Genetic Algorithm based Design of a Reinforced Concrete Continuous Beam

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***Abstract*-This paper demonstrates an application of the genetic algorithm to the design of reinforced concrete continuous beam. Genetic algorithm is used to find out the depth and width of the beam, the number and diameter of bars and the diameter and spacing of stirrups. A program is created based on genetic algorithm to carry out the design in MATLAB. The loading conditions considered are uniformly distributed load in the full span of the beam. Design constraints for the optimization are considered according to the Indian Standard specifications. The program requires the user to input design parameters like the grade of concrete and steel, the design live loads, uniformly distributed load and the cover required. The algorithm computes the area of concrete and steel at the sections, by minimising the overall cost of materials involved, namely concrete and steel. A trial design of beam is carried out using the program and the results obtained are compared with those obtained by manual calculations for their feasibility. Genetic algorithm based design method gave results satisfying the design code guidelines, but sometimes infeasible results are also obtained due to the random nature of genetic algorithm.**

Key words:* *Genetic algorithm, Design constraints, Optimum design

I. INTRODUCTION

The wide spread use of concrete materials in engineering in recent decades has led to many design methods for improving the performance of structures. An optimal solution means the most economical solution and that which satisfies the functional aspects of the structure. Feasible designs are obtained by optimization using numerical models of decision-making processes and satisfaction of specified objectives. The optimization theory, with the availability of many mega hertz of processing speed serves to improve design processes.

In this paper a method using genetic algorithm have been proposed for the design of an RCC continuous beam. The program analyses the moments and forces and generates the sections and the reinforcements required. The program is based on the IS: 456-2000 design guide lines.

A. Genetic Algorithm in Structural Optimization

Genetic algorithm (GA) belong to stochastic heuristic optimization techniques. GA is inspired by Darwin's theory of evolution, where the best individuals have the greatest chance of survival and to become parents of new offspring [1]. GA is iterative in nature. GA works with a whole population of solutions. The population contains many individuals. GA starts with an initial population and thereafter generates successive populations using three operations: reproduction, crossover, and mutation. Reproduction is the process of copying individual strings to an objective function value. Objective function defines our aim. It is the function which the user intend to minimise or maximise using GA. The objective function is also called the fitness function. The value of the fitness function is called the fitness value. Copying of strings according to their fitness value means that strings which are having, a higher value in case of maximisation problems and lower value in case of minimisation problems, has a greater possibility of creating the next generation. This is similar to natural selection existing in nature. GA also uses mutation. Mutation is a small but random change in the population of solutions. Mutation allows individuals to adapt to the changing environment. The GA provides a number of feasible solutions to a given problem.

Optimization studies using GA were initially focussed on steel structures. The weight and the cost were considered as the objective functions and were minimised. David Shaw et al. demonstrated the application of Genetic programming to civil engineering design problems [2]. They described and demonstrated by using a suitable form of representation, how genetic algorithm can be applied to structural design problems to produce improved solutions. Charles Camp et al. studied the optimisation of a steel frame using GA. The objective function was weight, which was minimised while satisfying the serviceability and strength requirements. A program was developed based on GA. This program included features like multiple loading conditions, nodal displacements, element stresses etc. checked using AISC-ASD specifications [3].

P Sivakumaer et al., performed study on design improvements on lattice towers using GA. Each bay was considered as an object & treated as a member. Being treated as a member reduced the search space needed and enhanced the convergence of the solution [4]. M.P Saka designed a GA for the optimization of steel framed pitched roofs with haunches for the rafters and eves. The GA correlated cost of the haunch to the size and length in order to develop an ideal design. The buckling and torsion of columns and rafters were also analysed [5].

Jiaping Yang used tournament selection scheme to find the optimization of a structure's design. In tournament selection process at each step two random individuals from the population is selected and among them the individual with the higher/lower fitness value is selected. A comparative study between the differences of using Roulette wheel selection and Tournament selection process was also carried out. Tournament selection technique was found to be more efficient, and the program had greater potential for solving optimization problems [6]. In roulette wheel selection each individual of the population occupy an area on the wheel based on their fitness value. Higher/lower the fitness value, higher is the area occupied on the roulette wheel, and hence greater chance of being selected.

Matˇej Lepˇs et al. studied the application of genetic algorithm to minimize the cost of a steel reinforced concrete beam. They searched for a design characterized by a minimum price, while all strength and serviceability requirements are satisfied for a given applied load [7]. Yousif S.T & Najem R.M used genetic algorithm for the optimum design of reinforced concrete continuous beams based on the specifications of the American Concrete Institute. The beam dimensions and the area of reinforcing steel in this research were introduced as the design variables, considering the flexural and shear, effects on the beam [8].

S. A. Bhalchandra and P.K.Adsul, studied optimum design of simply supported doubly reinforced beams with uniformly distributed and concentrated loads. The design objective was to minimize the total cost of a structure. The resulting structure not only was lower in cost but also satisfied all strength and serviceability requirements as per IS: 456-2000. A comparative study between the classical optimization techniques, the Generalized Reduced Gradient Method, Interior point algorithm optimization technique and the Genetic Algorithm was carried out [9]. The results obtained from the Genetic Algorithm optimization technique showed a lower cost.

II. OPTIMUM DESIGN OF REINFORCED CONCRETE CONTINUOUS BEAM

In this study, the basic design criterion is the cost of the continuous beams. The objective is to design an RCC continuous beam while minimising the cost without violating the constraints. The cost of the beams includes the costs of the concrete and the reinforcing steel. The total cost of the RC continuous beam is

$$F = Vc\ Cc + Ws\ Cs, \qquad (1)$$

where V c is the concrete volume, Ws is the reinforcement weight including the tension steel and the stirrups Cc and Cs are the unit costs of concrete and reinforcement, respectively.

A. Design variables and design parameters

The design variables selected were the concrete section width and thickness, the number of bars of the reinforcement, the diameter of the bars, the diameter of stirrups and their spacing. The number and size of stirrups, as well as the spacing to meet shear forces, are obtained optimally for the specified section. Other parameters used in design like the grade of steel and concrete and the cover for steel are specified by the user.

B. Design Constraints

The RC beam must have a structural capacity greater than the factored applied loading and should meet the specifications defined in the IS Codes. The IS Codes has restrictions on the cross-sectional geometry of a beam and the position and quantity of steel reinforcement. These restrictions are introduced into the design in the form of design constraints of the genetic algorithm. These constraints were in terms of the six design variables. These constraints were used to specify the main variables so that the designs are safe and stay within the limits of the used code, making the solution more realistic.

First constraint ensures the deflections are within the permissible limits. IS 456-2000 clause 23.2.1 specifies that,

$$\frac{Span}{Effective\ Depth} \leq 26, \text{ for continuous beams.} \qquad (2)$$

$$\frac{l}{d} \leq 26 \qquad (3)$$

To ensure that a doubly reinforced section in not required the design moment, Mu was kept below the limiting value of the moment, Mulim .

$$Mu \leq Mulim \qquad (4)$$

The reinforcements should be within the minimum and the maximum limits .The maximum value of tension steel, A_{st} was limited as per IS 456-2000 clause 26.5.1.

$$Ast \leq 0.04bd \qquad (5)$$

The minimum area of tension steel is,

$$\frac{Ast}{bd} \leq \frac{0.85}{fy} \qquad (6)$$

The difference in design shear strength, τ_c of the RC beam and the nominal shear stress, τ_v is to be taken care by providing stirrups. The magnitude of design shear strength has been introduced using the empirical formula,

$$\tau c = \frac{0.85 * \sqrt{((0.8fck))}(\sqrt{(1+5\beta)} - 1)}{6\beta} \qquad (7)$$

where

$$\beta = \frac{0.8fck}{6.89pt} \ \ or\ 1, whichever\ is\ greater\ ,$$

where,

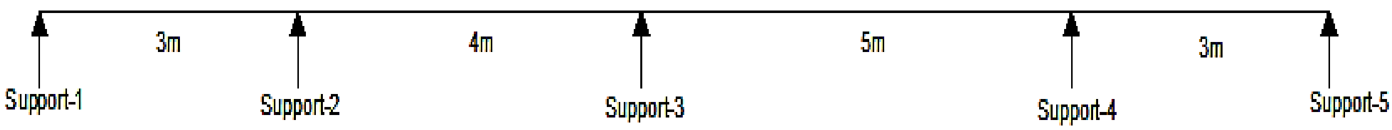
$$pt = \frac{100\,Ast}{bd}$$

so

$$\frac{(\tau c - \tau v) * b * d)}{0.87 * fy * d} = \frac{Asv}{Sv} \qquad (8)$$

where Asv is the area of shear reinforcement, Sv is the spacing of stirrups.

Fig-1. Continuous beam



The equations 4, 6, 10, and 12 also have been introduced as a constraint of the genetic algorithm in terms of the five design variables.

Finally the spacing of the stirrups, s were also introduced as a constraint as per IS 456-2000 clause 26.51.5. The spacing of the stirrups s is,

$$s \leq 0.75d \text{ or } s \leq 300mm \text{ which ever is smaller} \qquad (9)$$

C. MATLAB Formulation

Each of the above equations were introduced as constraints in MATLAB. Linear inequality constraints are of the form Ax-B<=0, where A and B are functions of the design variables, but sometimes B can also be a constant. So the design constraints in MATLAB are:

$$\frac{l}{d} - 7 \leq 0 \qquad (10)$$

$$Mu - Mulim \leq 0 \qquad (11)$$

$$Ast - 0.04bd \leq 0 \qquad (12)$$

$$\frac{Ast}{bd} - \frac{0.85}{fy} \leq 0 \qquad (13)$$

$$s \leq 0.75d \text{ or } s \leq 300mm \text{ which ever is smaller} \qquad (14)$$

Linear equality constraints are introduced in GA in the form Ax-b=0, where A is a function of the design variables and B is a constant. The linear equality constraint is:

$$\frac{(\tau c - \tau v) * b * d)}{0.87 * fy * d} - \frac{Asv}{Sv} = 0 \qquad (15)$$

D. Mutation and Crossover Functions

The mutation function chosen was Adaptive Feasible. Adaptive Feasible, is the function in which when there are constraints, it randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation. The mutation chooses a direction and step length that satisfies bounds and linear constraints. The mutation rate was 0.03. Too high and too low rates of mutation produced infeasible results. The crossover function was intermediate. The crossover function Intermediate, creates the next generation of solutions by taking a weighted average of the parents [10]. The mutation and crossover functions selected are the default functions for constrained genetic algorithm in MATLAB.

III. DESIGN EXAMPLE

This design example demonstrates the use of the program created to design an RCC continuous beam, Fig-1., of four spans of 3m, 4m, 5m and 3m, and subjected to factored live loads of

20kN/m, 30kN/m, 20kN/m, and 30kN/m. The grade of concrete chosen is M25 and the grade of steel is Fe415.The cover for steel is 25mm. The cost of concrete per cubic metre and that of steel per kg were taken as Rs 6000/- and Rs 40/- respectively.

A. Results and Discussions

Table-1 shows the width and depth of the beam at supports and midspan taken along the different spans of the continuous beam.

TABLE-1 DEPTH AND WIDTH OF BEAM

Span in meters	Width of beam in mm		Overall Depth of beam in mm
3	At support- 1	-	-
	At midspan	115.357	237.668
	At support-2	168.631	276.048
4	At support-2	168.631	276.048
	At midspan	100.37	363.862
	At support-3	116.337	393.304
5	At support- 3	116.337	393.304
	At midspan	116.650	346.676
	At support-4	102.813	372.275
3	At support- 4	102.813	372.275
	At midspan	100.000	304.390
	At support-5	-	-

Table-2 compares the moment of resistance of the section provided and the design moments. The moments are equal, ensuring that design moments are tackled by the section provided and singly reinforced sections will suffice.

TABLE-2 MOMENT VALUES

Span in meters	Moment of resistance of section generated by GA in kNm		Moment due to loading in kNm
3	At support- 1	-	-
	At midspan	18	18
	At support-2	36.6	36.6
4	At support-2	36.6	36.6
	At midspan	40	40
	At support-3	54.4	54.4
5	At support- 3	54.4	54.4
	At midspan	41.6	41.6
	At support-4	42.7	42.7
3	At support- 4	42.7	42.7
	At midspan	27	27
	At support-5	-	-

Table-3 compares the area of steel required from manual calculation to those obtained from the GA program. The area obtained from GA program is very slightly lower than that from manual calculations.

TABLE-3 AREA OF STEEL

Span in meters	Area of steel A_{st} required in mm^2		Area of steel A_{st} obtained from GA		
			No.	*Diameter*	A_{st}
3	At support- 1	-	-	-	-
	At midspan	292.19	2.25	12.858	292.15
	At support-2	504.21	2.75	15.278	504.14
4	At support-2	504.21	2.75	15.278	504.14
	At midspan	405.28	2.88	13.379	405.02
	At support-3	510.32	2.18	17.242	510.17
5	At support- 3	510.32	2.18	17.242	510.17
	At midspan	446.91	2.75	14.275	446.31
	At support-4	425.24	2.12	15.961	425.24
3	At support- 4	425.24	2.12	15.961	425.24
	At midspan	332.76	2.80	12.290	332.16
	At support-5	-	-	-	-

Table-4 gives the spacing of 8mm diameter 2 legged stirrups for the beam as per manual calculation.

TABLE-4 SPACING OF STIRRUPS

Span in meters	Shear Force in kN		τ_v	τ_c	Spacing required mm	Spacing calculated by GA in mm
3	At support- 1	27	1.1	0.645	725	300
	At support-2	36	0.85	0.645	1100	300
4	At support-2	72	1.7	0.645	214	213.99
	At support-3	72	1.6	0.645	342	300
5	At support- 3	60	1.4	0.645	433	300
	At support-4	60	1.6	0.645	387	300
3	At support- 4	54	1.5	0.645	433	300
	At support-5	40.5	1.4	0.645	504	300

Note:-Midspan concrete section and area of steel is provided at end supports

Spacing obtained from manual calculations are greater than the maximum spacing. The GA program as per the constraint gave a spacing of 300mm which is safe.

The Genetic algorithm based design gave design results which are comparable to that from manual calculations. GA gave a slightly lower area of steel, while all other results were at par with the manual designs. The difference in area of steel, even though is very feeble, can be of significance in the design of large structures.

IV. CONCLUSIONS

Genetic algorithm based design of continuous beam gave reasonable results, satisfying all constraints. This method has the advantage that the cost of concrete and steel can be incorporated into the design. This will help in obtaining reasonable sections and steel based on the cost. Other constraints can also be easily applied into the design, making the design to suit various requirements. The values obtained from the GA program are representative values only. The choice of practical values are left to the decision of the design engineers.

V. REFERENCES

[1] Iyengar,N.G.R. and Gupta,S.K, Structural design Optimization, East west press Ltd. New Delhi, 1997.

[2] David Shaw, John Miles and Alex Gray, Genetic programming within civil engineering, Organisation of the Adaptive Computing in Design and Manufacture 2004 Conference. April 20-22, 2004, Engineers House, Clifton, Bristol, UK.

[3] Camp,Charles, Pereshk, Shahram, Cao, Guozhong. ”Optimized design of two-dimensional structures using a genetic algorithm.” Journal of structural Engineering, ASCE, vol. 124 (5), pp.551-559, 1998.

[4] Sivakumar,P, Rajaraman,A, Knight, G.M. Samuel, Ramachandramurthy, D.S. ”Object-oriented optimization approach using genetic algorithm for lattice towers. ”Journal of computing in Civil Engineering, vol. 18, pp.162-171, 2004.

[5] Saka,M.P, “Optimum design of pitched roof steel frames with haunched rafters by genetic algorithm”. Computers & Structures, vol. 81, pp. 1967-1978, 2003.

[6] Yang, Jiaping,”Structural optimization by genetic algorithm with tournament selection.” Journal of computing in Civil Enginnering, vol. 11(3), pp. 195-200, 1997.

[7] M. Lepš, K. Matouš and Z. Bittnar, “Genetic algorithm in optimization of reinforced concrete beam”, Acta Polytechnica, vol. 39 (2), pp. 145-154, 1999.

[8] Yousif S.T, Najem R.M, “Optimum cost design of reinforced concrete continuous beams using Genetic Algorithm”, Int. Journal of Applied Sciences and Engineering Research, vol. 2 (1),pp. 79-92, 2013.

[9] S. A. Bhalchandra, P.K.Adsul, “Cost Optimization of Doubly Reinforced Rectangular Beam Section”, International Journal of Modern Engineering Research (IJMER), vol. 2 (5), pp. 3939-3942, 2012.

[10] Mathworks. (2011), Global Optimization Toolbox: User's Guide (r2011b), Retrieved August 29, 2014 from http://www.mathworks.com/help/pdf_doc/gads/gads_tb.pdf

[11] Kanpur Genetic Algorithm Laboratory (2005), GA Resources, Retrieved August 29, 2014 from http://www.iitk.ac.in/kangal/resources.shtml#3

[12] Krisna Raju N., Design of Reinforced Concrete Structures, (IS 456-2000) III Edition CBS Publishers.

[13] IS 456-2000, Code of Practice for Plain and Reinforced Concrete, Bureau of Indian Standards, New Delhi.

[14] S U Pillai & Devdas Menon, Reinforced Concrete Design, III Edition, Tata McGraw Hill, 2003.