization has been and continues to be an active area of research. Improving the efficiency of numerical procedures, locating the global optimum, including realistic definitions of design variables, and handling wider class of problems are topics of most importance. Many difficulties arise in the optimal structural design using traditional mathematical methods as the existence of large number of design variable together with extensive constraints in addition to the probability of converging to locally optimal regions. Heuristic algorithms seemed to be suitable for solving the complicated problem of structural optimizations. Among the different techniques of evolutionary algorithms (genetic programming, simulated annealing, differential evolution, tabu search, etc), genetic algorithms were reported as the most common in engineering optimization practice (*Hrstka et al (2003)*). Genetic algorithms are search algorithms based on the mechanics of natural selection and natural genetics (*Goldberg (1989)*). They combine survival of the fittest among string structures with a structured yet randomized information exchange to form a search algorithm with some of the innovative flair of human search. Genetic algorithms are now widely used for solving search and optimization problems. The efficiency of genetic algorithm in search and optimization attracts researchers for application in the field of structural optimization.

The application of genetic algorithms to the solution of optimal structural design problem was early done by Goldberg and *Santani (1986)*. Great attention is then directed toward the development of genetic algorithm based optimization procedures and tools in different fields. The optimal design of steel trusses and frames attracted the majority of research especially in the early developments (*Jenkins (1992), Maher et al (1995), Torregosa and Kanok-Nukulchai (2002)*). Steel design benchmark problems were applied in that work to make developments and enhancements on the procedures and techniques of genetic algorithms. Miscellaneous fields then attracted the application of genetic algorithms in different areas of optimum structural design. Additional investigations were made on the optimum steel design (*Chen and Rajan (1999) ,Ali et al (2003)*) and optimal design of concrete structures (*Rafiq and Southcombe (1998), Catallo (2004)*). Application of genetic algorithms extended to many other fields as the damage detection of structures (*Friswell et al (1998), Ratnam and Rao (2004)*), design of floor systems (*Miles et al (2001)*) and optimization of composite laminates (*Venkataraman and Haftka (1999), Grosset et al (2002), Lin and Lee (2004)*). The genetic algorithm had been also applied to the analysis, design and optimization of structures via applying the energy principles to avoid the formulation of nonlinear equations by *Kaveh and Rahami (2006)*. Structural control as a sort of structural optimization also attracted the research on genetic algorithm application. A genetic algorithm optimizer of the passive parameters of dampers and the controller gain was utilized for active and passive control of space structures (*Arfiadi and Hadi (2000)*) including mass damper and active bracing system. Controlling the torsional mode of vibration effectively in addition to flexural modes using TMDs to control torsionally coupled structures had been solved by *Ahlawat and Ramaswamy (2003)*. As multi-objective optimization problem, *Wongprasert and Symans (2004)* applied the genetic algorithm to the optimization of damper distribution in controlling a 20 story benchmark building for the largest response reduction of the building knowing the number of dampers and their properties.

In this paper, Genetic algorithm is applied to the optimization of outrigger location for minimum drift or core/wall base moments. At first a framework for the application of the genetic algorithms to the problem of optimization of outrigger location is developed. The equations presented by *Wu and Lee (2003)* are used for the analysis of outrigger system. As outriggers are always located in mechanical floors at which space is available for more depth of girders, the number of outriggers is assumed to be known. The objective function (fitness) is used as the drift or bending moments and the design variables are the location of outriggers while the dimensions and stiffness of members together with the number of outriggers are known. The outputs of the system are the locations of outriggers giving the optimum (minimum) drift or moment. The procedure is applied to high rise buildings with different dimensions and with two, three, four and five levels of outriggers for which the drift and moment of the optimized buildings reached levels lower than that extracted from curves for equally-spaced outriggers developed in the study. A parametric study is also carried out to investigate the effect of girder stiffness and the number of outrigger levels on the value of optimum drift / moment efficiency of the system.

2. SIMPLIFIED METHOD FOR OUTRIGGER SYSTEM ANALYSIS

To perform the analysis of symmetrical outrigger system, the simplified method derived by *Wu and Lee (2003)* is used. The method is based on several assumptions to enable the derivation of closed form solution of such system. Linear elastic behavior, uniform section of structural members through the building height and symmetrical system are basic assumptions. The outrigger is considered to be rigidly connected to the wall for which bending deformations are only considered and pin connected to columns which contribute to the system stiffness only by the axial rigidity. The dimensions and notations used in the equations are shown in Figure.1 and the flexibility matrix of the system can be derived as:

$$[K]\{M\}=\frac{wH^2}{6EIS}\{B\} \qquad (1)$$

For which [K] is the flexibility matrix, {M} is the force (outrigger moments) vector and right hand side of the equation represents the load derived displacement (slope) vector which can be written in detail as:

$$\begin{bmatrix} \omega+(1-\xi_1) & .. & 1-\xi_i & .. & 1-\xi_n \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1-\xi_i & .. & \omega+(1-\xi_i) & .. & 1-\xi_n \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1-\xi_n & .. & 1-\xi_n & .. & \omega+(1-\xi_n) \end{bmatrix} \begin{bmatrix} M_1 \\ \vdots \\ M_i \\ \vdots \\ M_n \end{bmatrix} = \frac{wH^2}{6EIS} \begin{Bmatrix} 1-\xi_1^3 \\ \vdots \\ 1-\xi_i^3 \\ \vdots \\ 1-\xi_n^3 \end{Bmatrix} \qquad (2)$$

Where;

n number of outriggers in the system.
w Applied Uniform lateral load
EI Flexural stiffness of the wall
$(EI)_O$ Flexural stiffness of outrigger
$(EA)_C$ Axial stiffness of column
ξ_i = Outrigger location factor $\frac{x_i}{H}$
$S = \frac{1}{EI}+\frac{2}{d^2 (EA)_c}$

$$\omega = \frac{\beta}{12(1+\alpha)}$$

$$\alpha = \frac{EI}{(EA)_c \frac{d^2}{2}}$$

$$\beta = \frac{EI}{(EI)_O} \frac{d}{H}$$

H Overall wall height
For constant details and derivation of the equations, refer to Stafford Smith and Coull (1991) and Wu and Li (2003).

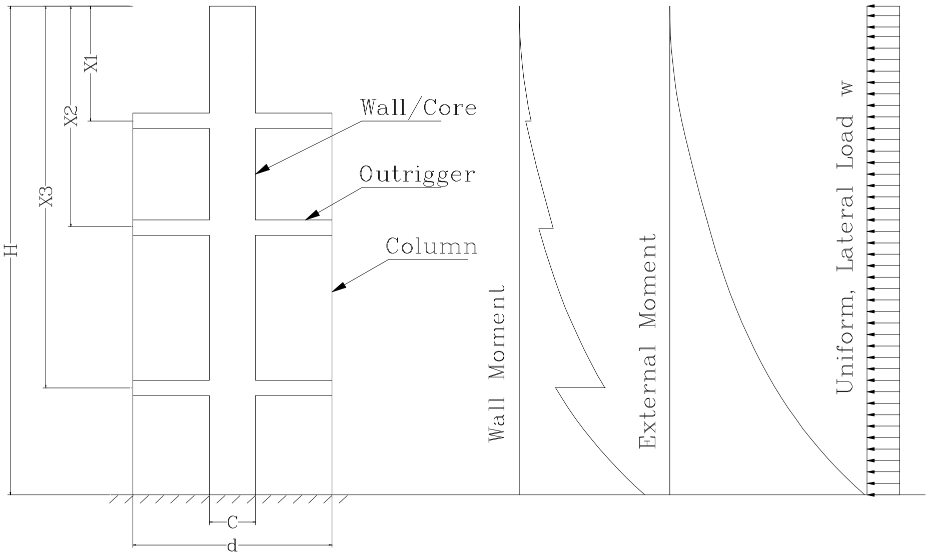


Figure.1. Wall-Outrigger System Dimensions and Notation

3. FRAMEWORK FOR THE APPLICATION OF GENETIC ALGORITHM TO OPTIMIZATION OF OUTRIGGER SYSTEMS

Genetic algorithms, as defined before, are search algorithms based on the mechanics of natural selection and natural genetics (Goldberg (1989)). They have been developed by John Holland, his colleague and his students in the University of Michigan. Genetic algorithm approaches the solution of a given problem by taking a set of individuals (solutions of the problem) which are randomly selected at the beginning of the algorithm and called parents. Operations (crossover and mutation) are performed on parents to produce a new set of individuals (offspring). Selection is then takes place among the population of parents and offspring letting certain individuals (the fittest) to survive into the next generation. Fitness of an individual is a value that reflects its performance (i.e., how well it solves a certain task). In engineering optimization the fitness usually represents the objective function to be maximized or minimized. Although randomness plays a large rule in order to avoid stagnation in the population's evolution, ideally the offspring should eventually become better, i.e. fitter (*Ignat (1998)*). Simulation of genetic algorithm procedure is shown in the flow chart in Figure (2) and the procedure and terms of the technique are illustrated through the application to the in hands problem.

A GA starts with a population of randomly generated chromosomes, and advances toward better chromosomes by applying genetic operators modeled on the genetic processes occurring in nature. A chromosome is a data structure represents a solution of the problem and holds a "string" of task parameters, or genes. This string may be stored, for example, as a binary bit-string (binary representation) or as an array of integers (floating point or real-coded representation) that represent a floating point number. The collection of chromosomes (Solutions) at specified generation is called a population which represents a subset of solution space. In our problem, as the main design variables are the heights of different outriggers, the chromosome used is a (6×N) bits long where N is the known number of outriggers and each 6 bits represent the height of single outrigger. For example for 4 outrigger problem population can be represented as shown in Figure (3).

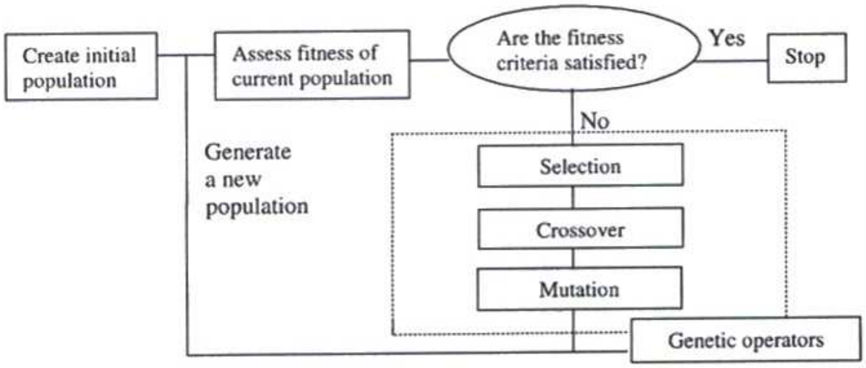


Figure (2) Systematic representation of Genetic Algorithms (Miles et al (2001))

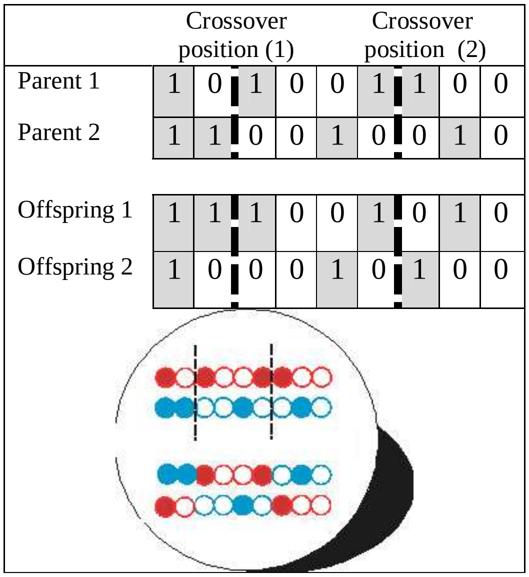
	Genotype (Chromosome structure)				Phenotype (Floor of outrigger)			
					H_1	H_2	H_3	H_4
Population	100111	010111	100000	010000	39	23	32	16
	010001	001101	011101	101000	17	13	29	40
	100001	001111	011100	010010	33	15	28	18
	000111	011101	100000	010000	7	29	32	16
	.	.	.	.	.	.	.	.
	010101	100100	100001	001001	21	36	33	9

Figure (3) Coding of the Outrigger Problem

The population undergoes evolution in three main steps: initialization, selection and generation. Initialization is the selection of the first population that starts the genetic algorithm which is in most cases generated randomly. Selection operator is applied to the current population to create an intermediate one based on the fitness of individuals of the current population. Generation is the derivation of the next generation through the application of crossover and mutation operators. Crossover is a reproduction operator, which produces two offspring from the selected parents by combining parts of each of the two parental chromosomes resulting in new generation. The combination of parent chromosomes to produce the offspring can be applied through one, two, or multiple point crossover operator. In our study two-point crossover operator is used which was reported to be more efficient approaching the global optima (***Hamada et al (2002)***). In 2-point crossover, individuals (parents) are cut at two randomly selected positions and exchange of bits is made between both the inner portion between the two points or outer points as shown in Figure (4). Mutation operator introduces new genetic structures in the population by randomly changing some of its building blocks, helping the algorithm escape local minima (**Hamada et al (2002)**) as shown in Figure (5). The process of going from the current population to the next population constitutes one generation in the evolution process of a genetic algorithm. If the termination criteria are satisfied the procedure stops, otherwise, it returns to again to selection and generation.

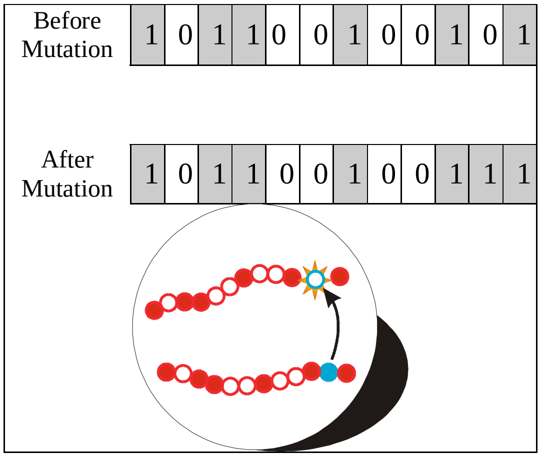
4. VERIFICATION OF RESULTS

To verify the proposed procedure, a limited study has been carried out for the relation between the drift or base moment reduction efficiency of the system and the average location of outriggers. Drift or moment reduction efficiency is defined here as the gain obtained from using outriggers over the case of separate walls and columns. The efficiency is considered to be zero for totally separate system (i.e. zero outrigger stiffness) and 1 for fully coupled system (infinite outrigger stiffness) and varies linearly between these limits. The study includes the results of three selected 20 stories, 40 stories and 60 stories height example buildings. For each example, four values of outrigger stiffness are considered and cases of one, two, three, four and five outrigger levels are studied.



		Crossover position (1)				Crossover position (2)			
Parent 1	1	0	1	0	0	1	1	0	0
Parent 2	1	1	0	0	1	0	0	1	0
Offspring 1	1	1	1	0	0	1	0	1	0
Offspring 2	1	0	0	0	1	0	1	0	0

Figure (4) Two-point crossover



Before Mutation	1	0	1	1	0	0	1	0	0	1	0	1
After Mutation	1	0	1	1	0	0	1	0	0	1	1	1

Figure (5) Mutation

At Figure 6, the drift and moment reduction efficiency is plotted against the outrigger heights (x/H) for different girder stiffness for the 20 story building with one outrigger level. The location of outrigger which gives the optimum behavior is observed to be at the upper half of the wall for optimum drift and at the lower half for optimum wall base moment. For both drift and moments, the optimum location of outrigger becomes higher for lower outrigger stiffness. The contribution of outriggers is clearly obvious such that for medium value of outrigger stiffness, one outrigger gives the wall efficiency of 71 % in drift resistance and 48% in moment reduction. The value of optimum drift/moment efficiency obtained from the proposed system is observed to be more than the value shown in the curve and the optimum position of outrigger is very close to the peak of the curve. The same relations shown in Figure 6 are shown in Figures 7, 8 for two outrigger levels in 40 story building and 3 outrigger levels in the 60 story building, respectively. Plots show that the optimum drift is obtained when outriggers are distributed above the mid height to two thirds of the height while base moments are optimized by locating the outriggers near the building base specially in case of very stiff outrigger girder. The contribution of outriggers in drift resistance is observed to be more than their contribution in moment resistance in terms of higher values of efficiency. As illustrated, the optimum value of efficiency obtained from the proposed system is significantly more than that in the plot. This can be attributed to the selection of equally spaced outriggers in the plot while optimum value may be a result of other unequally spaced pattern of outriggers. This observation indicates clearly that the optimization procedure matches the maximum efficiency with any desired distribution of outriggers. For optimum values of moment efficiency, the average position of outriggers is observed to be in the lowermost part of the curve, especially for the 60 story building, indicating that the optimum moment efficiency is obtained by locating the outriggers near the building base.

5. EFFECTS OF IMPORTANT PARAMETERS ON OUTRIGGER EFFECINCY

This section investigates the effects of different design parameters on the value of optimum drift and base moment of outrigger system. At first, the effect of outrigger girder stiffness on the value of optimum lateral drift is shown in Figure 9. The optimum lateral drift efficiency is plotted against the outrigger girder stiffness for one, two, three, four and five levels of outrigger for Examples 1,2 and 3 in Figures 9.a, b, and c respectively. As shown in the figure, for all cases, the efficiency of outrigger system in drift is enhanced as the outrigger stiffness increases. The enhancement for lower values of girder stiffness is more pronounced than that for higher values as the slope of all curves in the beginning is more than the slope at the end of the curve. More number of outrigger levels lead to less effect of outrigger stiffness such that the value at which the efficiency increases becomes less in case of 4 and 5 outrigger levels than that in case of one or two outriggers levels especially for high values of girder stiffness. The effect of outrigger stiffness on the drift efficiency is more pronounced in case of lower building (Example 1). For one outrigger level as a result of increasing the girder stiffness, the efficiency is increased by 183% (from 0.42 to 0.77) while for Example 2, 3, the increase is by 159% and 142%, respectively. The efficiency of the outrigger braced system is observed to increase to values near unity (0.97 for case of 60 story, large stiffness, and 5 outriggers) which means that the system approaches the behavior of fully coupled system at which the core and columns behave as one composite section.

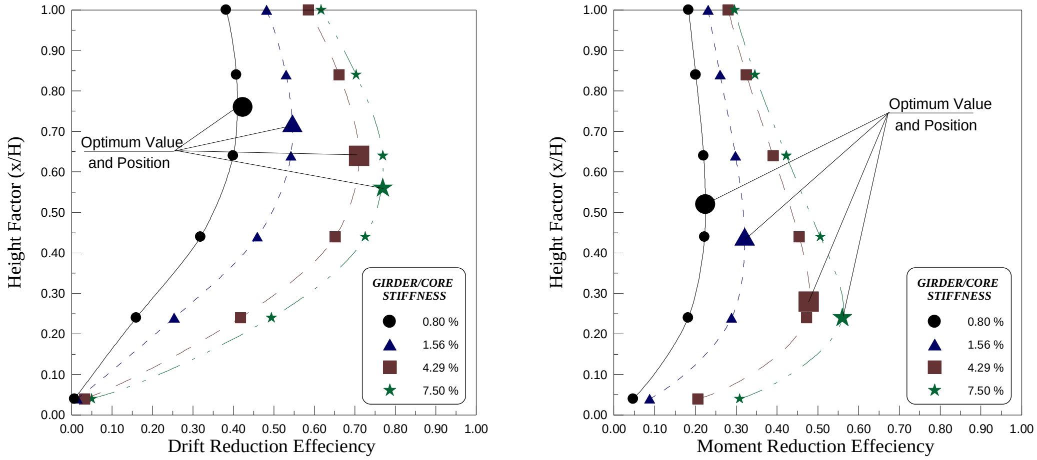


Figure 6. Drift and Base Moment Efficiency vs Average height of outrigger
20 Story Example Building – One outrigger Level

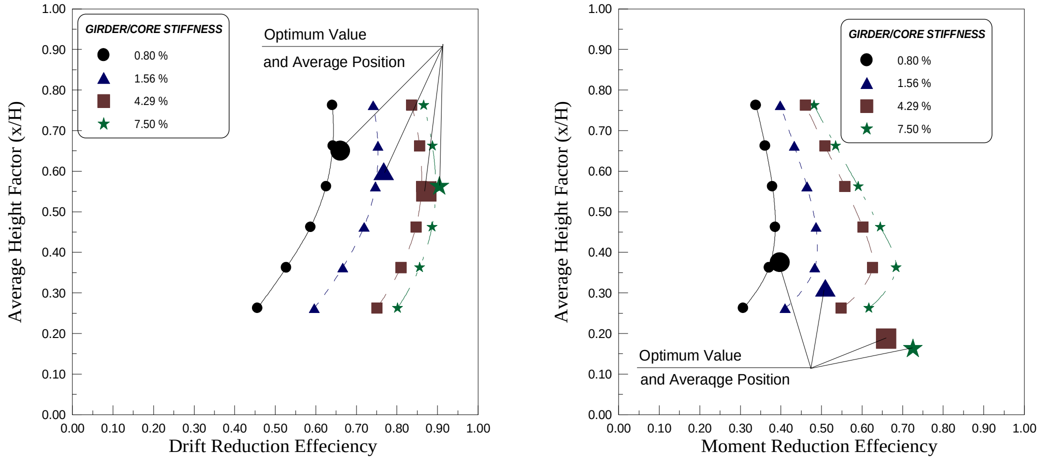


Figure 7. Drift and Base Moment Efficiency vs Average height of outrigger
40 Story Example Building – Two outrigger Levels

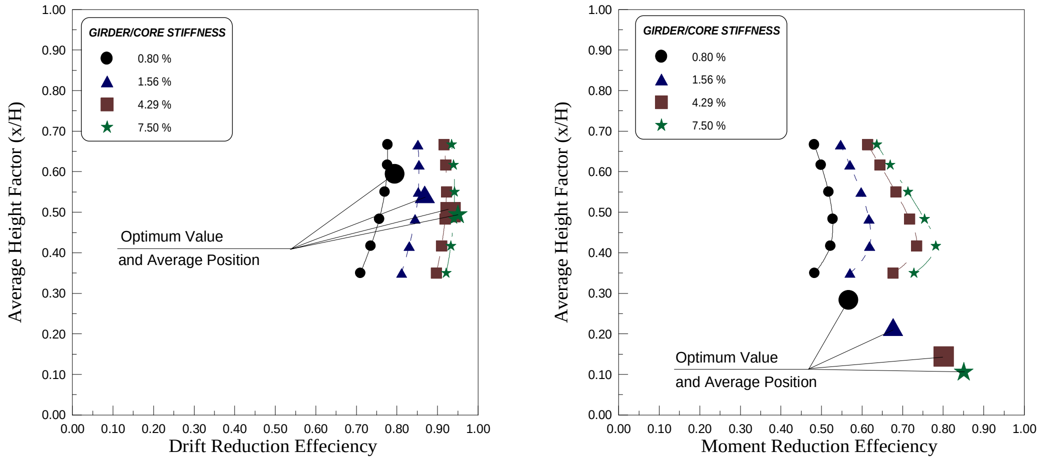


Figure 8. Drift and Base Moment Efficiency vs Average height of outrigger
60 Story Example Building – Three outrigger Levels

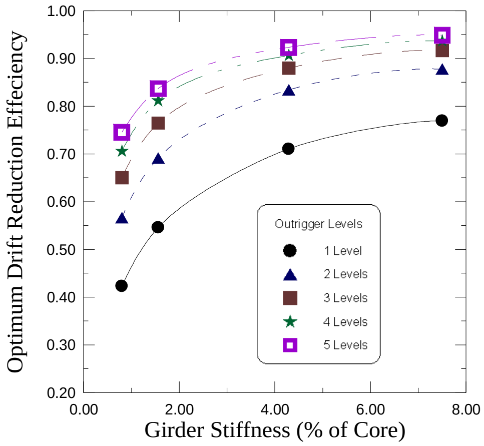
The same relationships are plotted in Figure 10 for the efficiency of the base moment reduction. The effect of girder stiffness on the moment reduction efficiency is similar to its effect on the lateral drift reduction efficiency such that increasing the girder stiffness enhances the efficiency in base moment reduction for all cases with the same manner. The base moment reduction efficiency at general is observed to be less than that of lateral drift efficiency. The maximum efficiency concerning the base moment in all cases studied is 0.89 compared to the corresponding value for drift efficiency which recorded 0.97 as maximum efficiency. This indicates that the contribution of outrigger system in drift is more pronounced than its contribution in base moment. The enhancement of moment efficiency is also less for high girder stiffness and for more levels of outriggers as observed for lateral drift. The effects of number of outrigger levels on the drift and moment efficiency are investigated in Figures 11 and 12. The drift efficiency is plotted against the number of outrigger levels in Figure 11 for different girder stiffness for each of the studied examples. As expected, providing more levels of outriggers leads to more efficiency concerning drift due to the increase of coupling as direct result of increasing the number of connecting girders. For low girder stiffness, the drift efficiency is increased from 0.42 to 0.75 from 0.51 to 0.81 and from 0.59 to 0.86 for the 20, 40, 60 story building examples, respectively as result of increasing the number of outrigger levels from 1 to 5 for low stiffness girder. The enhancement of efficiency of drift is observed to be more pronounced in case of girder with relatively small stiffness and more for less building height.

Figure 12 shows the relation between the optimum moment reduction efficiency and the number of outrigger levels. The moment reduction efficiency of the outrigger system is also enhanced as a result of increasing the number of outrigger levels. The enhancement of moment reduction as result of adding more outriggers is observed to be less than that of drift efficiency enhancement. For low girder stiffness, the moment efficiency is increased from 0.22 to 0.51 from 0.28 to 0.56 and from 0.36 to 0.66 for the 20, 40, 60 story building examples, respectively.

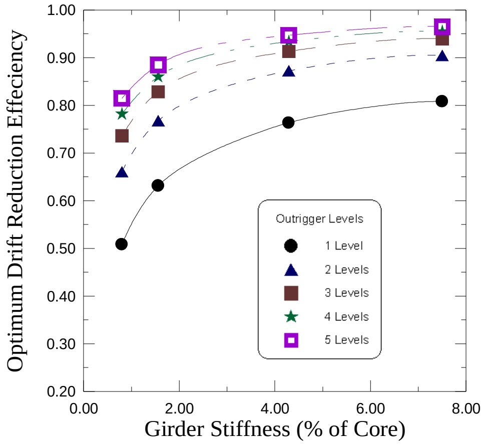
6. SUMMARY AND CONCLUSIONS

The present work investigates the application of genetic algorithm to the optimization of shear wall outrigger system. The goal function in the study is the top lateral drift or the base moment of the wall while the design variables are the locations of outrigger girder across the height of the building. Binary coded genetic algorithm with two point crossover is used for optimization and the simplified method presented by Wu and Lee (2003) is adjusted for the analysis of outrigger system. As compared with a limited parametric study for the effect of location of equally spaced outrigger girders on the drift and moment efficiency, the outputs of the proposed optimization procedure are observed to estimate the optimum efficiency of drift and moment for all studied cases. The procedure suggests the relevant distribution of outriggers that give the optimum solution.

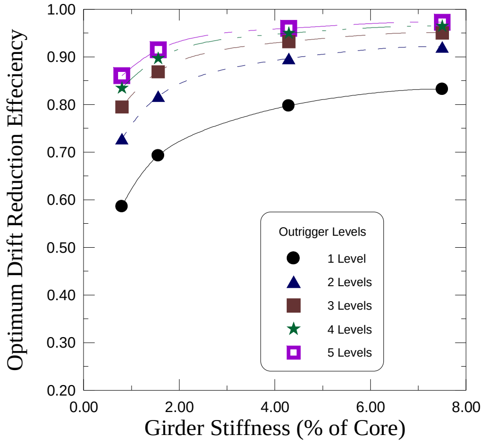
The proposed procedure was used to study the effect of two important parameters on the optimum drift or moment efficiency.



a. 20 Story Building

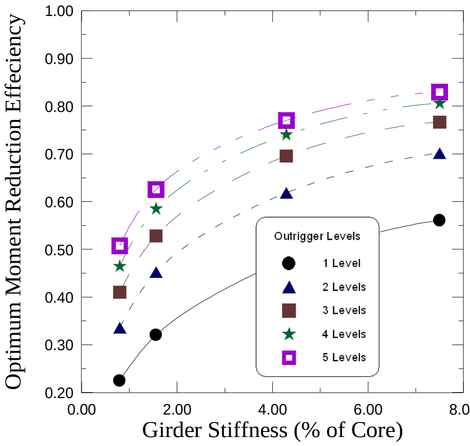


b. 40 Story Building

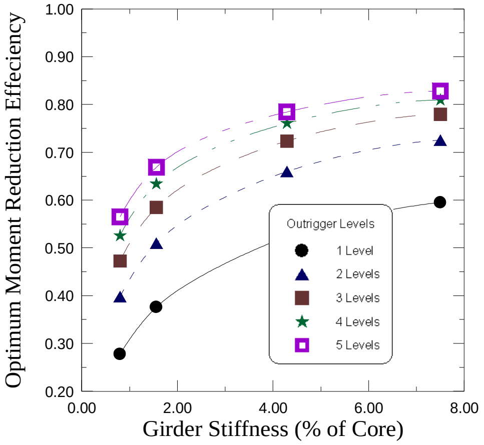


c. 60 Story Building

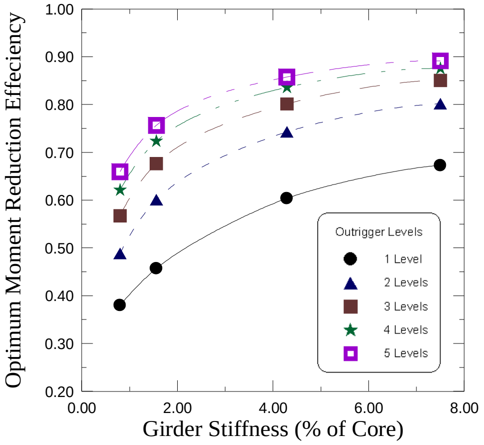
Figure 9. Optimum Drift Efficiency vs. Outrigger Stiffness



a. 20 Story Building

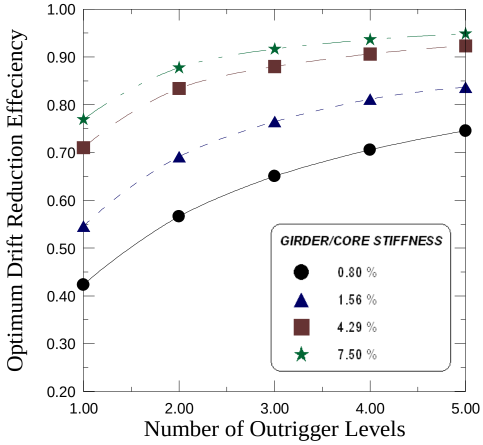


b. 40 Story Building

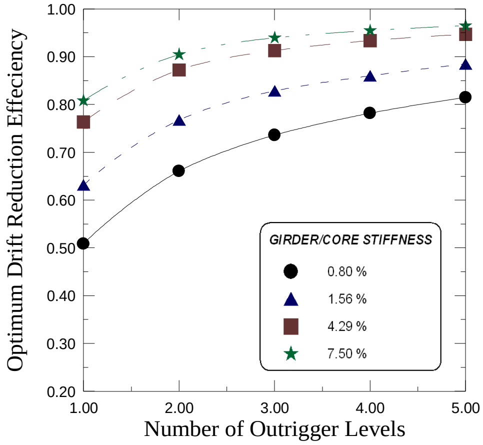


c. 60 Story Building

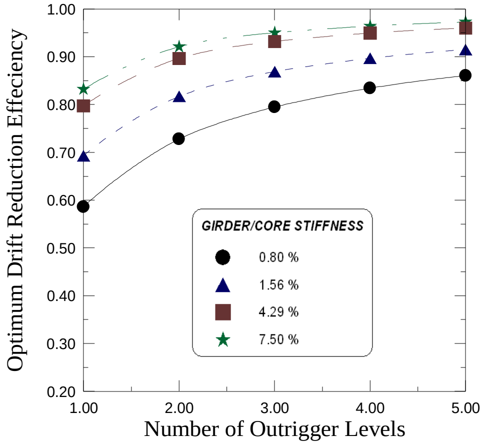
Figure 10. Optimum Base Moment Efficiency vs. Outrigger Stiffness



a. 20 Story Building

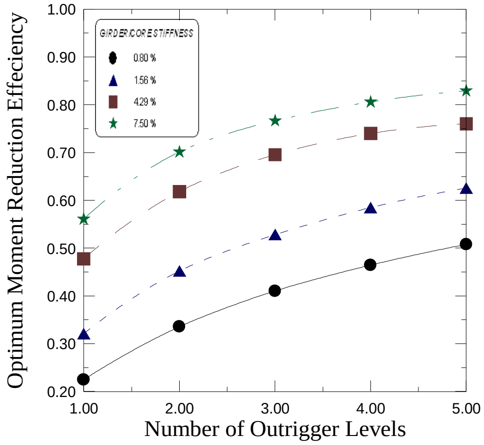


b. 40 Story Building

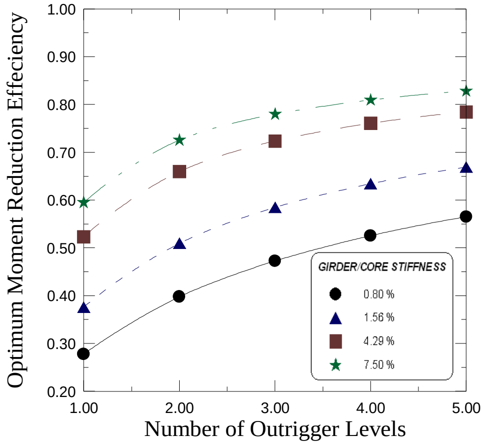


c. 60 Story Building

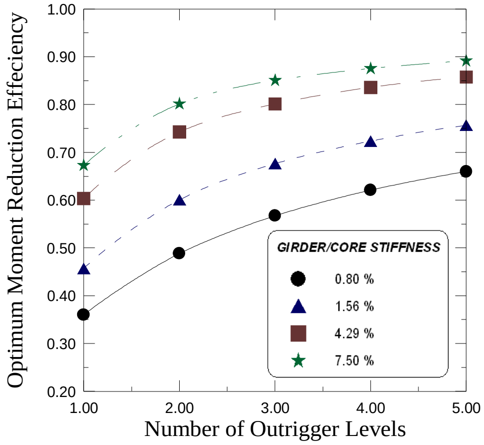
Figure 11. Optimum Drift Efficiency vs. number of outrigger levels



a. 20 Story Building



b. 40 Story Building



c. 60 Story Building

Figure 12. Relation Between Optimum Moment Efficiency and number of outrigger levels

The first is the girder stiffness that proved to enhance the efficiency of the system with its increase and the second is the number of outrigger levels for which the efficiency of the system showed better performance with more outrigger levels. At general, the contribution of outrigger system in drift efficiency was observed to be more than its contribution in moment efficiency. The effect of increasing the girder stiffness on drift and moment enhancement was observed to be more for less number of outriggers while the effect of increasing the number of outrigger levels was observed to be more for smaller outrigger stiffness. Lower building proved to be more affected by the increase of outrigger stiffness and number of outrigger levels.

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تستخدم أنظمه حوائط القص ذات المدادات في المباني المرتفعه كحل شائع للحد من الإزاحه الأفقيه والعزوم في الحوائط. ويعتبر النظام الكون من حائط القص والمدادات ذات كفاءه عاليه عند استخدامها في المباني حتى 60 طابق أو أكثر. في هذا البحث تم دراسة الأرتفاع الأمثل للمدامات للحصول على الحد الأدنى من الإزاحات أو العزوم فقد تم اعتبار ارتفاع المدادات خلال المنشأ كمتغيرات تصميميه في حين أعتبرت الإزاحه أو العزوم هي دالة الهدف. وقد تم استخدام تقنية الخوارزميات الوراثيه فى حل المسألهحيث تم تطوير إطارا لآستخدام الخوارزميات الوراثيه ذات التشفير الثنائي لحل هذه المسأله المعرفه مستعينا بطريقه تقريبيه للحل. للبرهنه على كفائة النظام المقترح تمت مقارنة مخرجاته مع نتائج دراسه بارامتريه عن تأثير ارتفاع المدادات على الإزاحات والعزوم في الحوائط كما تم استخدام النتائج في دراسه حول تأثير بعض المتغيرات التصميميه على الحد الأدنى للإزاحات والعزوم في الحائط.