

IMPROVED BIG BANG-BIG CRUNCH ALGORITHM FOR OPTIMAL DIMENSIONAL DESIGN OF STRUCTURAL WALLS SYSTEM

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ABSTRACT

Among the different lateral force resisting systems, shear walls are of appropriate stiffness and hence are extensively employed in the design of high-rise structures. The architectural concerns regarding the safety of these structures have further widened the application of coupled shear walls. The present study investigated the optimal dimensional design of coupled shear walls based on the improved Big Bang-Big Crunch algorithm. This optimization method achieves unique solutions in a short period according to the defined objective function, design variables, and constraints. Moreover, the results of the present study indicated that the dimensions of the coupling beam in the shear wall significantly affect the wall behavior by maximizing its efficiency which implies on its practical application by considering the wall in the flexural model.

Keywords: Optimization, Coupled shear wall, Big Bang-Big Crunch Algorithm, Design

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1. INTRODUCTION

Improving behavior of concrete structures has been a major issue among structural engineers, leading to developing different ways. In recent decades, profiting from other phenomena such as temperature, magnetism, and electricity in engineering applications has drawn a lot of interest among scientists. These phenomena are widely used in either developing smart structures or improving physical properties of concrete [1].

In many structures, the lateral load applied to the building is resisted by the separate reactions generated by the shear walls. However, under practical conditions, the walls are connected through bending-resistant members. For instance, in residential buildings, one or more rows of openings are included in the external walls as windows, and the internal walls

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also comprise a number of openings for the doors or hallways. Home units in residential complexes are usually designed and located longitudinally on the two sides of a central hallway along the building. This type of architectural spaces requires the construction of partition walls vertical to the building length as well as walls along the hallways and external faces of the building. In addition to partitioning the units, confining the spaces, and providing sound and thermal insulations between the units, continuous walls at appropriate places are responsible for carrying vertical and horizontal loads. Such shear walls connected through bending resistant members are known as coupled walls. Presence of such coupling bending members would increase the system stiffness and efficiency. Optimization methods can be employed to design the coupled shear walls having considerably lightweight, inexpensive and constituting materials.

In recent decades, various optimization techniques have been discovered and employed, among the oldest of which the genetic algorithm [2] and ant colony optimization algorithm [3] can be pointed out. Particle swarm optimization methods [4],[5], which are based on the flocking behavior of migrating of birds and harmony search method [6], have been tested on different structures in the past decade and acceptable results were obtained. The big bang-big crunch (BB-BC) method, which has been used in recent years, was introduced by Erol-Eksin [7] and was initially employed in civil engineering by Camp [8]. Taking into account the optimization procedure in this method, Camp improved the performance of this method by modifying the regeneration equipment and importing the best global solution to produce a candidate solution for each design variable. Inspired by the idea behind PSO algorithm, Kaveh and Talatahari [9] achieved a better convergence for the BB-BC method by importing the best global and local solutions in the population generation in the Big Bang (BB) stage. This method involves two stages, the first of which, i.e., BB, scatters the population, dissipates energy, and requires a long runtime. However, in the second stage known as the Big Crunch (BC), all the points are drawn into order around a point referred to as the center of mass, causing the optimization process to speed up. After a number of iterations in the BB-BC method, the space in which the particles are randomly distributed gradually gets smaller in the BB stage, and then the particles gather around the center of mass in the BC stage, consequently causing the algorithm and the convergence rate to speed up.

2. ANALYSIS OF COUPLED SHEAR WALLS

Similar to other structures, coupled shear walls can be analyzed both approximately and accurately. Shear Continuum Theory is the most important approximate method which makes simplifications by assuming all horizontally connected members create a continuous connection medium between vertical members along the entire height of the building. The result of this simplification is the transformation of the building from a 2D to a 1D model, where all main forces are a function of vertical coordinates across the building height. This enables us to explain the structural behavior through linear differential equations which will ultimately result in a closed-form solution. In order to keep the discussion short and to the point and since a practical point of view is a matter of concern in this study, the proofs for the equations are overlooked, and only the principal and practical equations are presented. Coupled shear walls, similar to other structures, can be analyzed both approximately and

accurately. The approximate methods are faster and more appropriate for manual calculations and in obtaining initial estimations of the cross-sectional dimensions; However, they can only be used for regular and semi-regular structures and loads. On the other hand, accurate methods are capable of analyzing irregular structures and complex loadings, but also require computers as their calculation tool. The analysis method is usually selected based on the structural form and the required degree of accuracy.

2.1 Continuous Medium Method

The initial assumptions of the analysis are as follows: (1) The details of the walls and coupling beams along the height are maintained, and the height of stories are identical. (2) The cross-sectional planes of all structural members maintain their form and remain as planes before and after bending. (3) Flexural rigidity EI_b of coupling beams, are replaced with flexural rigidity EI_b/h per unit height associated with the equivalent continuous coupling medium, where h is the storey height. To achieve further accuracy, the inertia of the highest beam is assumed to be half those of the other beams. (4) Horizontal displacement of the walls is identical due to the high rigidity of the surrounding slabs and axial stiffness of the coupling beams. Therefore, the slope of walls is similar in each level across the height. By directly employing the slope-displacement equations, it could be assumed that the coupling beams, i.e., the continuous coupling medium, experience a bending deformation with an inflection point in the middle. Moreover, this assumption also suggests that since the wall curvatures are similar at all heights, the bending moment in each wall is proportional to its flexural rigidity. (5) The axial and shear forces and the bending moments of the coupling beams can be replaced with the equivalent continuous distribution and intensities of n , q , and m per unit height, respectively as shown in Fig. 1 and Fig. 2.

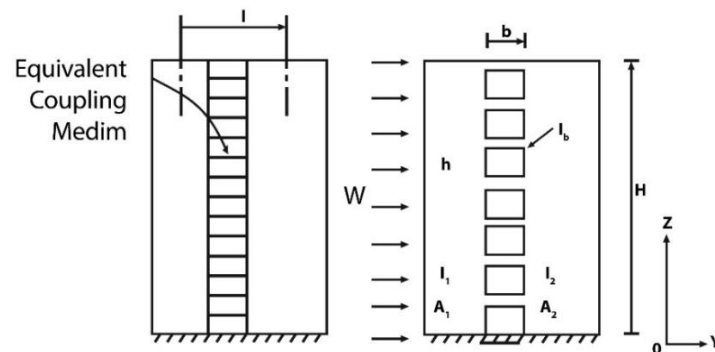


Figure 1. Demonstration of the coupled shear wall with the continuous model.

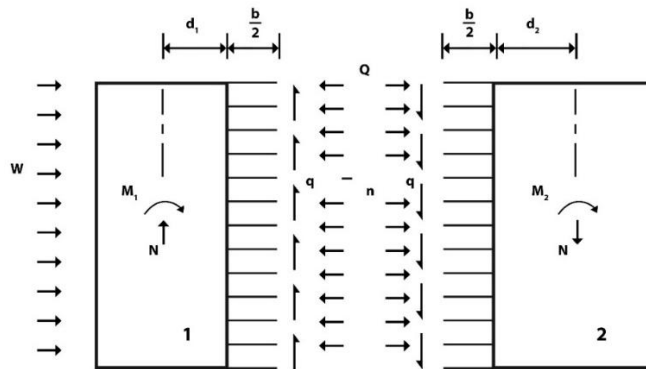


Figure 2. Internal reaction forces in the coupled shear wall.

The basic equations are as follows:

The governing differential equation for the coupled shear walls are expressed as:

$$\frac{d^2T}{dy^2} - \alpha^2 T = -\gamma M_0 \tag{1}$$

where T and M₀ are the axial force and the external moment, respectively. The value for α is obtained from the following equation:

$$\alpha^2 = \frac{12I_b}{C^3h} \left[\frac{a^2}{I_1 + I_2} + \left(\frac{1}{A_1} + \frac{1}{A_2} \right) \right] \tag{2}$$

where c is the free end of the beams. Other specifications are given in Fig. 3. Moreover, we may write

$$\frac{1}{K^2} = \frac{\gamma a}{\alpha^2} \tag{3}$$

where K is calculated as:

$$K^2 = 1 + \frac{I_1 + I_2}{a^2} \left(\frac{1}{A_1} + \frac{1}{A_2} \right) \tag{4}$$

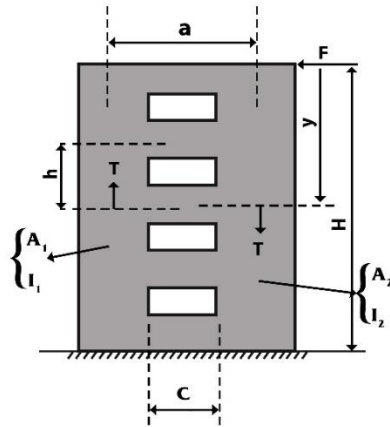


Figure 3. Specifications of the coupled shear wall employed in the equations.

When walls are subject to lateral loads, the ends of connected beams undergo rotation, vertical displacement, and two-axis bending to carry the moments in the wall. The flexural behavior of walls causes shear in the connected beams, and they, in turn, impose moments to both walls opposite to the applied external moments. The shears also cause axial loads in the walls. Therefore, the moment due to lateral load in any structural level is carried out by the sum of bending moments in the walls in the same level and the moment caused by the axial force [10].

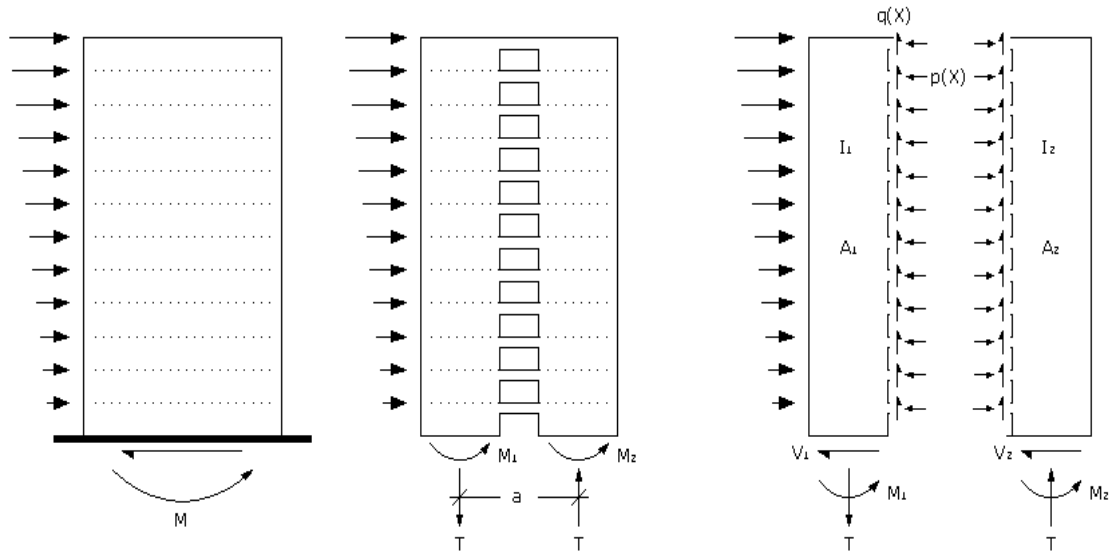


Figure 4. Demonstration of the forces formed in the coupled shear wall [10].

The axial load at each level is equal to the sum of shears in the coupling beams above the same level, which is dependent on the stiffness and strength of coupling beams. The degree of coupling for the wall η_w can be defined according to Eq. 5:

$$\eta_w = \frac{T_a \cdot a}{M_0} = \frac{T_0 \cdot a}{M_{w1} + M_{w2} + T_0 \cdot a} \quad (5)$$

where T_0 is the sum of shear forces in the coupling beams and a is the distance between the centers of each of the coupled walls according to Fig. 4. The degree of coupling for different walls usually ranges from 0.3 to 0.5.

$T_0 \cdot a$ denotes the inverse moment caused by bending of coupling beams resisting against free bending of the walls. This parameter approximates zero for walls with joint connections, while its maximum occurs in the case of infinitely rigid coupling beams. Accordingly, the length of the coupling beams the opening increases, the effect of axial force in the wall and the bases is decreased.

The diagram of Eq. 5 is demonstrated in Fig. 5 for a coupled wall comprising two walls with the stiffness of $EI_1 = EI_2$. The horizontal and vertical axes denote, respectively, the internal moment in each wall and the slenderness ratio h_b/I_b , where h_b and I_b are the height and span of the coupling beam. The slenderness ratio in our case is considered as the stiffness of the coupling beams. A slenderness ratio of zero in a beam is equivalent to no bending stiffness and, thus, the wall moments are divided proportional to the stiffness of each of the walls according to Eqs. 6 and 7. In other words, the axial force is zero in the walls [11].

$$M_{w1} = M_0 \frac{I_1}{I_1 + I_2} \quad (6)$$

$$M_{w2} = M_0 \frac{I_2}{I_1 + I_2} \quad (7)$$

$$M_{w1} + M_{w2} = M_0 \quad (8)$$

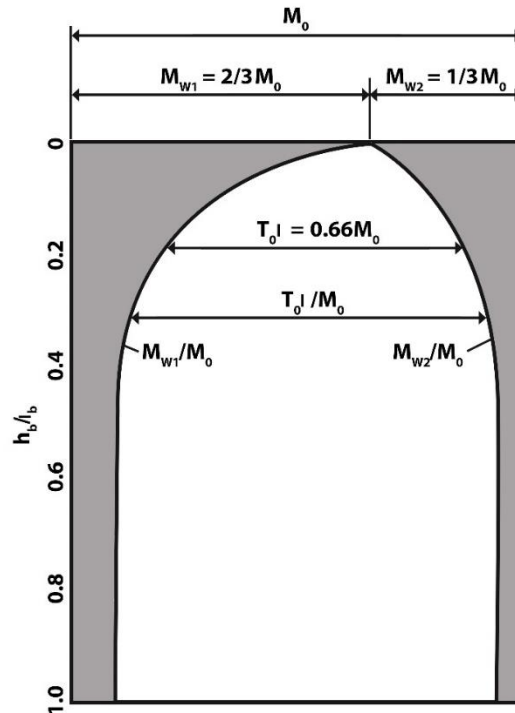


Figure 5. Effect of the stiffness of the coupling beam on the moments carried out by Walls 1 and 2, where $I_1=2I_2$ [11].

The shear in coupling beams is increased as their bending stiffness increases. Consequently, the contribution of overturning moment resisted by the axial couple $T_0 \times a$ is considerably increased. As their major effect, the coupling beams reduce the experienced M_{w1} and M_{w2} in the base of the two walls, which facilitates the transfer of wall reactions to the foundation. The coupling beams also decrease the lateral deformations. The two walls act as a single independent wall in case the beams are fully rigid, i.e. are of infinite stiffness. This is demonstrated in Fig. 5. Actual decomposition of the external M_0 moment into the internal moments M_{w1} , M_{w2} , $T_0 \times a$ depends on parameters such as h_b/I_b [12].

Harris [13] showed that the ductility capacity of a coupled wall system increases as the degree of coupling is increased. The degree of coupling is a function of stiffness and relative strengths of beams and walls. Saatcioglu et al. [14] demonstrated that coupling beams should be capable of improving a system with a displacement ductility of roughly 4 to 6.

Coupling beams may be rectangular or T-Shaped beams or a part of the floor slab. In earthquake-prone regions, the coupling beams may also comprise diagonal rebars.

The Canadian concrete regulations assert that the contribution of the moment $T_0 \times a$ should be at least 66 percent of the moment M_0 in seismic design, in which case the ratio h_b/I_b should be roughly 0.2 according to Fig. 5. In case this percentage is lower than the 66 percent threshold, the wall is referred to as partially coupled wall.

The general behavior of coupled shear walls against lateral loads should be such that the plastic joint is initially formed in the coupling beams (Fig. 6a). The coupled shear wall system undergoes a stiffness decrease, and the walls begin to necessarily operate as individual cantilever walls, in which case bending plastic joints are formed in the base of

the walls similar to the behavior of strong column-weak beam in a flexural frame system as shown in Fig. 6b [15].

The coupling beams should be of sufficiently high stiffness and strength so that the system can perform favorably. In any case, these beams should yield before the base of the walls reaches that point and, thus, should be ductile in their performance and demonstrate a high energy absorption property. In fact, the design objectives in this lateral force resisting system require the coupling beams to be the first members to fail, which is similar to the role of a primary fuse in limiting the overall demands of the system. As a result, they are usually subject to large plastic rotations and should provide a reliable energy dissipation mechanism.

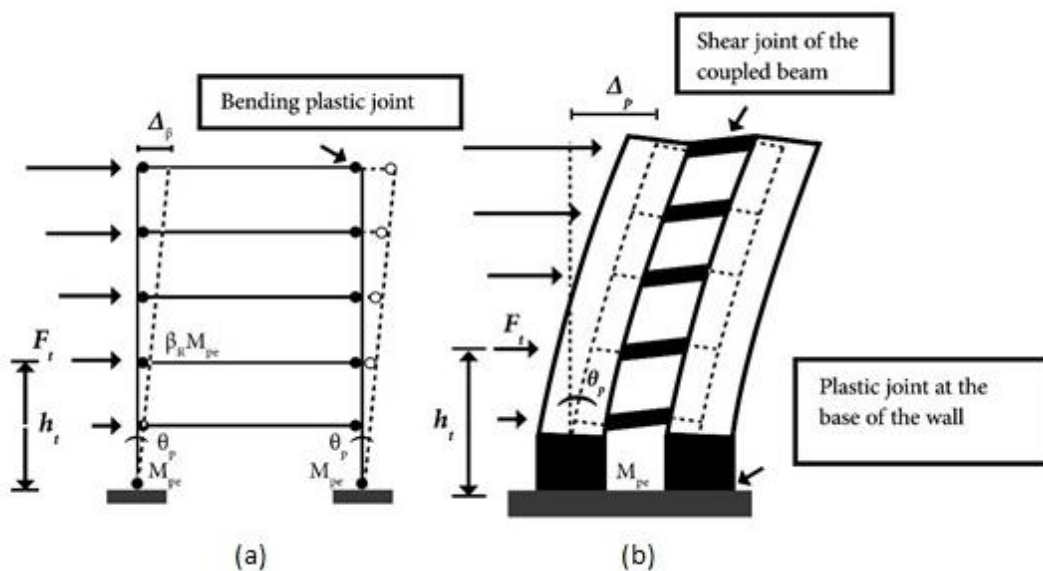


Figure 6. Locations for formation of plastic joints. (a) The system of the coupled shear wall, (b) Flexible system.

Flexural behavior is the dominant behavior in tall shear walls and/or walls with small-width bases, where the created moment in the wall due to the lateral loads are resisted by a couple and a moment.

In general, it can be concluded that the behavior of this type of walls is highly affected by the stiffness, strength, and ductility of the coupling beams. Understanding the critical regions including plastic areas and joints is of great importance in assessing the nonlinear behavior of shear walls.

In another study, Safari and Gharemani [16] concluded that increasing the height of the coupling beam leads to increased ultimate strength. However, increasing this height greater than 33 percent of the story height does not significantly affect the ultimate strength of the wall and, instead, decreases the ductility.

Kheyroddin et al. [17] proposed an equation to calculate the development length of steel coupling beams and concluded that the presence of this member results in the uniform development of cracks in shear walls, which in turn affects energy absorption and increases ductility.

The coupling beams connected to the structural walls provide stiffness and energy absorption. In some cases, geometrical and architectural limitations in the coupling beam lead to a large span-to-depth aspect ratio. Deep coupling beams may also be controlled by shear and undergo a drastic decrease in strength and stiffness when subject to seismic loads.

2.2 Different loading types

Lateral uniform distributed loading: Consider a two coupled shear walls supported by a rigid foundation and subject to uniformly distributed loading with a magnitude of w per unit height.

Equations for point loading applied from above and triangular distributed loading: In this section, the continuous method is used to solve the problem for two other forms of standard loading, i.e. point load P and triangular distributed load with a maximum magnitude of p , where both are applied to the top of the structure. (Triangular distributed loading with a magnitude of $p(z/H)$)

3. OPTIMIZATION

3.1 A Big Bang-Big Crunch method

This method includes two phases, namely the Big Bang (BB) and Big Crunch (BC) phases, respectively. In the former, the candidate solutions are randomly distributed in the search space. The random distributions lead to energy dissipation and cause generation of new candidate solutions for the next phase.

A description of the BB-BC method in the optimal dimensional design of coupled shear walls is given as follows:

- 1) Determining the objective function and design constraints:

$$\begin{aligned} \text{Minimize } W(\{x\}) &= \sum_{i=1}^n \gamma_c \cdot t_i \cdot h_i \cdot L_i \\ \text{Subject to:} \\ K_2 &= 200/3 \\ K_1 &= 100/3 \\ Y_H / H &\leq 1/500 \\ L_c / h_c &\leq 2 \\ 2 < L_c / h_c &\leq 5 \\ L_c / h_c &> 5 \end{aligned} \quad (9)$$

where $W(\{X\})$ is the structural weight, n is the number of structural members, γ_c is the specific weight of concrete, L_i is the length of the coupling beam or the shear wall depending on the element type, t_i is the thickness of the coupling beam or the shear wall depending on the element type, h_i is the height of the coupling beam or the shear wall depending on the element type, K_1 is the percentage of the individual cantilever behavior

(moment coefficient) of each wall in resisting moments, K_2 is the percentage of compound cantilever behavior (moment coefficient) of both walls in resisting moments, H is the overall height of the structure, Y_H is the maximum displacement at the highest point of the structure, and L_c and h_c are, respectively, the length and height of the coupling beam which can display shear, shear-bending, or bending behavior depending on the defined constraints.

2) Generating a given number of random initial candidate solutions for the design variables:

After defining the design variables, values are generated for them using the following formulas and based on the constraints of the candidate solutions:

$$h_i = h_{\min} + \text{Rand}(h_{\max} - h_{\min}) \quad (10)$$

$$L_i = L_{\min} + \text{Rand}(L_{\max} - L_{\min}) \quad (11)$$

$$t_i = t_{\min} + \text{Rand}(t_{\max} - t_{\min}) \quad (12)$$

3) Structural analysis according to the values of design variables suggested by a candidate solution and calculating the penalty functions for each candidate solution:

The methods that can be used to calculate the penalty values are different, and none significantly affects the optimization procedure. The value of a given constraint can either be within its allowed boundaries or out of the upper and lower boundary values. In the former case, the penalty value is considered zero, and in fact of latter case, the penalty is equal to the ratio of the difference between the constraint value and the allowed limit to the permitted limit.

$$\begin{cases} K_2 = 200/3 \Rightarrow \phi_{K_2}^{(i)} = 0 \\ \text{else} \Rightarrow \phi_{K_2}^{(i)} = \left| \frac{200/3 - K_2}{200/3} \right| \end{cases} \quad i = 1, 2, \dots, m \quad (13)$$

$$\begin{cases} Y_H / H \leq 1/500 \Rightarrow \phi_{Y_H / H}^{(i)} = 0 \\ \text{else} \Rightarrow \phi_{Y_H / H}^{(i)} = \left| \frac{1/500 - Y_H / H}{1/500} \right| \end{cases} \quad i = 1, 2, \dots, m \quad (14)$$

$$i = 1, 2, \dots, m \begin{cases} L_c / h_c \leq 2 \Rightarrow \phi_{L_c / h_c}^{(i)} = 0 \\ \text{else} \Rightarrow \phi_{L_c / h_c}^{(i)} = \left| \frac{2 - Y_H / H}{2} \right| \end{cases} \quad (15)$$

OR

$$\begin{cases} 2 < L_c / h_c \leq 5 \Rightarrow \phi_{L_c / h_c}^{(i)} = 0 \\ \text{else} \Rightarrow \phi_{L_c / h_c}^{(i)} = \left| \frac{5 \text{ or } 2 - Y_H / H}{5 \text{ or } 2} \right| \end{cases} i = 1, 2, \dots, m$$

OR

$$\begin{cases} L_c / h_c > 5 \Rightarrow \phi_{L_c / h_c}^{(i)} = 0 \\ \text{else} \Rightarrow \phi_{L_c / h_c}^{(i)} = \left| \frac{5 - Y_H / H}{5} \right| \end{cases} i = 1, 2, \dots, m$$

4) Calculating the fitness function

The value of fitness function for each candidate solution can be calculated according to the following equation. The candidate solutions can be classified based on their minimum fitness value, meaning that the minimum value of the fitness function corresponds to the optimal solution. The amount of the objective function is calculated from the following Eq. 16:

$$Mer^k = w^k (1 + \phi_{K_2}^k + \phi_{Y_H / H}^k + \phi_{L_c / h_c}^k)^\varepsilon \quad (16)$$

where w^k is the value of objective function under the influence of the k^{th} candidate solution, and ϕ_{σ}^k , $\phi_{Y_H / H}^k$, and ϕ_{L_c / h_c}^k denote the penalties caused to the structure by the k^{th} candidate solution. ε is a positive number which incrementally increases from 1.5 to 3 [9].

5) Calculating the center of mass

The center of mass can be calculated in the BC phase for each design variable based on the following equation and the inputs obtained from the BB phase:

$$A_i^{c(k)} = \frac{\sum_{j=1}^N \frac{1}{Mer^j} \cdot A_i^{(kj)}}{\sum_{j=1}^N \frac{1}{Mer^j}}, \quad i = 1, 2, \dots, m \quad (17)$$

where A_i^{kj} is the i^{th} component of the j^{th} generated candidate in the k^{th} iteration, N is the population size in the BB phase, Mer^j is the value of fitness function for the j^{th} candidate solution.

6) Calculating the values of new candidate solutions around the center of mass

$$A_i^{(k+1j)} = A_i^{c(k)} + \frac{r_j \alpha_1 (A_{\max} - A_{\min})}{k+1}, \quad i = 1, 2, \dots, m \quad (18)$$

In this equation, r_j is a normally distributed random number and α_1 is the parameter that

determines the contribution of the allowed interval associated with the design variables.

7) Returning to Step 2 and reiterating the algorithm until the termination criterion is reached.

The termination criterion can be a given number of times that the best solution is repeated.

3.2 An Improved Big Bang-Big Crunch method

Several optimization methods can be combined based on the principal ideal in the HPSACO algorithm [18] to derive a new metaheuristic method. As mentioned earlier, local search agents should be used to improve the HBB-BC algorithm. To this end, the ACO and harmony search (HS) algorithms can be employed and added to the original BB-BC algorithm to improve its performance. Similar to HPSACO algorithm, the ACO algorithm is used to perform a local search around the best global position of a particle, while HS is used to prevent violating the constraints in the IHBB-BC algorithm. To provide a better description of this algorithm, their incorporation in the proposed method is discussed as shown in Fig. 7.

The definition and description of the ant colony optimization algorithm and HS method can be found in [18] and [19], respectively.

3.2.1. Descriptions on IBB-BC

IBB-BC uses BB-BC in its core for global optimization. However, the steps involved in HBB-BC is used in IBB-BC due to its better performance compared to BB-BC. On the other hand, the ACO algorithm enters the optimization process as a local search agent and updates the position of particles, their current best positions, and their best global positions. The ACO algorithm suggests generation of as many ants as the number of particles in the population. In the ACO step, each ant generates a solution around P_{gbest}^k as expressed in the following equation:

$$Z_i^k = N(P_{gbest}^k, \sigma) \quad (19)$$

where $N(P_{gbest}^k, \sigma)$ is a normally distributed random value with an average and a variance of P_{gbest}^k and σ , respectively, where

$$\sigma = N(A_{max} - A_{min}) \times \gamma \quad (20)$$

In this relation, η is used to control the size of the search space. A normal distribution with an average of P_{gbest}^k can be considered an appropriate equivalent to continuous pheromone. In ACO algorithm, the probability of selection of a path with the highest pheromone is greater compared to others. Similarly, in normal distribution, the probability of selection of a solution from the neighborhood of P_{gbest}^k is higher than other solutions. These principals in IHBB-BC are factors which help directing exploration and increase control over exploitation.

In this method, the value of the objective function $f(Z_i^k)$ is calculated and the current

position of i^{th} ant, i.e. Z_i^k , is replaced with the current position of i^{th} particle or X_i^k in case $f(X_i^k) > f(Z_i^k)$ and the i^{th} ant is located in the search space. Moreover, the best global and local positions of particles can be updated by making appropriate comparisons.

Instead of particle-to-particle comparisons, overall comparisons can be constructively used to improve the performance of this step in the algorithm. Therefore, the population within which both the primary particles and the ant population are present is sorted in an ascending order to create a new population with the same number of particles, and this new population is considered the basis of further calculations. Thus, this process retains all good particles. However, in case the comparisons were made particle-to-particle, some particles with competency to remain in the particle population could have been removed in the comparison procedure due to their higher fitness function values, which consequently would have allowed weak particles to enter the population.

The particles that violate the allowed range of variables can be revised based on the HS principals. Two methods are proposed in this regard, one of which is similar to the HPSACO method proposed by Kaveh and Talatahari [5], where an HM is hired to be filled with the best global particles $P_{g_{best}}^k$ in each iteration of the algorithm. As one of the drawback in this method, the HM is gradually filled as it stores new particles in each iteration. Therefore, lower number of particles are available in the memory in the first iterations, hence limiting the selection domain for the violating variables and decreasing the exploration rate for that variable. As another drawback, the particles with small errors, which may be capable of generating appropriate values for this type of variables using the PAR operator, may not enter the memory. The effect of HM on the optimization procedure may be weakened since only one particle at a time is allowed to enter this memory, and the particle is definitely error-free given its lower objective function value. Despite this, as the number of iteration increases and better particles enter the memory, the exploitation power is increased. Hence, the particle is stored in an HM with a size half, third, or fourth the number of particles in the population. Then, those components of the (particle) vector which have violated the permitted boundaries can then be randomly generated by updating the HM and applying the HS algorithm. This allows the particles with low penalty values to enter the HM in the initial iterations and help generating proper values for the violating particles using HS parameters, consequently increasing the exploration power of the algorithm from the very beginning.

As the process develops, the particles with penalties are removed, making space for those particles with low objective function values which can be highly influential similar to the memory in the previous case. As a side note, the optimal values of some variables may be located near the boundary values and, therefore, the generated values for which during the optimization procedure may violate the boundaries. In case, similar to the original algorithm, such violating values are replaced with neighboring values within the permitted range or reassigned a newly generated value; the optimization procedure may be derailed or require a more significant number of iterations to achieve the optimal solution.

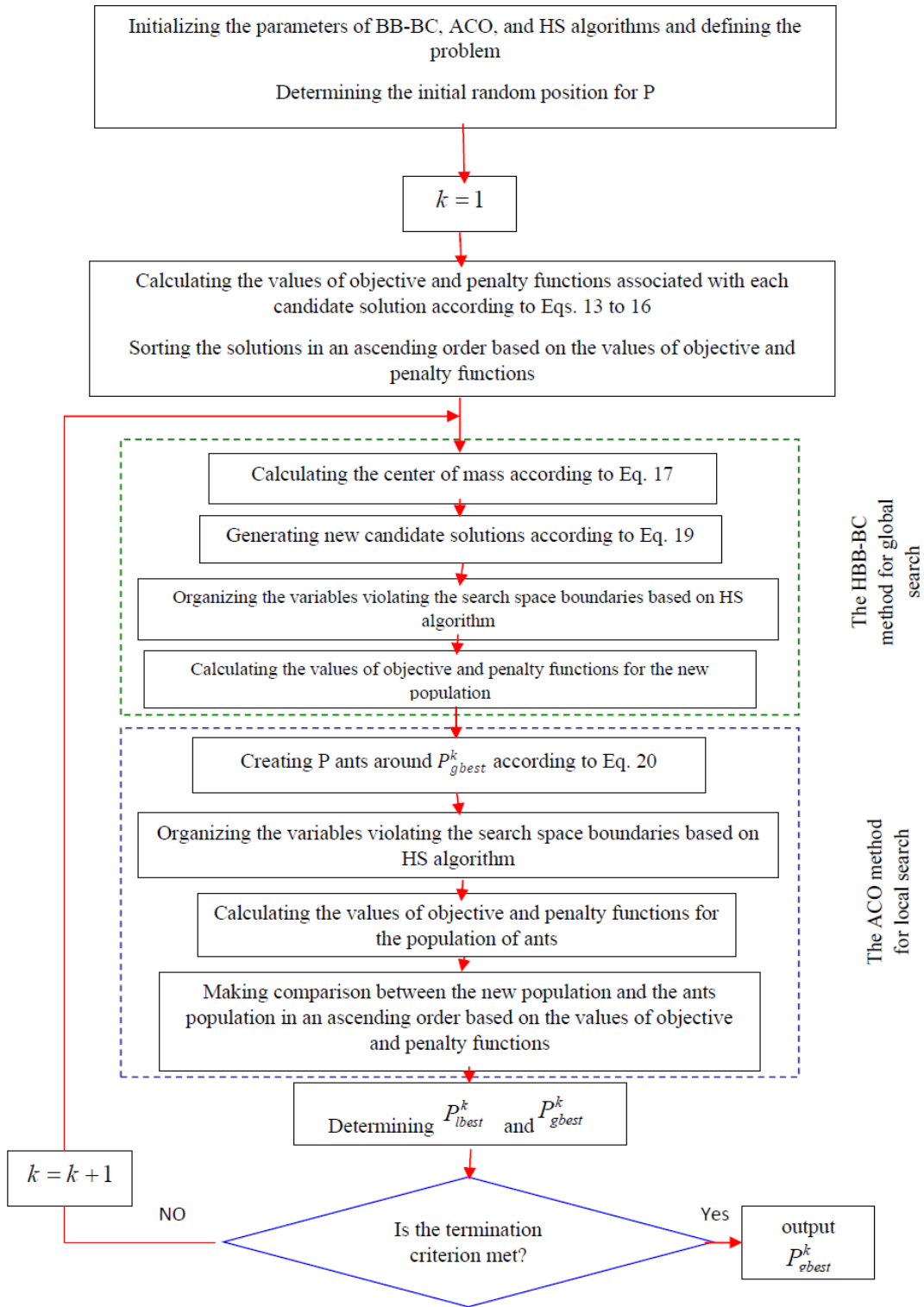


Figure 7. Flowchart of the IBB-BC algorithm.

However, in our case, the governing principals of HS algorithm can be employed to assign new values to such variables from the solutions stored solutions in the HM, which are more appropriate and closer to the optimal value. This process has proven to be very efficient in optimization problems with continuous and discrete variables with equal distances in their values since solutions of high precision can be generated for this type of problems.

4. DESIGN EXAMPLES

In this section, the above equations regarding the design of coupled shear walls are used along with the aforementioned optimization methods to solve some cases so that the efficiency of the optimization methods in the optimal design of coupled shear walls can be validated.

4.1 Example one

Given the geometrical specifications of the shear walls on the two sides, as well as the length and thickness of the coupling beam, determine the optimal height of the coupling beam using the presented optimization methods so that the given constraints are satisfied.

The considered building comprises 20 stories. A coupled shear wall with the following specifications is used in one of the spans of this frame with a 14 m length. This coupled shear wall in this frame is only subject to lateral loading, all of which should be resisted by the shear wall as its lateral resisting system requires so. The objective is to obtain the optimal height of the coupling beam according to the type of lateral load applied to the structural frame by taking into account the following constraints.

Design constraints:

The height of the coupling beam should be obtained so that the moment coefficients of the compound contribution and the individual cantilever contribution, i.e. K_2 and K_1 , respectively, are obtained as 67% and 33%. This constraint is selected so due to the fact that the performance of this type of walls is higher under such conditions and hence the coupling beam works as a fuse. In addition, the ratio of maximum displacement of the top point of the building to its height should be smaller than 0.002. Moreover, the weight of the wall should be minimized with respect to the optimal height of the coupling beam.

$0 \leq \text{height of the coupling beam} \leq \text{storey height}$

Geometric specifications of the coupled shear wall:

Overall structural height: 56 m

The height of each story: 2.8 m

Length of the wall on the right side: 7 m

Length of the wall on the left side: 5 m

Length of the shear wall: 2 m

The thickness of the wall and the coupling beam: 0.3 m

Note that this coefficient was calculated for the most critical case, i.e. the moment at the base of the structure.

Table 1. Calculation of the optimal height of the coupling beam for the first example.

Loading type	Loading magnitude	Optimal height (m)	K_2	$\frac{L}{H_{optimal}}$	$K\alpha H$	Optimal weight (kN)	Optimization time (s)
Uniform distributed loading	16.5(kN/m)	0.52	66.75	3.85	4.776	259.8	1.03
Triangular distributed loading P(z/H)	25(kN/m)	0.45	66.63	4.45	4.02	258.75	0.44
Point loading	100(kN)	0.36	67.16	5.56	3.031	257.4	0.51

As shown, the optimal height for the coupling beam was obtained within a significantly short duration using the described optimization method. As mentioned earlier, the value of $K\alpha H$ parameter should be within 1 and 8 so that the coupled shear wall acts as a compound element resisting against lateral forces. This fact is hence validated in this study according to the results according to Table. 1.

It can also be concluded from the results that the obtained optimal height is one third the story height. As mentioned before, coupling beam heights higher than one-third of the story height are not efficient and, in addition, increase the weight of the wall.

Moreover, the program for the optimization and design procedures was written in MATLAB and run on a CORE i7 CPU. The termination criterion was considered 1000 unchanging solutions, and more than 50000 candidate solutions were tested for each optimization process.

4.2 Second Example

The same building subject to similar loadings as that of Example 1 is considered in this example, with the two following exceptions: the geometric specifications of the shear wall on both sides are unknown, and only the length of that span of the frame within which the couple shear wall is to be placed is given. In this example, the length, height, and thickness of the coupling beam along with the lengths of the shear walls on both sides, which are considered identical, as well as the thickness of the shear walls on both sides, which is equal to the thickness of the coupling beam, are considered the independent optimization parameters.

Design constraints:

The independent parameters of the coupled shear wall which were mentioned in the example should be obtained such that the moment coefficients of the compound contribution and the individual cantilever contribution, i.e. K_2 and K_1 , respectively, are obtained as 67% and 33%. In addition, the ratio of maximum displacement of the top point of the building to its height should be smaller than 0.002. Moreover, the weight of the wall should be minimized with respect to the optimal height of the coupling beam.

Other constraints:

Frame span length: 14 m

$0 \leq \text{height of the coupling beam} \leq \text{storey height}$

0.2 m \leq thickness of the coupling beam and the coupled shear wall \leq storey height

1.5 m \leq length of the coupling beam \leq frame span length

Note that this coefficient was calculated for the most critical case, i.e., the moment at the base of the structure.

Table 2. Calculation of the optimal parameters of the coupling beam in the second example.

Loading type	Loading magnitude	$L_{optimal}$ (m)	$H_{optimal}$ (m)	$t_{optimal}$ (m)	Optimal Length of the Shear Wall (m)	$\frac{L_{optimal}}{H_{optimal}}$	Optimal weight (kN)	$k\alpha H$	K_2	Optimization time (s)
Uniform distributed loading	100 kN	7.05	0.55	0.23	3.475	12.82	134.2	3.08	67.65	20.09
Triangular distributed loading $P(z/H)$	25 kN/m	7.77	0.69	0.29	3.115	11.26	165.34	3.96	66.25	20.39
Point loading	16.5 kN/m	7.07	0.81	0.25	3.465	8.73	157.1	5.05	66.75	16.7

As shown, the optimal height for the coupling beam was obtained within a significantly short duration using the described optimization method. As mentioned earlier, the value of $k\alpha H$ the parameter should be within 1 and 8 so that the coupled shear wall acts as a compound element resisting against lateral forces. This fact is hence validated in this study according to the results as shown Table. 2.

It can also be concluded from the results that the obtained optimal height is one third the story height. As mentioned before, coupling beam heights higher than one-third of the story height are not efficient and, in addition, increase the weight of the wall. Moreover, by assuming the length of the coupling beam and the wall and their thickness are variable in addition to the height of the coupling beam, it was shown that the weight of the coupled shear wall is lower than that in the previous examples, which is a more optimal solution.

We may also impose another constraint on this problem for further investigations and to reach a meaningful conclusion. This constraint is the ratio of the optimal length of the coupling beam to its height, the effect of which on the performance of the coupled shear wall is a matter of concern to us. As explained before, the coupling beam can be considered shear, shear-bending, or bending if the ratio of its span length to its height is, respectively, smaller than 2, between 2 and 5, and greater than 5. Therefore, this raises the question that what value should be assigned to this ratio so that the above constraints are met? In this case and for a better comparison, the thickness of the coupled shear wall was considered 0.3 m for all situations.

As illustrated in the diagram of Fig. 8, in order to take advantage of the total capacity of the coupled shear wall, its weight should be minimized and 67% percentage of the external

moment should be carried by the coupling beam. To this end, the ratio of span length to the optimal height of the coupling beam should be greater than 5, meaning that it should act as a bending beam. This is obviously demonstrated in the previous tables. The weight of the wall begins to decrease as the length of the coupling beam is reduced in a frame span with a fixed length.

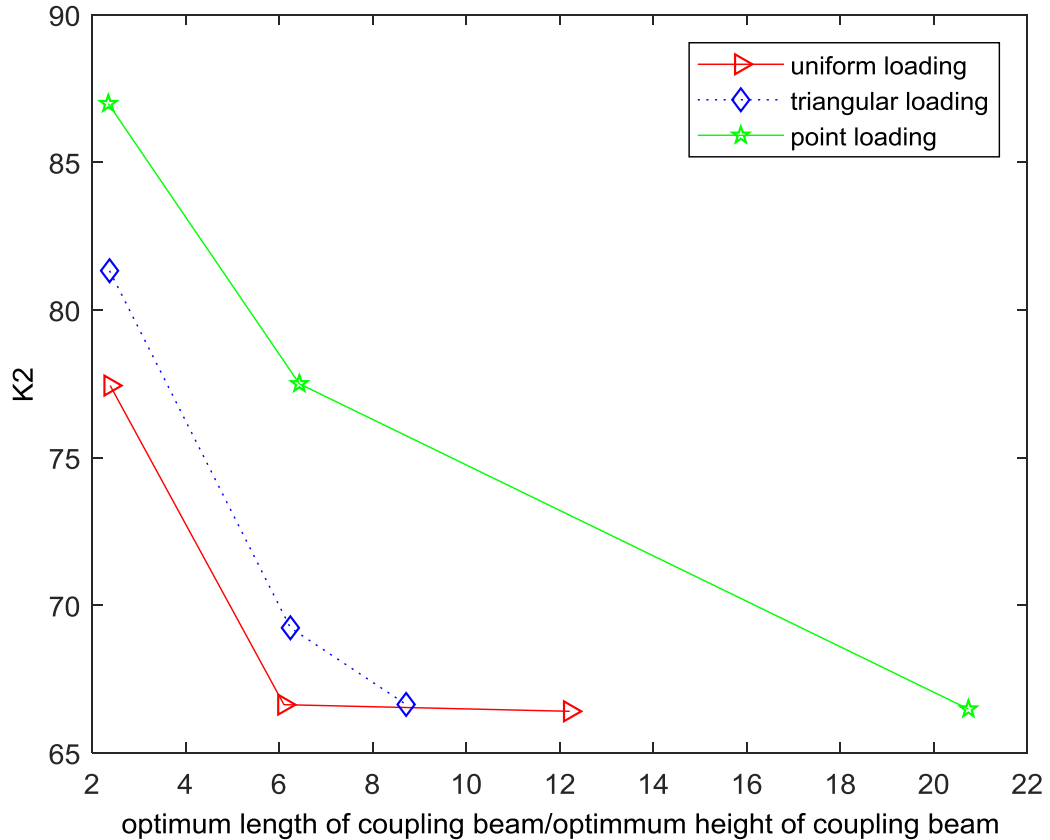


Figure 8. Diagram of values of K_2 with respect to different ratios of the optimal length of the coupling beam to its optimal height.

5. CONCLUSION

A new meta-heuristic algorithm was introduced which is considered as one of the best optimization techniques. The method avoids solving complex mathematical equations and merely uses a randomized procedure to generate optimal solutions for a problem. In this method, the problem is solved in an optimized manner through defining objective functions and design constraints which act as penalty functions. These methods are capable of achieving acceptable solutions in a short time by repeating a set of limited optimization operations. In fact, the convergence rate in this algorithm is higher than the other optimization methods which are all based on solving complex mathematical equations. The

IBB-BC obtains considerably good results since in structural optimization, a number of local solutions exist in the neighborhood of the optimal solution. Therefore, the probability of finding a good optimum is increased by additional searches in the vicinity of the local optimum. This algorithm conducts an extra search around the local optimum and, therefore, has a good chance of obtaining a good solution in a few number of iterations. Thus, not only the results are improved by increasing the exploitation power through of applying the pheromone guiding mechanism to update the particle positions, but also the magnitude of standard deviation is decreased. As well as the present method employs two factors, namely the random search and the selected information from the search space during the optimization process. The former factor dominates the latter in the initial iterations. However, as the number of iteration increases, the strength of factor of selected information gradually increases and takes over the factor of a random search. In IHBB-BC, the ACO stage acts as a supporting rule to increase the speed of applying the factor of selected information, subsequently causing a rapid increase in the convergence rate. Moreover, this prevents particles from violating the specific constraints of the problem and creating decreased exploration. This problem can also be tackled by the HS algorithm. Coupled shear walls are widely used in high-rise buildings as they are very rigid and allow preparation of appropriate spaces for implementation of elevators and stairways. Therefore, it of utmost importance to optimize the weight of this structural resistive system. As the results indicated, in case the length of the coupling beam is greater than five-fold of its height, i.e., the beam is highly rigid, it acts as a bending beam, and the entire capacity of the wall and the coupling beam can employ to resist external moments. Finally, as reported by previous studies, the optimal length of a coupling beam should be smaller than one-third of the story height so that its entire capacity can be utilized and simultaneously its weight could be optimized.

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