Design Optimization of RC MomentFramesbySwarmOptimization and FiniteElementMethodusingSystemofDesign Rules

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Abstract

The main objective of seismic design is to design buildings that do not collapse but incur repairable structural damages after an earthquake event. Seismic design codes stipulate minimum design provisions with the expectation of rendering a seismically safe structure. Nevertheless, the design can be formulated as optimization problems where a measure of structural performance *(e.g.*, nonlinear seismic behavior) is optimized, while satisfying critical design constraints. This paper presents such an optimization procedure for design of RC moment frames. Cross-section properties of frame members are optimized considering constraints specified by design codes. For the purpose, Artificial Bee Colony (ABC)methodis adopted, where the cross-section properties of frame members are optimized iteratively to improve the seismic behavior of the frame. The structural design provisions enunciated in Indian Standards IS456 (2000), IS1893 (2016) and IS13920 (2016) are used as system of design rules, to interact with Finite Element Method of analysis of frames developed for the study. Inter-story drift capacity of the frame that help monitor improvement in theseismic behavior of the frame is considered as the objective function for optimization. The cross-sectional properties ofstructural members are chosen from a set of pre-defined sectional properties from the database developed (commonlyadopted cross-sectional properties of beams and columns forms the database), to form design variables compliant withIndian Standards. The optimized design & detailing of frame elements are obtained after the 2-dimensional framestructure is analyzed under the action of multiple load (dead load, live load, and earthquake load) combinations. ABC method can then be applied, to improve the Nonlinear Static Response (*e.g.,* inelastic drift capacity) of the frame.

Keywords: Seismic Design; Optimization;Artificial Bee colony; Finite Element Method;NonlinearStatic Response

1. Introduction

One of the main objectives of construction projects is to complete the construction with the least possible cost. Optimal designing of structures has a major role in reduction of material usage which leads to reduction in the construction cost. Optimum design of frame structures is an approach to find sections of frameelements with no violation of design constraints. In general, optimization of frame structures can be considered as size, shape andtopology optimizations.Size optimization deals with cross-sectional areas of members, shape optimization finds the best position of nodes forming the cross-section, andtopology optimization includes presence or absence of members. While light-weight structures are mostly preferred to reduce the cost, quality of designs and structural safety should not be compromised. Design codes define the required constraints that guarantee at least a minimum quality in designs. For moment frame buildings, lateral stiffness, lateral strength (in particular, flexural strength, assuming to have precluded shear failure of members), and lateral displacement capacity are the crucial and common constraints which control feasibility of designs. Any violation of these constrains should be viewed with caution to ensure that all required properties are achieved in a final design.

Due to the difficulty and complexity involved in arriving at an optimum design of frame structures, stochastic search algorithmswhich are proven to be effective in finding the global optimal have been employed by researchers. Various algorithms using stochastic approach have been developed and applied to structural optimization. The key features of these algorithms are: gradients of objective functions are not required, discrete and continuous variables can be dealt with, and different optimal solutions for a specific optimization problemcan be provided. These features make *nature inspired* approaches one of the popular and effective methods for optimization problems in different fields.

Artificial Bee Colony (ABC) algorithm is a novel *nature inspired* algorithm, based on the for aging behaviour of *honeybee swarm* [1]. Further, it is a population-based optimization which can be used for nonlinear optimization problems. Also, the performance of ABC algorithm is compared to those of other stochastic algorithms on some test problems [2-4]. Different satisfactory applicationsof ABC algorithmhavebeenreported in literature [1-8], namely (a) design methodbasedon ABC algorithmfor digital IIR filters[5]; approach or the leaf-constrained minimum spanning tree (LCMST) problem which showed the superiority of the new ABC algorithm over other approaches[6]. Recently, a discrete artificial bee colony (DABC) algorithm for the lot-streaming flow shop scheduling problem isused, and an ABC optimized edge potential function approach developed to target recognition for low-altitude aircrafts. This demonstrates efficiency of ABC based algorithms compared to the classic genetic algorithms (GA) [7, 8].

In this study, section optimization of frame structures using ABC algorithm is considered. The proposed optimization algorithm is used for the optimization of RC sections of a frame which is subjected to the lateral loads and other gravity load cases. Here, the optimization algorithm proposed is for nonlinear optimization task such as beam and column section optimization involving multiple design constraints. These constraints are decided according to the design clauses mentioned of Indian Standards, namelysuch IS 456(2000) [9], IS 1893(2016)[10], and IS 13920(2016) [11].

1.1 Methodology

ABC algorithm based on the foraging behaviour of honeybee swarmis employed in numerical optimization problems. In this model, the foraging bees are classified into three different types: employedbees, onlookers and scouts. A bee which has found a food source to exploit is called an employed bee. Onlookersare those waiting in the hive to receive the information about the food sources from the employed bees andScouts are the bees which are randomly searching for new food sources around the hive. After exploiting a foodsource, an employed bee returns to the hive and shares the information about the nectar amount of the foodsource with other bees by dancing in the dance area of the hive. The duration of the dance is proportional to the profitability of the food source. As the quality of a food source enhances, the dancing duration related to this food source increases, making it more probable for an onlooker to choose this source. After watching several dances, an onlooker bee selects a food source and becomes employed. In a similar way, a scout is called *employed*, when it finds a food source. After completely exploiting a food source, the food source is abandoned,and all the employed bees change into onlookers or scouts. In this algorithm, a food source position is considered as a candidate solution for the optimization problem and the fitness of the solution is represented by the nectar amount of the food source. By assumingthe number of food sources as NS which is equal to the number of employed or onlooker bees, and D as the dimension of each solution vector, the main steps of an ABC algorithm can be defined as follows:

Step 1:

A random population (X_1,...,X_n) is initialized, where $X_i = \{x_{i1}, x_{i2}, ..., x_{iD}\}$ and each solution vector is generated using:

$$x_{ij} = x_{\min j} + \text{rand}\,[0, 1] \times (x_{\max j} - x_{\min j}) \text{ for } j = 1, 2,.., D \text{ and } i = 1, 2, ..., NS, \quad (1)$$

where $x_{\max j}$ and $x_{\min j}$ respectively represent the upper and lower bounds for the dimension j. After Initialization of the population, the fitness of each food source is evaluated.

Step 2:

Each employed bee searches the neighbourhood of its current food source to determine a new foodsource using:

$$v_{ij} = x_{ij} + Ø_{ij}\,(x_{ij} - x_{kj}) \quad (2)$$

where k €{1, 2, ..., NS} and j €{1, 2, ..., D} are randomly chosen indexes. It must be noted that k must be different from i. $Ø_{ij}$ is a random number between [-1, 1]. Parameter values produced by Eq.(2) which exceedtheir boundary values are set to their boundary values .

Step 3:

After generating the new food source, the nectar amount of it will be evaluated and a greedy selection will be performed. If the quality of the new food source is better than the current position, the employed bee leaves its position and moves to the new food source; in other words, If the fitness of the new foodsource is equal or better than that of X_i, the new food source takes the place of X_i in the population andbecomes a new member.

Step 4:

First an onlooker bee selects a food source by evaluating the information received from alltheemployed bees. The probability p_i of selecting the food source i is determined by:

$$p_i = \frac{f_i}{\sum_{i=1}^{NS} f_i} \quad (3)$$

2.The Section optimization of RC structural elements using ABC algorithm

Optimization of Frame structures using the ABC algorithm can be formulated as follows [12]:

Find: $X = \{x_1, x_2 \ldots, x_d\}$,

$$x_{\min n} \leq x_n \leq x_{\max n}\; n = 1, 2, \ldots, D \quad (4)$$

To minimize: $f(X) = M(X) + P(X)$, (5)

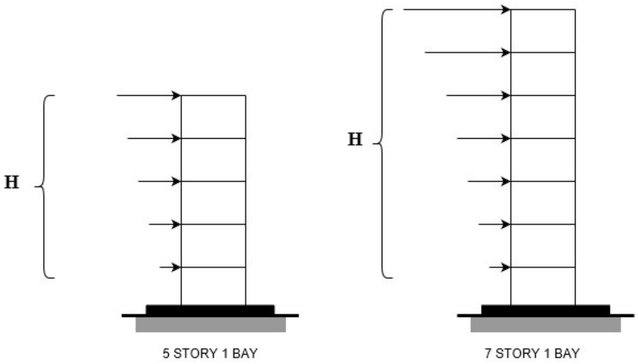
Subjected to: $g_i(X) = M_{Design} / M_{Demand} \geq 1.2,\ i = 1, 2, \ldots, NM$, (6)

$$g_{i,j}(X) = M_{designcolumn@P=0} / M_{designbeam} \geq 1.4, i,j = 1, 2, \ldots, ND, \quad (7)$$

where in Eq.(4), X is a candidate design, $x_{\min n}$ and $x_{\max n}$ are the lower and upper bounds of the n-thdesign variable x_n (here, they are breadth, depth & reinforcement percentages of member cross-sections), and D is the total number of design variables of a food source. In Eq.(5), f(X) is the objectivefunction, M(X) is the design moment of thestructural element and P(X) is the axial load capacity function, used for handlingconstraints[13,14]. In Eq.(6) M_{Design} to M_{Demand} ratio is assumed to be 1.2 in the i-th member, and P_{Design} to P_{Demand} for column design is >1. The design process keeps the design parameters by minimizing the objective function by following the design constraints parameters according to the code.

3. Numerical Study

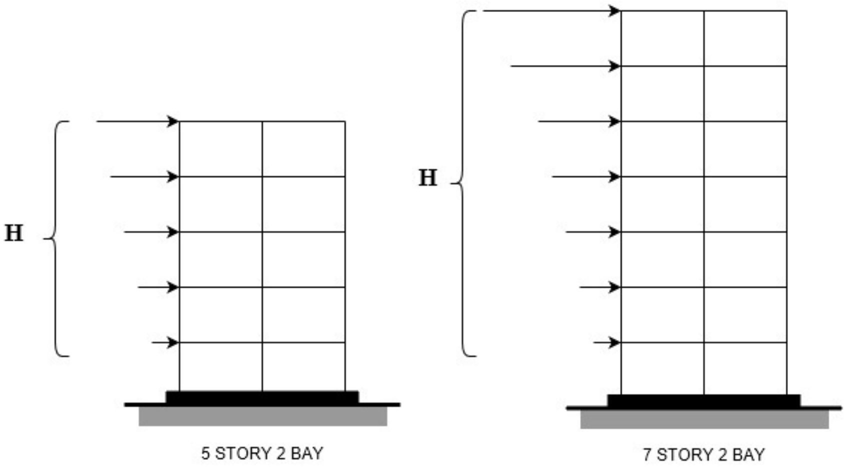
Performance of proposed ABC algorithm is evaluated through typical optimization examples of planar structural frame elements.The frames considered have typical storey height of 3 m and bay size 6 m.For each example, the algorithm is executed 30 times and the best design is reported. Here,in ABC algorithm, the colony size is taken as 100; therefore, the number of employed bees which is equal to the number of onlookers would be 50. The limiting values are selected for each design parameters before the start of the design. The design parameters here are breadth, depth and reinforcement percentages of member cross-sections, whose values are feasible as per tothe Indian Standards.The loading of 10 kN/m^2 is applied on each beam and the lateral load estimated according to IS 1893and given as input. The design check in program ensures that column-to-beam strength ratio $M_{designcolumn@P=0} / M_{designbeam} \geq 1.4$ is maintained. The frames considered for study are shown in figure 1&2, andobtained reinforcement percentages from the algorithm are listed in Tables 1 to 4.



5 STORY 1 BAY

7 STORY 1 BAY

Fig. 1– Elevation of Study frames—Single bay



5 STORY 2 BAY

7 STORY 2 BAY

Fig. 2– Elevation of Study frames—2 Bay

Table 1: Optimised details of 5 storey-one bay frame

Storey	Beams			Columns	
	B × D (mm×mm)	A_{st} (%)	A_{sc} (%)	B × D (mm×mm)	A_s (%)
5	230 × 300	0.35	0.32	300 × 300	1.33
4	230 × 300	0.35	0.34	300 × 300	1.00
3	230 × 300	0.65	0.29	300 × 300	1.00
2	230 × 300	0.68	0.32	300 × 300	1.51
1	230 ×300	0.72	0.35	300 × 300	1.55

Table 2: Optimised details of 7 storey-one bay frame

Storey	Beams			Columns	
	B × D (mm×mm)	A_{st} (%)	A_{sc} (%)	B × D (mm×mm)	A_s (%)
7	230 × 300	0.35	0.30	300 × 300	1.34
6	230 × 300	0.35	0.30	300 × 300	1.00
5	230 × 300	0.65	0.32	300 × 300	1.04
4	230 × 300	0.65	0.32	300 × 300	1.06
3	230 × 300	0.65	0.35	300 × 300	1.59
2	230 × 300	0.68	0.35	300 × 300	1.59
1	230 × 300	0.68	0.35	300 × 300	2.28

Table 3:Optimised details of 5 storey-two bay frame

Storey	Beams			Columns		
	B × D (mm×mm)	A_{st} (%)	A_{sc} (%)	B × D (mm×mm)	$A_{s\ (interior)}$ (%)	$A_{s\ (exterior)}$ (%)
5	230 × 300	0.35	0.32	300 × 300	0.89	1.39
4	230 × 300	0.39	0.30	300 × 300	1.36	1.44
3	230 × 300	0.53	0.32	300 × 300	1.39	1.54
2	230 × 300	0.59	0.35	300 × 300	2.01	2.05
1	230 × 300	0.97	0.58	300 × 300	2.09	2.09

Table 4: Optimised details of 7 storey-two bay frame

Storey	Beams			Columns		
	B × D (mm×mm)	A_{st} (%)	A_{sc} (%)	B × D (mm×mm)	$A_{s\ (interior)}$ (%)	$A_{s\ (exterior)}$ (%)
7	230 × 300	0.35	0.32	300 × 300	1.85	1.76
6	230 × 300	0.35	0.32	300 × 300	2.03	1.92
5	230 × 300	0.63	0.65	300 × 300	2.04	1.94
4	230 × 300	0.71	0.65	300 × 300	2.19	2.14
3	230 × 300	0.83	0.74	300 × 300	2.19	2.14
2	230 × 300	1.49	0.74	300 × 300	2.19	2.69
1	230 × 300	1.37	0.68	300 × 300	2.28	2.69

Algorithm developed is now limited to optimization of two-dimensional frames. Reinforcement percentages obtained in the pilot studies complies with the minimum and maximum percentages of reinforcement recommended in design standards used for the purpose. Further, to understand the nonlinear static behavior of the designed frames, pushover analysis is performed in commercial structural analysis software SAP2000. Designed sections are modeled using section designer option and inelasticity in frame members defined using default hinges option, in SAP 2000.Nonlinear static responses of the study frames demonstrate that the optimised flexural design obtained from the algorithm developed in this study are reasonably good to provide reasonable deformability to the structure (Fig. 3). Inelasticity developed in the frames are also desirable for forming a ductile mechanism; plastic hinges have formed at ends of beams and column bases (Figs.4& 5). Presently, the focus of this study is limited to design optimisation that helps achieve a desirable collapse mechanism. Further evaluation of the proposed methodis required to realistically improve seismic behavior; improving the lateral drift capacity is ideally the goal of lateral loading optimization problems of moment frames, in addition to maintaining a reasonably good lateral stiffness and strength capacities.This can be achieved by conducting parametric studies on 3D benchmark moment frame structures. Studies for the purpose are ongoing and the following objectives are looked at for implementation in future work: (a)design for shear, (b) moment-curvature characteristics, (c) computer program for performing nonlinear static analysis, and (d) fine-tuning algorithm with more constraints to improve lateral drift capacity of moment frames. The ongoing work when implemented will yield more robust design optimization of moment frames that help improve the earthquake resistance of typical moment frames. Documentation on the developed algorithm will be made available on:"https://github.com/harshavardhan-99/research.git."(on request).

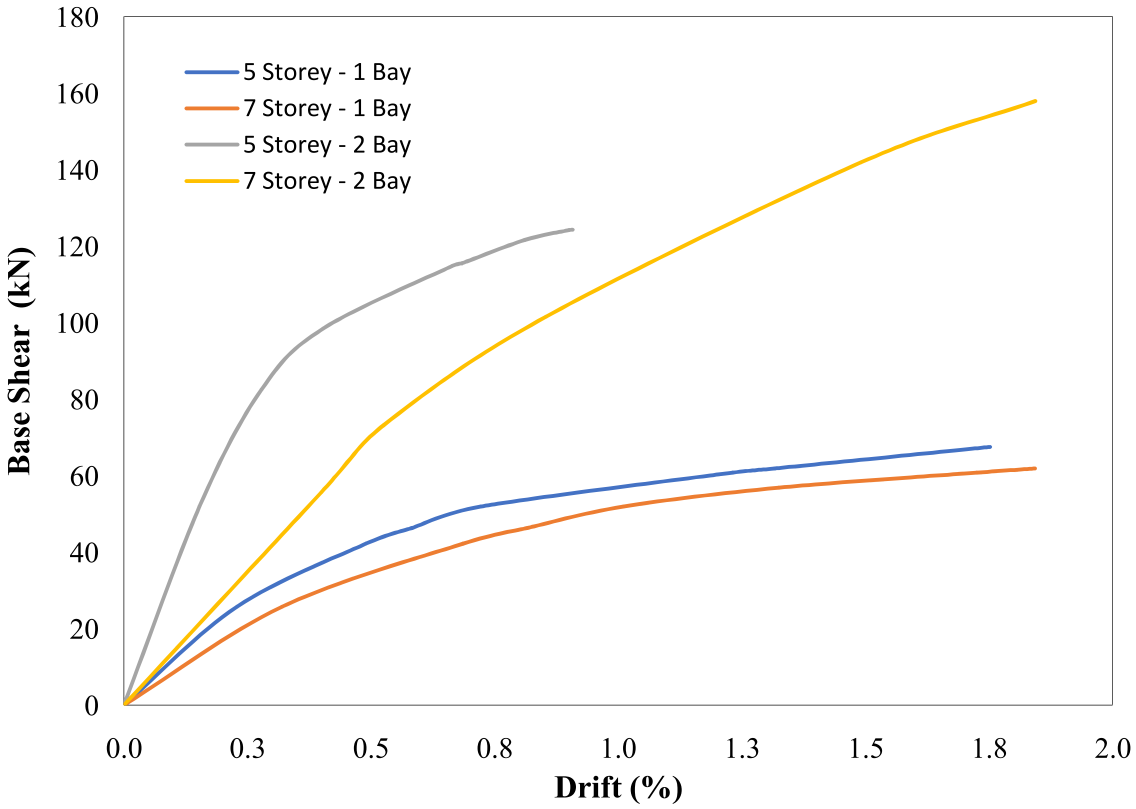


Fig. 3– Nonlinear Static Response Curves of Study Frames

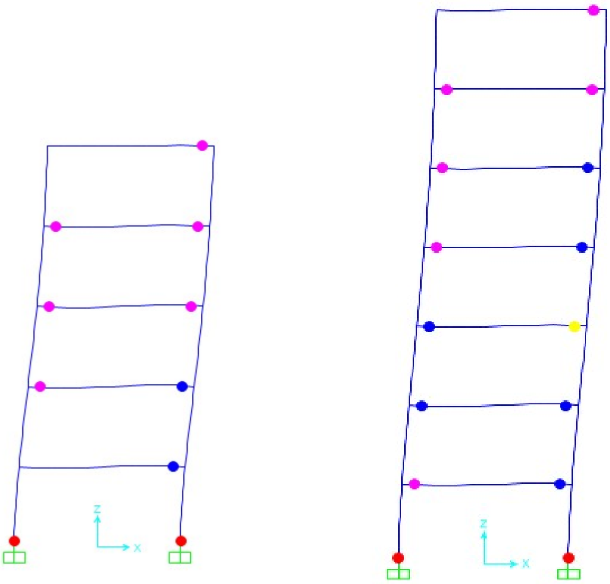


Fig. 4 –Inelasticity in One Bay Frames

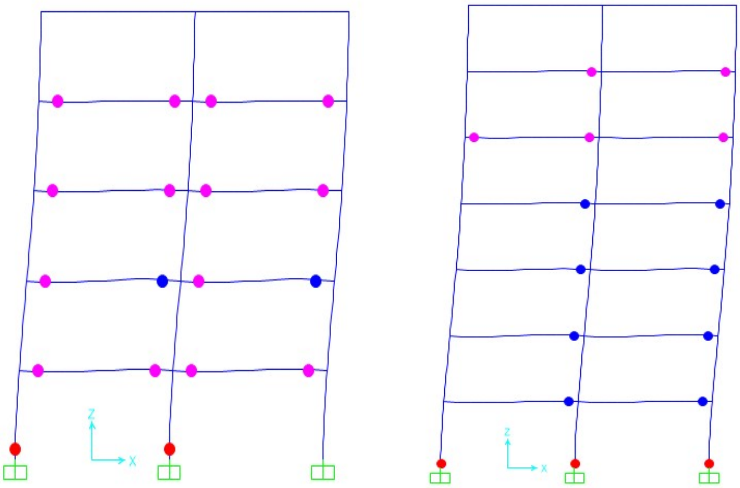


Fig. 5–Inelasticity in Two Bay frames

4. Summary and Conclusions

The pilot study presented in the paper and the detailing obtained is representative of *optimized design*, which complies with the current Indian design standards, used in design of two-dimensional frames. Further, the method can be easily extended to more complex frames which has more design constraints. The efficacy of the design can be fine-tuned to employ user requirements. For *e.g.,*by iterating the design, the *drift capacity* can be increased for normal structures to achieve *no collapse* performance requirement and*drift capacity* can be reduced for important structures to achieve *occupiability* performance requirement. The above requires inputs of moment-curvature characteristics of designed sections, which can be implemented in the algorithm. Furthermore, results can be improved by modelling three dimensional frames which represent actual structures.

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