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Weight and topology optimization of outrigger-braced tall steel structures subjected to the wind loading using GA

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Abstract. In this paper, a novel methodology is proposed to obtain optimum location of outriggers. The method utilizes genetic algorithm (GA) for shape and size optimization of outrigger-braced tall structures. In spite of previous studies (simplified methods), current study is based on exact modeling of the structure in a computer program developed on Matlab in conjunction with OpenSees. In addition to that, exact wind loading distribution is calculated in accordance with ASCE 7-10. This is novel since in previous studies wind loading distributions were assumed to be uniform or triangular. Also, a new penalty coefficient is proposed which is suitable for optimization of tall buildings .Newly proposed penalty coefficient improves the performance of GA and results in a faster convergence. Optimum location and number of outriggers is investigated. Also, contribution of factors like central core and outrigger rigidity is assessed by analyzing several design examples. According to the results of analysis, exact wind load distribution and modeling of all structural elements, yields optimum designs which are in contrast of simplified methods results. For taller frames significant increase of wind pressure changes the optimum location of outriggers obtained by simplified methods. Ratio of optimum location to the height of the structure for minimizing weight and satisfying serviceability constraints is not a fixed value. Ratio highly depends on height of the structure, core and outriggers stiffness and lateral wind loading distribution.

Keywords: tall buildings; optimization; outrigger-braced structures; exact wind loading; optimum design

1. Introduction

Due to massive amount of materials used in construction of tall frames, optimum design of these large-scale structures is essential. As the price of the land increases in metropolitan cities, engineers tend to construct tall structures. Achieving the minimum weight and cheapest structure, not only saves a considerable amount of money, but also lowers consumption of resources, significantly. In order to reach the optimum design, engineers may apply meta-heuristic algorithms to their optimization problems. However, in case of tall structures due to massive modeling process and high computational costs, this will be an arduous effort.

Outrigger-braced tall structures are common structural system as they are cheap and easy to build compared to the other structural systems proposed for tall buildings. Behavior of building outrigger is simple, outriggers act as stiff arms interacting with outer columns. When the building

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is subjected to a massive lateral load which causes a central core to bend, rotation of the core at the level of outrigger induces a tension-compression couple in the peripheral columns. Couple acts in the opposite direction, resulting in a restoring moment at the core level (see Fig. 1).

Optimum location of outriggers is a consequential parameter to be considered mostly in preliminary design steps. Locating optimum story to construct an outrigger is usually done in the preliminary design stages. Taranath (1975) suggested mid-height of the structure as the optimum location for the outrigger (h=0.455 of the total height from top or 0.545 from the bottom of the structure). Mcnabb and Muvdi (1975) proposed 0.312 and 0.685 of the total height of the structure, for the first and second outrigger, respectively. Stafford (1981) presented a simplified method. Assumptions included linear static behavior of the structure while sectional properties were supposed to be constant up-height the structure. Columns were assumed to resist the axial force only, and the structure was subjected to the uniform lateral load. Ding (1991) modified the simplified method by altering sectional properties of the structure. Tarnath (1998) investigated the optimum location for the second outrigger using the same method. Kameshki and Saka (2001) implemented genetic algorithm to optimally design non-swaying tall structures. Among the 15 story frames, X-braced core were the lightest frame. An outrigger-braced frame was also evaluated. The results showed that, outrigger-braced frame is the second lightest frame. Outrigger were fixed on the top floor and the tallest frame of the design instances was a 15 story frame. Wu and Lee (2003) presented a non-linear optimum design procedure for reducing the base moment in the core. Hoenderkramp and Bakker (2003) presented a graphical method based on five non-dimensional parameters for the preliminary design of the outrigger-braced structure with truss core and shear wall. Flexible foundation effect is considered and central core is a shear wall, and wind load distribution is assumed to be uniform. By evaluating benchmark example it was proved that the more precise models, the more alteration of the optimum location. Optimum location was found to be on 0.3 and 0.4 of the structure height, respectively. Zeidabadi *et al.* (2004) method is derived on the basis of continuum method. The method analyzes structural behavior of coupled shear walls stiffened by internal beams and outrigger. Results of analysis showed that, the effect of laminar shear on the optimum location of outrigger is substantial. Including laminar shear in the analyses yielded the optimum location of the outrigger to be on 0.4 height from the bottom, leading into the minimization of laminar shear. Optimum location to maximize resistant moment, occurred when the outrigger was placed from 0.2 to 0.4 height of the structure. In order to minimize the lateral drift and moment assigned to the core, Lee *et al.* (2008) evaluated the effect of shear deformation in optimum location of outriggers. Hoenderkramp (2008) modified his graphical method to obtain the optimum location for second outrigger. A simple mathematical (Rahgozar *et al.*) model for approximate static analysis of combined system of framed tube, shear core and two outrigger-belt truss structures subjected to lateral loads is presented. In the proposed methodology, framed tube is modeled as a cantilevered beam with a box section and interaction between shear core and outrigger-belt truss system with framed tube is modeled using torsional springs placed at location of outrigger-belt truss. In another work, Safari *et al.* (2011) optimized a 22 story moment resisting frame considered as a tall building using a modified GA. An integrated wind-induced dynamic analysis and computer-based design optimization technique for minimizing the structural cost of general tall buildings subjected to static and dynamic serviceability design criteria is proposed by Huang *et al.* (2011). Jahanshahia and Rahgozar' method (2012) determined the fundamental frequency of tall buildings that consist of framed tube, shear core, belt truss and outrigger systems the effect of belt truss and outrigger system is modeled as a concentrated rotational linear spring at the belt truss and outrigger system location, same as simplifications made in previous studies.

Lee *et al.* (2012) evaluated outrigger belt truss layouts using topology optimization and the main objective was to conceptually orientate optimized layouts of outrigger belt trusses by strut-and-tie truss models utilizing a topology optimization method. Nanduri *et al*. (2013) investigated optimum location of an outrigger location under wind and earth quake loading. However, outriggers were assumed to be in arbitrary positions and the model which yielded the minimum deflection was categorized as the optimum result.

Based on these background studies, the simplified method of outrigger-braced structure analysis has been well-established. The method is straight forward. However, all the studies suffer from the assumptions including simplifications of structures and lateral loadings (see Fig. 1).

In the context of structural shape and size optimization, outrigger-braced tall structure's optimization has not been well-established. On the other hand, previously presented simplified methods do not account for exact wind loading distribution. Despite the previous researches, effect of exact wind loading distribution to the optimum design of outrigger-braced tall structures is investigated. In this paper, wind load pressure and wind-induced forces are calculated according to ASCE 7-10. Due to the complicated nature of tall buildings optimization, improving GA's performance is essential. Therefore, to improve the performance of genetic algorithm a new penalty coefficient (β) is proposed. In addition to this, several design instances are studied to assess the influence of height and stiffness of beams, columns, core, and outrigger on the optimum design. Finally, the aim of study is to consider the effects of proposed method's considerations on the optimum design of outrigger-braced structures.

2. Proposed algorithm

2.1 Objective function

Application of GA to frame optimization typically yields a discrete sizing or topology optimization problems. In the current study, objective is to find a vector of integer values

$$I^T = [I_1, I_2, I_3, \ldots, I_n] \tag{1}$$

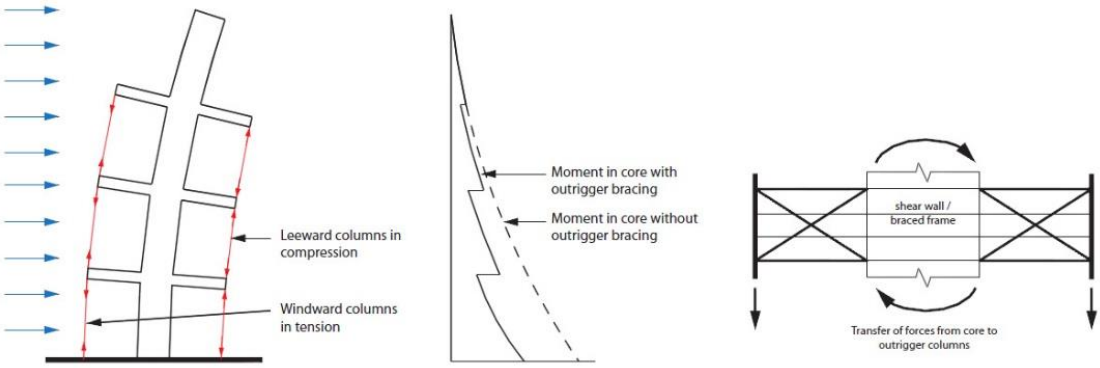


Fig. 1 Interaction of core and outrigger (Source: Tarnath)

To minimize the weight of the structure

$$W = \sum_{i=1}^{N_d} \gamma_i A_i \sum_{j=1}^{N_t} L_j \tag{2}$$

where, N_d is the design groups composed of N_m member group, A_i is cross-sectional area of the standard steel sections assigned to member group i, γ_i is the unit weight of the steel section, L_j is the length of the j^{th} member belonging to the group i, and N_t is the total number of members belonging to the group i. Commonly, members with the same characteristics are categorized as same groups. This will seriously reduce the computational cost. Hence, in the current study, same approach of member grouping is utilized.

2.2 Constraints

2.2.1 Strength constraint

For the current problem of optimization constraints are serviceability, strength and constructability. According to AISC-LRFD (2010) method of design all members assigned to flexure and compression should satisfy Eqs. (3) and (4).

$$C_{Iel}^{i,Strength} = [\frac{P_r}{\phi_c P_n}] + \frac{8}{9}[\frac{M_{rx}}{\phi_b M_{nx}} + \frac{M_{ry}}{\phi_b M_{ny}}] - 1 \le 0 \qquad \text{for} \qquad [\frac{P_r}{\phi_c P_n}] \ge 0.2 \tag{3}$$

$$C_{Iel}^{i,Strength} = [\frac{P_r}{2\phi_c P_n}] + [\frac{M_{rx}}{\phi_b M_{nx}} + \frac{M_{ry}}{\phi_b M_{ny}}] - 1 \le 0 \qquad \text{for} \qquad [\frac{P_r}{\phi_c P_n}] < 0.2 \tag{4}$$

where, P_r is required axial strength, M_r is required flexural stiffness flexural, $\phi_c P_n$ is the design axial strength, $\phi_b M_n$ is the design flexural stiffness, $\phi_c P_n$ and $\phi_b M_n$ are determined in accordance with AISC-LRFD specification, Iel is the element number belonging to the design group i, Nel is the total number of elements, subscripts x and y represent strong and weak axes of bending, respectively. Clearly, this constraint penalizes beam or column members violating strength limit-states. Nominal strengths should be calculated in accordance with the regulations of AISC-LRFD. In the current study all the limitations regarding calculation of nominal strengths are satisfied precisely for any cross-sectional shapes.

Along with the strength limit-states, serviceability constraint plays an important role in the tall frame optimization.

2.2.2 Serviceability constraint

Generally, serviceability limit-states govern the design of high-rise frames, as long as occupant comfort in tall structures strongly depends on these factors to be satisfied. Consequently, it is prevalent to categorize design method of tall buildings as displacement based. Therein, drift constraint is defined as the following

$$C_f^{Drift} = \frac{\delta_f}{\delta_f^{\text{limit}}} - 1 \le 0 \tag{5}$$

where, δ_f is horizontal drift of the f^{th} story ($f=1,2,3,\dots,n$). ASCE 7-10 (2010) limits the drift of the tall buildings subjected to the wind loading to $\delta^f_{\lim it}=0.0025h$ (h:typical story height). According to Griffis (2003) most of the codes limit the total drift of the structure too, while it is not clear whether the limit-states refer to total drift or inter-story drifts. Therefor a new constraint is proposed. Total drift constraint is defined to achieve a faster convergence. Eq. (6) represents total drift constraint.

$$C^{TotDrift}_{ind}=\frac{\Delta_i}{\Delta^{\lim it}_i}-1\leq 0 \tag{6}$$

In Eq. (6), $C^{TotDrift}_{ind}$ is obtained for each individual in the population, Δ_i is the total drift and $\Delta^{\lim it}_i$ corresponds to the allowed total drift ($H/500$ where H is the total height of the building).

2.2.3 Constructability constraint

For the purpose of reaching practical standards of tall buildings construction, constructability constraint is defined. For the two adjacent stories, constructability constraint prevents construction of columns with larger section depth, above the columns with lower section depths. Thus, constructability constraint can be stated as following

$$C^{i,Const.}_{Iel}=\frac{d^{top}_i}{d^{bot.}_i}-1\leq 0 \tag{7}$$

where, d^{top}_i and $d^{bot.}_i$ are section depth of the columns for two adjacent stories located on the top and bottom floors, respectively.

3. Constraint handeling

Establishing a fitness criterion requires transformation of the constrained design problem to an unconstrained one. Typically, penalty function is defined to reach this purpose. Penalty function is calculated for each individual belonging to randomly selected population. In this paper to achieve a faster convergence, new constraint violation coefficient for the penalty function is proposed. Coefficient is suitable for the nature of problem and it is proposed as

$$\begin{aligned}&\beta=0 \quad \text{if} \quad C\leq 0\\&\beta=C^{C+1} \quad \text{if} \quad C>0\end{aligned} \tag{8}$$

where, C is obtained using Eqs. (3)-(7). Proposed coefficient penalizes infeasible solutions with convenient gens less drastically compared to the ones violating constraint significantly.

This is beneficial for preserving and survival of individual with appropriate characteristics. Fig. 2 illustrates a simple graphical comparison between the common penalty coefficients and the newly proposed penalty coefficient.

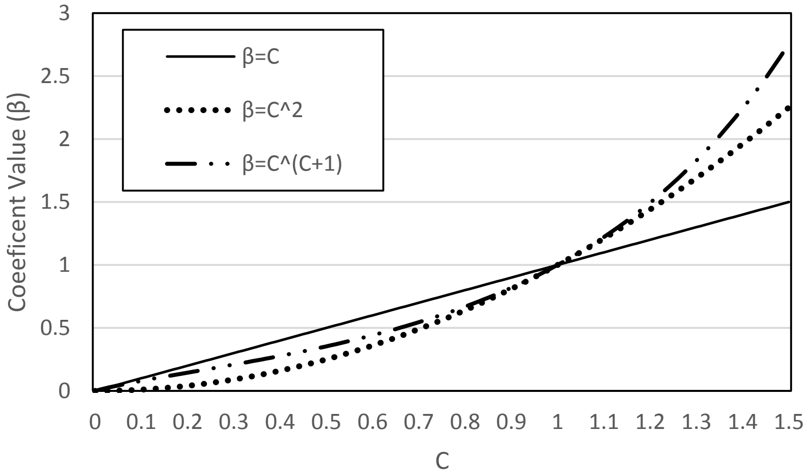


Fig. 2 Common and proposed penalty coefficients

For the violations less than 1, proposed coefficient penalizes properly compared to the other common penalty coefficients. However, for the violation values more than 1, infeasible individuals will be penalized more drastically. This will result in considerable faster convergence of the algorithm.

Several types of penalty functions are defined by Coello Coello (2000). According to the nature of the problem, following penalty function is proposed

$$P_m = W_m + W_m R\left(\sum_{f=1}^{N} \beta_f^{Drift} + \sum_{Iel=1}^{Nel} \beta_{Iel}^{i,Strength} + \sum_{Iel=1}^{Nel} \beta_{Iel}^{i,Const.} + \beta_m^{TotDrift}\right) \tag{9}$$

where, P_m and W_m is the penalized objective function and weight of the frame for m^{th} individual, respectively. R represents static penalty function coefficient and the optimum value of it is considered as 10. Selection of this value is to tune the intensity of penalization as a whole.

Finally, fitness function for each individual will be obtained using Eq. (10).

$$F_m = P_{\max} + P_{\min} - P_m \tag{10}$$

In Eq. (10) F_m represents fitness value for the m^{th} individual. $P_{\max}$ and $P_{\min}$ are the maximum and minimum values of penalized objective function, respectively. P_m is the penalized objective function value for the m^{th} individual.

4. Optimum design algorithm

GA is utilized for the optimization of the frame structures. Genetic algorithm, of the current optimization problem, includes following steps:

1. Generation of the initial population. Each population size is 50 individuals which are generated randomly.
2. Conversion of binary coding to a base-10 sequence of numbers for each individual. Each individual property is assigned to the corresponding tall frame. Infeasible individuals are penalized using newly proposed penalty coefficient to preserve appropriate gens. Fitness value for each chromosome is calculated using Eq. (10).
3. Based on individual's fitness, chromosomes are selected. Brindle's selection method is utilized for the selection of the parents for the mating pool. Crossover and mutation operators are implemented at this stage. All individuals will experience uniform crossover. Mutation possibility is 0.02. Considerable rate of the mutation is due to large search space. Elitist strategy is followed in the design algorithm. Elitism noticeably contributes to fast convergence and avoids the algorithm to get trapped on the local optima.
4. Initial population is replaced by the new population and the same steps are repeated until dominance of an individual among the whole population, and convergence criterion is satisfied.

Fig. (3) illustrates optimization flowchart for the design algorithm. To consider the stochastic nature of optimization, each design optimization instance is solved independently for 20 times. Results of analysis show small deviation of the average solution from the best individual. Small standard deviation between the results of each example proves the robustness of the algorithm and consistency of the solutions.

5. Wind and gravity loading

A computer program is developed in Matlab in conjunction with OpenSees. Selection of OpenSees is because of considerably fast analysis and reliability of the obtained results. Exact modeling of the structure, considering deformations, and consideration of each structural members contribution to the structure's response are the primary aims of this study. In addition to that, optimizing weight of the structure is the objective while keeping lateral displacement in the range of serviceability limit states is essential.

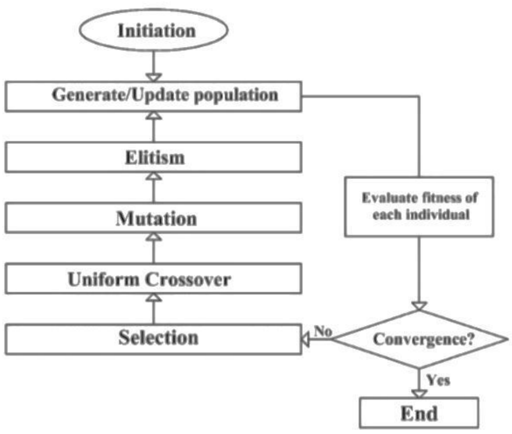


Fig. 3 Optimization flowchart

As mentioned in literature review, researches focus attention on minimizing lateral displacement only. However, proposed methodology of current study determines minimum weight while satisfying serviceability limit-states. Optimum location of outriggers, optimum topology of core and optimum number of outrigger, is investigated.

Optimum location of an outrigger for a minimum drift or lateral deflection won’t necessarily yield the optimum design. Here, the optimum location and optimum number of outriggers to obtain a minimum weight are investigated. In addition to that, three different types of core are evaluated to consider the effect of core rigidity on the optimum location of an outrigger. Major feature of the current study which is novel compared to the available literature is the exact wind loading distribution. As mentioned, in most of the theoretical methods uniform, triangular or combination of the both is used for the wind load distribution. Calculation of the wind load according to available standards yields different lateral load distribution. ACSE 7-10 offers two different procedures for designing wind loads on components and cladding: 1.Analytical method 2. Wind tunnel procedure. Analytical method consists of six parts. Part three’s provisions is applicable to an enclosed or partially enclosed building with a mean roof height of h>18.3m. Hence, section three’s provisions are applied to this study. New York is the metropolitan city in which design examples are located. Basic wind speed for New York is 51.4 m/s (115 mph). In order to obtain wind load values, multiple factors should be calculated. Topographic conditions contribution should be considered through the calculation of the topographic factor (K_{zt}). Gust effect factor is obtained by estimating natural frequency using approximate natural frequency relations. In terms of closure classifications, all the buildings in the current research are assumed to be enclosed. Eq. (11) yields velocity pressure (q_z) at the height of z.

$$q_z = 0.613 K_z K_{zt} K_d V^2 \tag{11}$$

where, K_d is the wind directionality factor. K_z is the velocity pressure exposure coefficient and V is the basic wind speed.

Wind load pressure for the main wind force-resisting system regarding buildings of all height is determined using following equation

$$P = qG_f C_p - q_i GC_{pi} \tag{12}$$

In Eq. (12) C_p is the external pressure coefficient and C_{pi} is the internal coefficient. It should be noted, Eq. (12) yields wind load pressure for the enclosed or partially enclosed buildings.

Dead and live load cases are applied to the structure. Beams are subjected to distributed gravity loading of 24.52 $^{kN}\!/_{m}$ and 9.8 $^{kN}\!/_{m}$ for the dead and live loads, respectively. Due to massive nature of problem limiting design variables is essential. Hence, design governing load combination is selected based on engineering rules of thumb and experience. Eq. (13) is the governing design load combination of ASCE 7-10 defined for the design method of LRFD

$$Q = 1.2D + L + W \tag{13}$$

where, W is the wind load, D and L are the dead and live loads, respectively.

Structural steel properties are same for each design optimization instance. ASTM (2013) structural steel type of A572-Grade 42 (high strength low alloy steel) with the elasticity modules of $205.94\,(GPa)$ and a yield stress of 290 (MPa) is selected. Material unit weight is supposed to be $76.98\,{}^{kN}\!/\!_{m^2}$. For each design example a list of standard steel sections including W and MC sections is selected. For beams and columns W-sections are limited to a range 64 sections starting from W27 to W18. Although the diversity of listed sections creates vast search space, it results in lighter frames to a feasible extent. In order to provide more axial strength for columns, box sections are defined. This is mainly because of significant increase in axial load of lower stories columns in taller frames. Box sections labels, represent their respective dimensions. For a box section labeled as "Box αxβ", α indicates length and width and β is the thickness of the hollow section in cm. All hollow sections defined in the current study, fulfill the requirements of AISC provisions for a compact section. For core and outrigger braces of the frames with lower height, double channel sections are used. Double channel sections are MC sections, fabricated symmetrically to form semi-box section. For taller frames, box sections are selected to assign to the outrigger and core braces.

6. Design examples

6.1 Typical outrigger-braced frame

Fig. 4 demonstrates typical elevation for a simple outrigger-braced frame with a braced core at the mid-span. This type of core is applicable for the frames of lower height as it provides less lateral stiffness. Due to a single X bracing in the mid-span this type of frame is labeled as 1X core.

All the design instances are assumed to be symmetric in plan. For a tall building including n stories and 5 bays, typical story height is $3.4\,(m)$. As mentioned, each example members are divided into separate design groups to simplify the problem. Exterior (edge) and core columns are categorized as the same groups. This group is subjected to considerable axial load and labeled as $C(2n-1)$ columns (see Fig. 4). Columns placed between, must resist significant bending moment. Hence, they are classified as $C(2n)$ columns. For each floor, beam sections are identical and labeled as $B(n)$. Core braces of a same story are supposed to be in same groups. Likewise, same sections will be assigned to outrigger elements. Sections of each design group will be altered every 5 stories to limit the design variables. Table 1 presents the results of analysis for three different models. It is realized as the height of the frame increases, weight of structure increases significantly.

For taller frames box sections are assigned to the peripheral and core columns. For frames of more height, core and exterior columns will be resisting more axial load due to structural behavior of outrigger braced structures. Table 2 lists optimum location for the outriggers of design instances. Ratio of the optimum location to the height of the structure $(X/H \cong 0.56)$ is almost the same with a slight rate of increase. This value is almost the same as the value proposed by Tarnath for the optimum location of the first outrigger.

Significant increase of wind pressure for taller frames will probably result in different solutions as long as outriggers and core are the main wind force resisting systems. Therefore, it is essential to analyze design instances with different height and different core topology.

Table 1 Design details of 1X core

	Model					
Section Label	**Nd**	**1X-20 Story**	**Nd**	**1X-25 Story**	**Nd**	**1X-30 Story**
C(2n-1) for n=1:5	1	W24X229	1	Box 80X3.5	1	Box 92.5X3.5
C(2n) for n=1:5	2	W27X217	2	Box 92.5X3.5	2	Box 92.5X3.5
C(2n-1) for n=6:10	3	W24X192	3	Box 75X2.5	3	Box 75X3
C(2n) for n=6:10	4	W27X194	4	Box 90X3.5	4	Box 92.5X3
C(2n-1) for n=11:15	5	W24X94	5	Box 60X2	5	Box 70X2.5
C(2n) for n=11:15	6	W27X84	6	Box 90X3	6	Box 90X3
C(2n-1) for n=16:20	7	W21X57	7	Box 40X2	7	Box 70X2.5
C(2n) for n=16:20	8	W27X84	8	Box 75X2.5	8	Box 75X2.5
C(2n-1) for n=21:25		-	9	Box 35X2	9	Box 70X2.5
C(2n) for n=21:25		-	10	Box 45X2	10	Box 60X2
C(2n-1) for n=26:30		-		-	11	Box 35X2
C(2n) for n=26:30		-		-	12	Box 35X2
B(n) for n=1:5	9	W27X94	11	W27X94	13	W24X279
B(n) for n=6:10	10	W27X129	12	W27X114	14	W27X217
B(n) for n=11:15	11	W27X84	13	W27X146	15	W27X194
B(n) for n=16:20	12	W21X48	14	W27X84	16	W27X194
B(n) for n=21:25		-	15	W27X84	17	W27X194
B(n) for n=26:30		-		-	18	W21X68
Br(n) for n=1:5	13	2x MC8X21.4	16	2x MC12X31	19	2x MC8X22.8
Br(n) for n=6:10	14	2x MC6X18	17	2x MC10X28.5	20	2x MC12X14.3
Br(n) for n=11:15	15	2x MC12X10.6	18	2x MC12X10.6	21	2x MC8X21.4
Br(n) for n=16:20	16	2x MC6X18	19	2x MC12X14.3	22	2x MC12X10.6
Br(n) for n=21:25		-	20	2x MC10X6.5	23	2x MC10X6.5
Br(n) for n=26:30		-		-	24	2x MC18X51.9
O(1)	17	2x MC6X18	21	2x MC12X14.3	25	2x MC10X25
Weight (kN)		1647.6		3811.9		5916.9

Table 2 Other details for 1X core

Model	Weight (kN)	Opt. Location (Story)	Ux (cm)	Maximum Drift Ratio	X/H
1X-20 Story	1647.6	11	14.46	0.0025	0.55
1X-25 Story	3811.9	14	18.63	0.002478	0.56
1X-30 Story	5916.9	17	23.08	0.0025	0.57

Values of drift ratio for each example are almost the value of ASCE 7-10 limit state. This positive feature yields the optimum location for an outrigger while satisfying all requirements of provisions. Values for maximum lateral displacement are also listed in Table 2.

6.2 Investigating core and outrigger rigidity

To evaluate effect of outrigger and core rigidity on the optimum location and number of outrigger new types of cores are defined. Fig. 5 illustrates new topologies including zipper braced and 2X core. Among the frames 2X core will have the most lateral stiffness. Zipper braced frames will resist more lateral loads compared to 1X core. Also, influence of outrigger stiffness is assessed by bracing two adjacent stories of 2X core frame to form an outrigger (2X-RO). This type of outrigger is common in real world designs. More details is illustrated in Fig. 5(c). Fig. 6 demonstrates convergence history of three different types of cores for the 20 story frames.

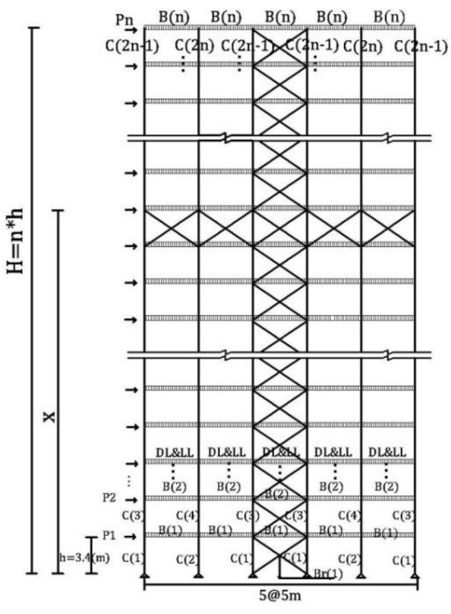
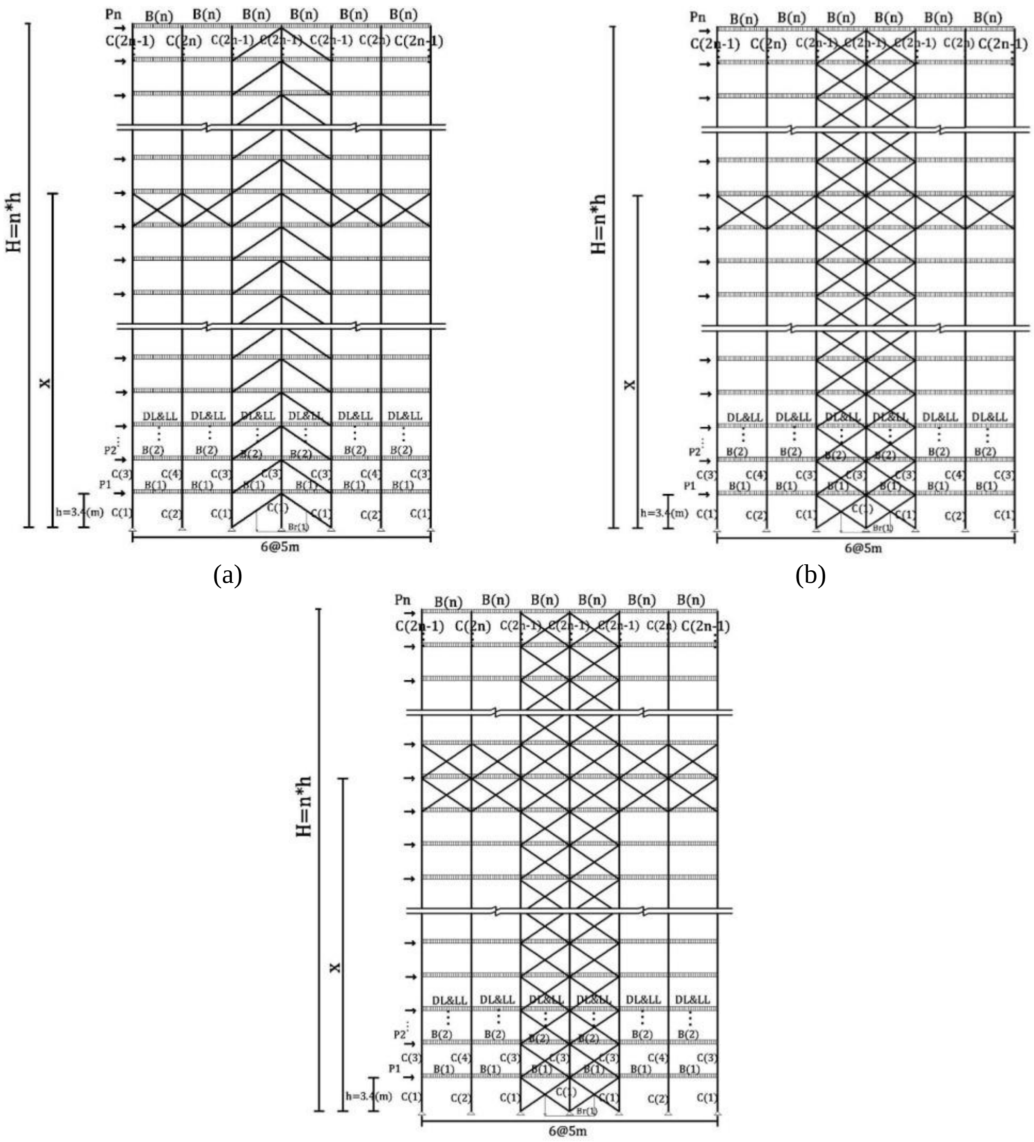


Fig. 4 1X core frame- 5 bays- n stories

Results of optimization are listed in Table 3. It is noticed, specific optimal core topology exists for each design with a certain height. For instance, up to 25 stories zipper column core will be more efficient as it provides sufficient lateral stiffness and more space for non-structural components like windows. Although, maximum lateral displacement for this type of core $(19.5\,cm)$ will be more than the other types, maximum weight of the structure for 20 story frame will be less than the other core types. It is also noted, 2X core is proper for taller building up to 35 story. However, for a 40 story frame a more rigid outrigger will yield a lighter frame. The reason is this type of core topology which leads to more lateral stiffness.



(a) (b) (c)

Fig. 5 (a) Zipper column brace core- 6 bays - n stories and (b) 2X core- 6 bays- n stories (c) 2X-RO core frame- 6 bays- n stories

Results show the more rigid the outrigger, the lower optimum location for the outrigger. For the models of same core rigidity, the model with more outrigger rigidity will have a different optimum location. Core rigidity plays an important role on process of locating the optimum location of an outrigger. Optimum location of outrigger for zipper column core is on higher levels compared to the 2X core.

Exact distribution of wind load and mostly the considerable contribution of height to the wind pressure are obvious in the design examples; to illustrate this, a comparison is made between different heights. Fig. 7 shows the difference between wind pressure distributions of each example. It can be noted, wind pressure increases substantially for the examples of different height.

For frame of more height, optimum weight increases significantly. In addition to that, X/H is not a constant value for frames of different height, core topology, and outrigger rigidity. Values of X/H are in direct relationship with height of the structure. The reason is employing longer length of exterior columns resulting in more axial strength, therefore providing more lateral stiffness. However, growth rate for the ratio is strongly depends on the factors mentioned earlier. For zipper braced frame X/H value is in the range of 0.55 to 0.65. For a more rigid core (2X) X/H value is less than zipper-braced frame in case of lower heights. However, the ratio increases for taller frames. Values of X/H for this type of core are in the range of 0.45 to 0.77.

Using a more rigid outrigger (2X-RO) lowers the ratio of the optimum location to the total height of the structure. Fig.8 demonstrates weight of the single outrigger-braced structures categorized in three different groups. Diagram highlights effect of the height on the ultimate weight of the structures and gives clue about wise choice of optimum design to achieve minimum weight. Values of X/H are compared for each height and topologies and presented in bar chart of Fig. 9. Table 4 presents maximum drift and displacement for each design.

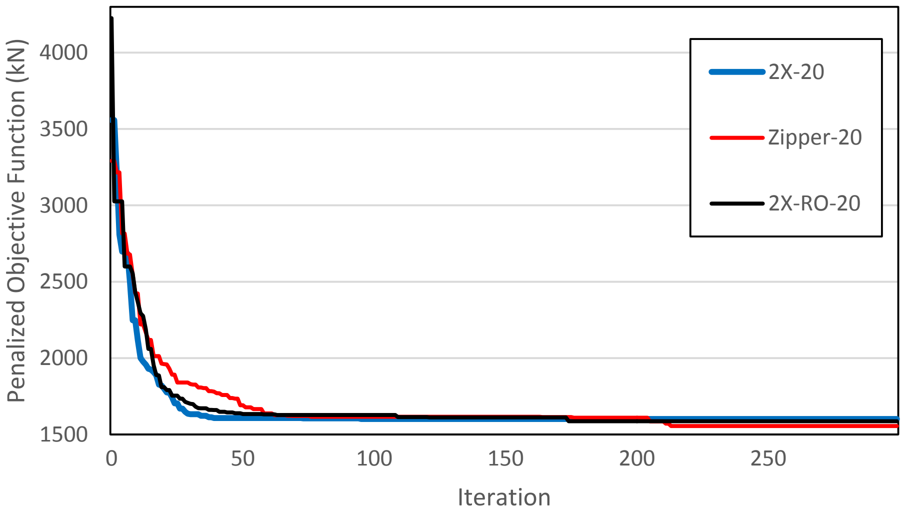


Fig. 6 Convergence history of 20 story frames (300 Generations)

Table 3 Optimum weight and outrigger location of single outrigger-braced frames

	Optimum Weight (kN)			Optimum Location (Story)			X/H		
Story	2X	2X-RO	Zipper	2X	2X-RO	Zipper	2X	2X-RO	Zipper
20	1601.6	1586.6	1554.8	9	6,7	11	0.45	0.3	0.55
25	2939.5	2925.9	3010.3	15	8,9	16	0.6	0.32	0.64
30	5346.9	5282.8	5411.2	21	13,14	18	0.7	0.43	0.6
35	8660.3	8740.7	9424.6	26	21,22	21	0.74	0.6	0.6
40	13796.9	13687.7	14393.1	31	26,27	26	0.77	0.65	0.65

Table 4 Maximum drift and lateral displacement values

	Maximum Drift Ratio			Maximum Lateral Displacement (cm)		
Story	2X	2X-RO	Zipper	2X	2X-RO	Zipper
20	0.0024987	0.0024979	0.0024785	14.68	14.00	14.16
25	0.0024974	0.0024989	0.0024999	18.93	17.65	19.05
30	0.0024953	0.0024982	0.0024994	23.18	22.88	23.20
35	0.0024983	0.0024982	0.0024974	27.39	27.17	26.78
40	0.0024991	0.0024994	0.0024991	31.94	31.44	31.63

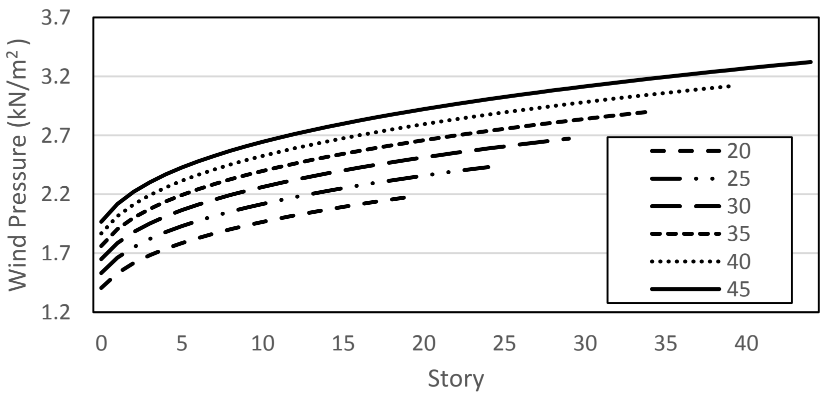


Fig. 7 Wind pressure distribution

Keeping drift and lateral displacement values close to the limit-states will result in lighter frames and optimum design. For the frames with more rigid outrigger and core, lateral displacement and drift values will be less compared to the other designs, yet these frames are not the optimum design.

In summary it can be stated that, the optimum design of outrigger braced tall structures is not the one which minimizes the lateral displacement.

During each run, constraints related to design optimization instances are monitored carefully. Ratio of drift and strength to the corresponding limit-sates for each optimum result are obtained. Average of each ratio is demonstrated on Figs. 10 and 11. Based on the results of analysis, as the structures reach higher levels, drift constraints are tending to be more violated. Hence, design of taller frames will be displacement-based. Unlike serviceability constraint, strength constraint will be less violated. Figs. 12 and 13, show strength ratio values for columns of 20 and 40 story structures. x and y axes represent coordinates of columns and z axes is the ratio values. It is clear that, strength values for the 20 story frames are more than 40 story frames.

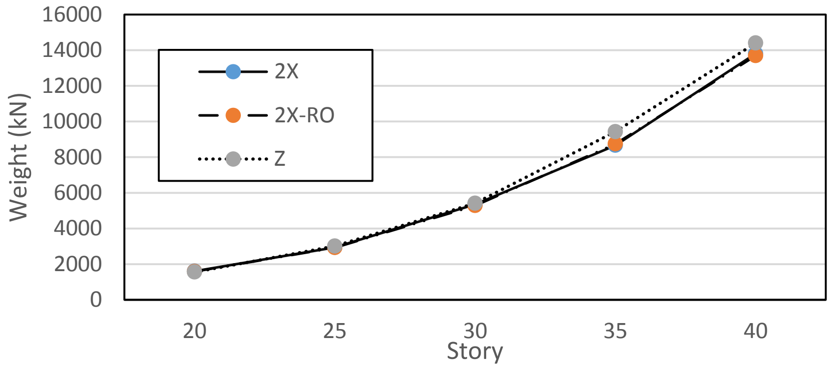


Fig. 8 Weight increase

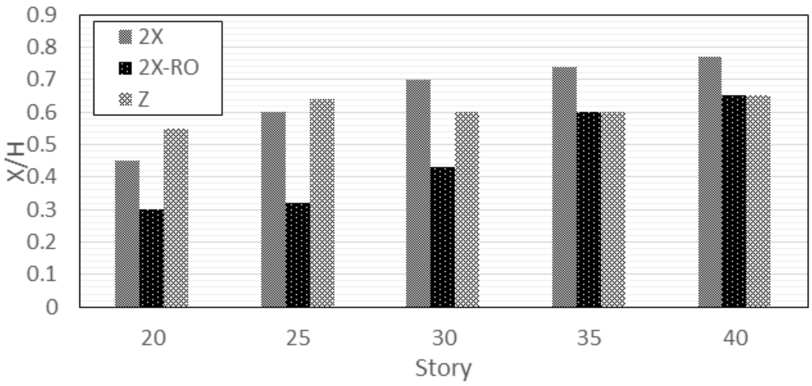


Fig. 9 Bar chart of X/H values for single outrigger-braced structures

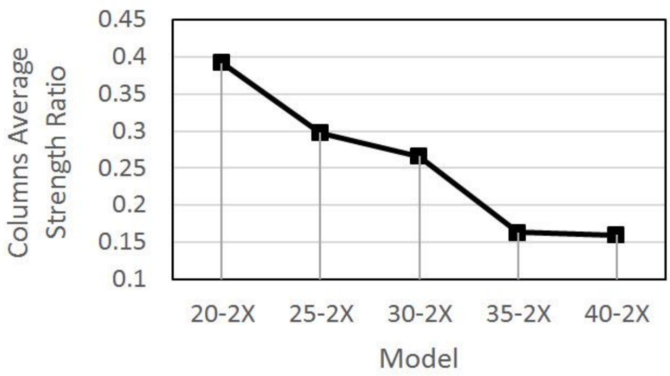


Fig. 10 Columns average strength ratio

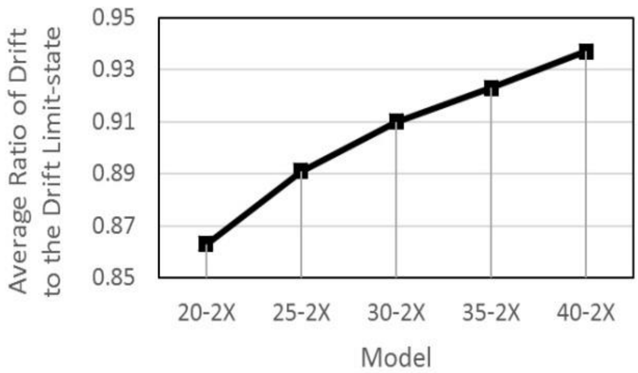


Fig. 11 Average Ratio of Drift to the Drift Limit-state

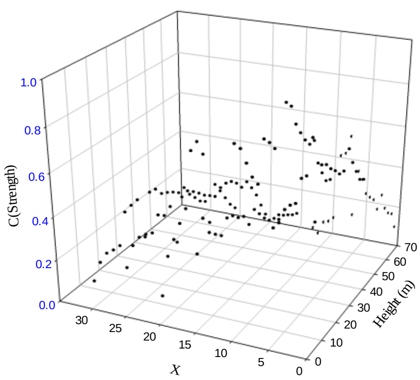


Fig. 12 Strength ratio values for columns of 2X 20 story structure

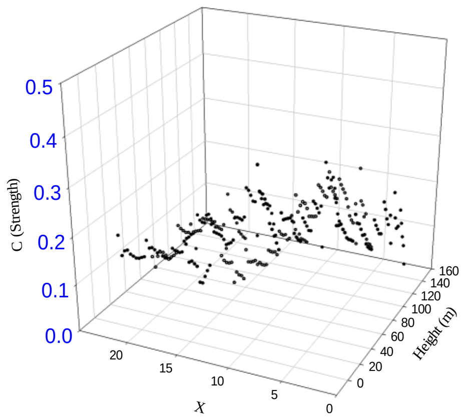


Fig. 13 Strength ratio values for columns of 2X-40 story structure

7. Second outrigger at optimum location

In this section optimum location for the second outrigger will be discussed. New examples containing a second outrigger are presented. For zipper braced and 2X cores simply a second outrigger will be added to the designs. Similar to the single outrigger-braced models, contribution of outrigger's rigidity on the optimum design will be assessed. Thus, couples of outriggers which are braced in two different adjacent stories are modeled. Results of optimization are presented in Table 5. Non-dimensional parameters X_1/H and X_2/H refer to the ratio of the optimum location for the first and second outrigger to the total height, respectively. According to the results of analysis, first outrigger's location for the zipper braced core will be in the range of 0.35 to $0.67X_1/H$. For the second outrigger range of 0.75 to $0.87X_2/H$ will be the interval of optimum location. Based on the results, zipper braced core is not applicable for taller frames. This is mainly because, utilizing this type of core yields a heavier frame. For the frames lower than 40 stories 2X core is a wise choice as it provides sufficient lateral stiffness and results in a lighter frame compared to the other examples. For first and second outriggers intervals of 0.47 to $0.67X_1/H$ and 0.62 to $0.83X_2/H$ are suggested, respectively. It can be stated, while the height of the structure increases the ratio of X_1/H and X_2/H slightly decreases. Using a more rigid outrigger will result in amazingly lighter frame for a 45 story structure. As mentioned before wind loads increase significantly for taller frames.

Constructing structures with more rigid outriggers (bracing two adjacent stories) for taller frames will be effective to achieve a lighter structure. In addition to that, structures with lighter frames will absorb less seismic forces. For a 45 story 2 X-RO frame ultimate weights will be 19% less than the 2X core. Reduction of weight for this topology is considerable. It can be estimated, after a certain height third outrigger would be a wise choice.

Table 5 Details of feasible solutions for structures with a second outrigger

Model	Optimum Weight (kN)	First Outrigger (Story)	Second Outrigger (Story)	Lateral Displacement (cm)	Maximum Drift Ratio	X_1/H	X_2/H
30 Story-Zipper	5215.822	20	26	23.22	0.0025	0.67	0.87
35 Story-Zipper	8814.656	16	25	26.76	0.00249	0.45	0.72
40 Story-Zipper	13708.94	14	30	31.53	0.0025	0.35	0.75
30 Story-2X	5059.525	20	25	22.73	0.0025	0.67	0.83
35 Story-2X	8484.336	17	26	26.76	0.0025	0.48	0.74
40 Story-2X	13416.81	19	31	31.36	0.0025	0.48	0.77
45 Story-2X	32317.55	21	28	36.5	0.0025	0.47	0.62
30 Story-2X (RO)	5128.371	16,17	25,26	22.23	0.0025	0.53	0.83
35 Story-2X (RO)	8850.74	17,18	25,26	25.55	0.0025	0.48	0.71
40 Story-2X (RO)	13493.97	20,21	27,28	31.35	0.0025	0.5	0.67
45 Story-2X (RO)	26183.4	22,23	30,31	35.58	0.0025	0.49	0.67

8. Conclusions

In this paper a new approach to investigate the optimum locations of first and second outriggers is proposed. The method is optimization based and considers weight minimization of the structure as the main objective. Despite the previous studies, exact wind load distribution is subjected to the structures. To improve the convergence rate of GA a new penalty coefficient is proposed. The main objectives of current study is evaluating effects of exact wind load distribution, modeling all structural members including beams and columns, and also considering weight minimization while satisfying serviceability limit-states. Based on the results of analysis, following conclusions are made:

- Ratio of the optimum location to the total height of the structure is not a fixed value. Alteration of this value depends on the several factors. Exact wind load distribution, core and outriggers stiffness and exact modeling of the structures are the main factors contributing to the alteration of this ratio.
- As the height of the structure increases, wind load significantly increases. Thus, assumptions of simplified method regarding wind load distribution are not recommended. Wind load increase, significantly increases weight of the frames. In this case, wise choice of core topology, and outrigger rigidity are solutions of weight reduction.
- Constructing a second outrigger will reduce weight of the structure. However, optimum number of outriggers should be investigated carefully to consider the criteria regarding architectural considerations.

- The penalty coefficient which is proposed in this paper is suitable for the current problem of optimization and can be consistent with most of the frame structures optimizations as it preserves appropriate gens of chromosomes and results in noticeably faster convergence.

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