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Reinforcement Layout Optimization of RCC Beam using Firefly Algorithm

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Abstract

The optimization of layout design of steel in the domain of concrete has been an interesting topic during the last few years. The main focus of this study is to make an attempt to determine the optimal layout of steel in the concrete domain using metaheuristic algorithms. In this study, firefly algorithm is used. Two different approaches have been studied and the merits and demerits have been put forward. The results obtained have been checked with the method proposed in IS 456-2000. This study is a basic attempt to automate the layout process of steel in the reinforced concrete elements.

Keywords: *Layout optimization, reinforced cement concrete, firefly, topology*

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INTRODUCTION

Layout optimization differs from design optimization. In case of layout optimization of reinforced concrete structures, the distribution of steel in the domain of concrete is designed. In case of design optimization of reinforced concrete structures, the area of the concrete and steel required to safely transmit the given loading is optimized [1]. In case of layout optimization, the stresses carried by the material are evaluated using finite element analysis and checked with the maximum permissible stress.

The dimensions of the concrete domain remain constant and not changed during the process of the layout optimization. In case of design optimization of continuum structures, a large domain is considered initially and is subjected to loading, the distribution of material changes and so the geometry of the design domain changes during the entire process of optimization.

The optimum dimensions of concrete and quantity of steel can be found using an excel sheet. Layout optimization requires a finite element analysis package and is not normally available with any commercial package [2]. For this purpose, a sample code is composed in C++ and stresses are evaluated throughout the domain.

LITERATURE REVIEW

'Topology optimization, theory, methods and applications' by Bendsoe and Sigmund, attempts to provide a unified presentation of methods for the optimal design of topology, shape and materials for continuum and discrete structures [3]. The emphasis is on the now matured techniques for the topology design of continuum structures and its many applications. In one of the methods, the entire design domain is discretized using plane quadratic elements having four nodes each. The design domain consists of two meshes having unit thickness, one each made of concrete and steel. The concrete and steel elements have nodes in common.

The elements in the concrete mesh carrying tension will be excluded from the analysis. The elements in the steel mesh carrying compression were excluded in the analysis. The relative density of these elements is made equal to 1e-5. The final layout consists of distribution of steel in the design domain. In the second method, a steel grid is used to model the layout of the steel. Steel is modeled as one dimensional element carrying axial stress only. Oded and Sigmund have used a steel grid having cross members, and without diagonal members [4]. The principal stress is calculated at the centroid of each element. The strut and tie approach to identify the flow of forces in a concrete continuum is being used. This method

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is widely used in many building codes as well [4]. Steel is provided in regions where the principal stress is tensile in nature. 'Design optimization of reinforced concrete three dimensional structures considering frequency constraints via a charged system search' by Kaveh and Behnam, presents an optimal design of three dimensional multi-story reinforced concrete structures using recently developed meta-heuristic algorithms, namely; the charged system search and the enhanced charged system search [5]. Kim and Baker applied evolutionary structural optimization and studied the design problem using a strut and tie model [6]. They checked the principal stresses for stress violation constraint.

In their research paper, 'Optimization of Shear Strengthened Reinforced Concrete beams' Yapa and Lees have used external pre-stressed carbon fiber reinforced polymer straps to strengthen shear-deficient reinforced concrete structures [7]. For an efficient shear retrofitting system, the optimum combinations of parameters such as the number of straps, strap locations, strap stiffness and initial strap pre-stress need to be identified. A multi-bay and multi-storey reinforced concrete structure has been designed and presented by Guerra and Kiousis using non-linear programming [8]. Oded and Bogomonly modelled the nonlinear behavior of concrete and by its different strengths in tension and compression [9]. Ng *et al.* presented their study on bond element between the steel and the concrete [10].

To model it as the epoxy adhesive between joint surfaces, the epoxy element is developed from the nonlinear linkage element. Reinforced concrete is composition of two constitutive construction materials, namely, concrete and reinforcing steel. When steel bars are embedded into concrete, apart from resisting axial tension or compression, the steel bars also interact with concrete in manifold ways. These composite interactions, or simply interactions, include: (1) The bond action between concrete and reinforcement which stiffens the concrete through the bond force transferred; (2) Dowel action of reinforcing bars intercepting cracks to restrain shear sliding of concrete across the crack surfaces; and (3) Confine reinforcement to enhance the load carrying capacity of concrete in compression.

ANALYSIS

The assumptions made during the analysis are as follows:

1. Concrete is carrying only compression.
2. The concrete elements carrying tension are dropped, in other words, the relative density of these elements is made equal to 1e-5.
3. Steel is used only on the tension face.
4. Minimum reinforcement, say bars in compression face and development length were not included in the analysis and were included in the optimized layout once after the analysis is completed.
5. The principal stresses were calculated at the centroid of each element.
6. The supports were distributed over several nodes to avoid the stress concentration issues. The stresses at the support are not validated.
7. Concrete is assumed to be in plane stress condition.
8. Steel is embedded in the concrete throughout its length, and steel is assumed to be in plane strain condition.
9. The stresses were calculated in the bent up bars and the bars carrying maximum principal stress are considered and the remaining bent up bars are removed in the final design. The stress carried by the bent up bars is checked with the minimum stress criteria as well.

There are two different methods used here to model a reinforced concrete beam.

Method-1

Concrete and steel are distributed throughout the design domain initially. The entire design domain is discretized using plane quadratic elements having four nodes each. The design domain consists of two meshes having unit thickness, one each made of concrete and steel. The concrete and steel elements have nodes in common. The elements in the concrete mesh carrying tension will be excluded from the analysis. The elements in the steel mesh carrying compression were excluded in the analysis. The relative density of these elements is made equal to 1e-5. The final layout consists of distribution of steel in the design domain [4]. The analysis is done for two sections, namely, the cross section of the beam and the longitudinal section of the beam. The analysis is done using the approach proposed by

Archana, *et al.* discussed in Appendix A [11]. The dark regions are elements where tensile stress is found. Figure 1 shows the distribution of reinforcement when the cross section is analyzed. Figure 2 shows the distribution of steel when the longitudinal section is considered. Figure 3 shows the distribution of steel by Oded which is similar to Figure 2 [4].

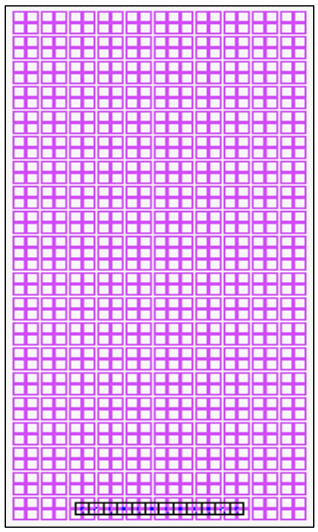

Fig. 1: *Cross Section of the Reinforced Concrete Beam.*

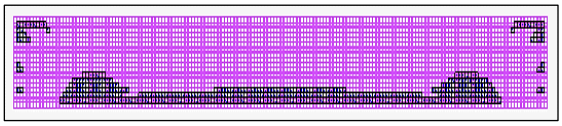

Fig. 2: *Longitudinal section of the Reinforced Concrete Beam.*

A similar result was obtained after optimization by Oded and Sigmund.

Fig. 3: *Optimized Layout [4].*

The region where the elements carry tensile stresses and are grouped together clearly indicates that the bars have to be bent up at this location [12]. This is similar to the output from the study conducted by Oded and Sigmund where in, the material carries principal stresses which are tensile in nature along that direction and the steel bars have to be bent along that direction.

Method-2

In this method, a steel grid is used to model the layout of the steel. Steel is modeled as one dimensional element carrying axial stress only. Oded and Sigmund have used a steel grid having cross members, and without diagonal members is used [4]. The principal stress is calculated at the centroid of each element. The strut and tie approach to identify the flow of forces in a concrete continuum is being used. This method is widely used in many building codes as well. Steel is provided in regions where the principal stress is tensile in nature.

Numerical Problem

A reinforced concrete beam simply supported at its both ends has a span of 3200 mm. It carries a load of 40 N/mm throughout the entire span. f_{ck}=20 MPa, f_y=200 MPa. The section is designed using IS Code method. The cross section dimensions calculated using IS Code method are 250×320. The amount of steel is 5 nos. 20 mm dia steel is provided as reinforcement. When the uniformly distributed load is 40 N/mm, the maximum stress in concrete is 13.6 MPa (Comp). When the uniformly distributed load is increased to 50 N/mm, the maximum stress in concrete is 17.5 MPa (Comp). The entire concrete domain is discretized using 4-node plane quadrilateral elements. A total of 2560 elements were used to discretize the concrete domain. The principal stresses in bent up bars starting from the left are respectively –0.6, 1.5, 0.8, and 0.9 MPa respectively. Table 1 shows the results of the analysis and Figure 4 shows the snapshot of the stress and displacements in the member.

Table 1: *Showing the Results of Maximum Displacement and Stress in the Beam.*

	UDL Load 40 N/mm	**UDL Load 50 N/mm**
Maximum Stress in Concrete (MPa)	13.6	17.86
Maximum Stress in Steel, (MPa)	65	73.446
Maximum Nodal Y Displacement	–0.9456 mm	–1.1526 mm

The screen shot of the output showing the maximum nodal displacements, maximum stresses in steel and concrete is as shown in the Figure 4 below.

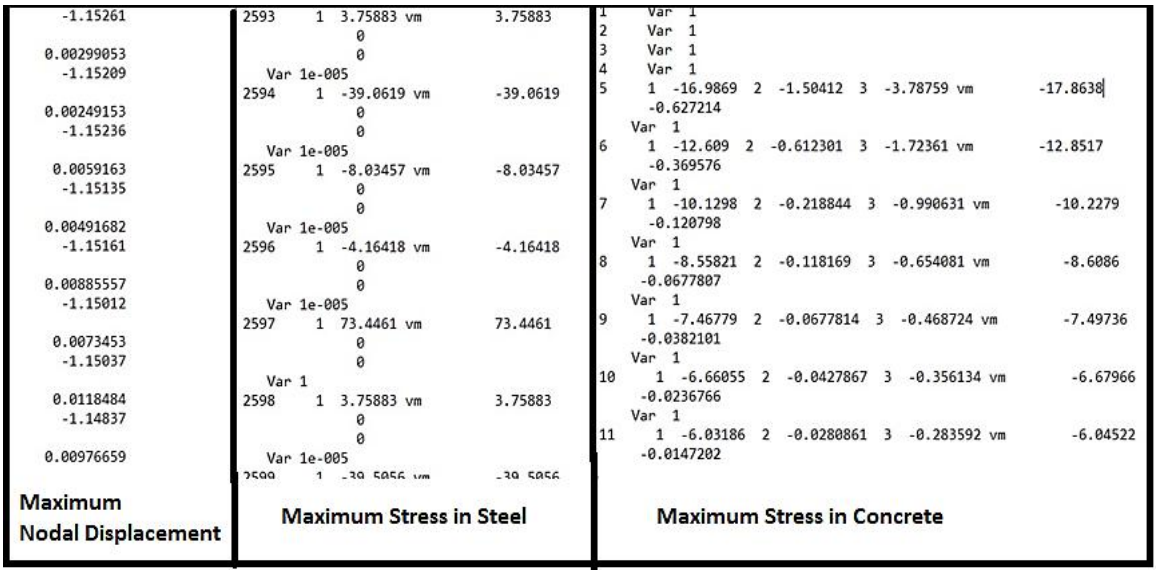

Fig. 4: *Showing the Maximum Nodal Displacement and Stresses in Steel and Concrete.*

The finite element analysis output of the layout design is as shown in the Figure 5.

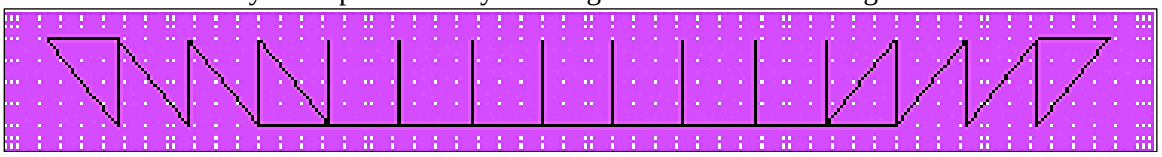

Fig. 5: *Showing the Layout Design of Steel Reinforcement in the Domain of Concrete.*

The above distribution is valid from a finite element analysis point of view. From a practical point of view, the following changes were made:

1. Add minimum reinforcement is provided in the top;
2. Bars are extended by development length;
3. The bent up bars are provided at only one location where the principal stress is maximum.

The minimum reinforcement is provided at the top. The development length is calculated and the bars were extended by the development length. The layout design of reinforcement is as shown in the Figure 6 after we include the minimum reinforcement and development length.

The bars were bent up at the location where the principal stress is maximum and a minimum stress criterion is used to obtain a final layout of reinforcement. In the IS code method of design, the bars are bent at a location which is at least equal to or greater than the depth of the beam.

The stresses in the bent up bars were checked and it is found that the second bent up bar from the edge of the beam carries the maximum value of the principal stress. Hence, this location is taken as the optimum location to bend the bars up and which is at a distance of 500 mm (> depth of beam) from the edge of the beam. The bent-up bars at other points were not included in the final layout.

As shown in the Figure 6, these changes were made manually and the analysis was performed again and the stresses were checked with the maximum permissible stress. The analysis shows that, the maximum compressive stress in the concrete is 12.24 MPa. The maximum stress in concrete in the cover at the centre of the beam is 2.77025 MPa and the maximum stress in concrete at the level of steel is 1.682 MPa. The bars were bent up at the same section now carrying the principal tensile stress of 2.6 MPa. The maximum Y-displacement in the beam is 0.945634 mm in the downward direction.

Limitations

1. The finite element analysis cannot include the development length, top reinforcement, and identify single location for bent up bars.

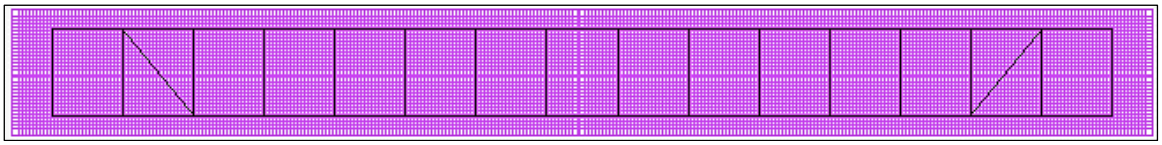

Fig. 6: *The Layout Design of Reinforcement after the Changes were Made.*

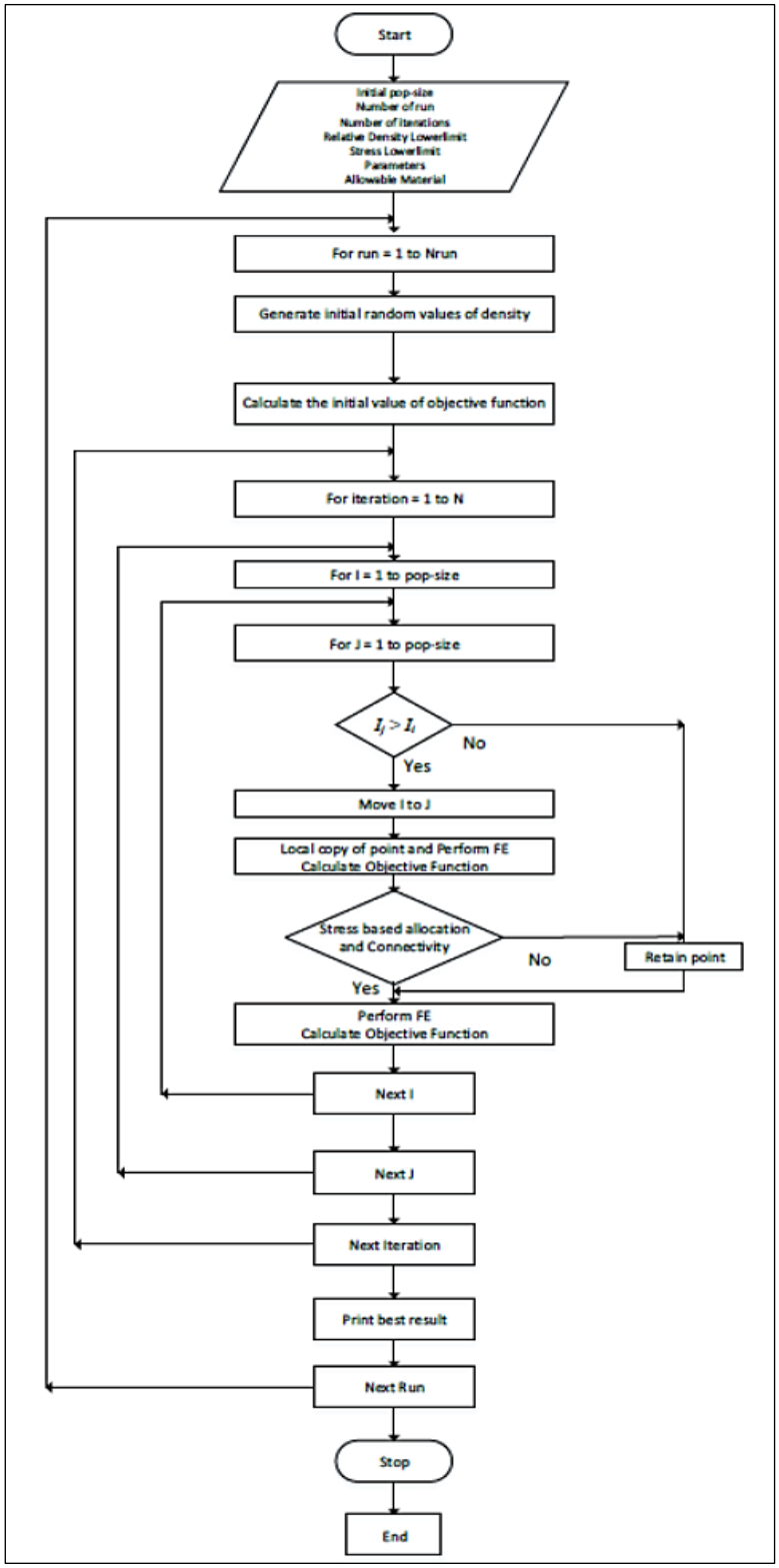

Fig. 7: *Flowchart for Optimization Process.*

CONCLUSION

This study is one step towards automating the layout design to distribute steel within the domain of the concrete. The literature review has been performed. Two popular methods were used to identify the optimal design of layout. In the first method, the concrete domain and steel domain were distributed throughout the design domain. The domain is modeled using first order 4-node quadrilateral elements. The concrete in the tension region is made zero and the presence of steel elements in the compression region were made zero. The analysis shows the region of distribution of steel in the tensile regions in the beam. The region clearly identifies the zone where in the steel elements were carrying principal stresses on an inclined plane indicating that the bars have to be bent up in this region. In the second method, a steel grid is considered in the concrete domain.

The presence of steel in the compressive region is neglected. The steel bars were modeled using 2-node line elements carrying axial stress. The bars are laid according to the axial stress in the steel. The steel bars were bent up in the region where the axial stresses were observed on an inclined plane. Finally, the hanger bars were included and the bars in tension were extended by the development length to obtain the final distribution of the steel in the beam. The finite element analysis is then performed again to check the stresses carried by each element and nodal displacements with the permissible stresses and displacements. The results clearly indicate that the structure is safe in stress and deflection.

Future Study

The introduction of bond element at the interface of steel and concrete will be a better way to model a reinforced concrete beam. The constitutive relations can be used and thus the behavior of steel and concrete can be modeled.

Scope of this Study

1. The finite element analysis is performed using first order linear elements, although concrete behavior is non-linear.
2. The study is valid only within the linear elastic limit.

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APPENDIX A
THE OPTIMISATION APPROACH

The present study deals with the topology optimization of structures using firefly algorithm as an optimizer and a two FEA approach. The initial relative density is randomly generated for each element varying between [0, 1]. '1' denotes the element with full material and '0' denotes the element having no material, for all practical purposes, the minimum value of this relative density is taken as 1e-5. The Young's modulus of the element is multiplied with the relative density raised to power of the penalization factor. The initial value of the objective function is calculated for all flies as inverse of the weight of the structure as firefly algorithm is a maximization algorithm. The flow chart is given in the Figure 2. The first FEA is performed and the stresses for each element are computed. The principal stresses are computed at the centroid and checked with the maximum permissible stress value.

This approach should identify the elements that carry material and all the elements that shall not carry material having the relative density as the minimum value of 1e-5. This reallocation of relative density for each element can be termed as 'stress based proportioning' of material carried by each element. This approach to identify the elements which carry material is much simple and easy. The next stage is, performing second FEA, in which all the elements having the relative density greater than a certain minimum value is taken as 1 (full material) and the remaining elements carry the relative density 1e-5 (no material). The relative density can be taken as the thickness; in reality, thickness may not vary for each element and is constant. The second FEA is performed with the relative density as either '1' or '1e-5'. The stresses are found at the centroid for each element. The error component can be computed if the stress value exceeds the maximum permissible stress. The actual solution is the second FEA, in which the relative density of the element is either '1' or '1e-5'. One of the main advantage of using this approach is to achieve lower weight in fewer number of FE

computations as well, which is the goal of optimization.

A2: The Program Consists of Two Main Modules

a. Finite element module connectivity analysis is performed in case of both plane and solid elements. The connectivity analysis will remove all the elements that have a relative density of 1e-5, elements connected by corners and also all the isolated elements as well. The distribution of material along with the load and support conditions will be solved further for displacements by using the finite element analysis. The stresses are calculated for each element at all the points of integration Gauss points, and the centroid as well. The principal stresses are calculated and checked with the maximum permissible stress.

b. Optimizer module in which a new set of normalized densities is assigned to each element. In this paper, firefly algorithm is being used to generate the newer set of normalized densities.

A3: Optimization Process

The optimization is done using fire fly algorithm and two finite element analysis (FEA) approach. In the first FEA, the stress values are computed for each element at the centroid of each element. The stress values are checked with the permissible stresses, the principal stresses are computed as the Eigen values of the stress matrix. Error component can be calculated if the stress values exceed the permissible stress. This step should identify all the elements that can carry material during the second FEA. If the stresses are below the lower cut off, i.e., the minimum stress, these elements will be assigned the relative density value as 1e-5. The relative density for seed element is always made equal to 1, for these elements shall carry material at all times during the entire process of optimization. Connectivity check is done after which the newer values of relative density are assigned for each element. In case the connectivity analysis does not contain any output, then the original point is retained. In reality, as there is no change in thickness of the element, the relative densities of all the elements having the relative density above the minimum are taken as 1, to depict the reality. The second FEA is done to verify the stress of each element at centroid to be below the permissible stress limits. In order to analyze the response of the structure at a finer level one way is to discretize the continuum into a finer mesh which means higher number of elements and finite element analysis could be prohibitively expensive, one other better way is to compute the stresses at different locations within the element. The objective function is the weight of the structure calculated using the weight density times volume of the structure. This process is iterative and until the minimum weight of the structure is reached satisfying all the constraints. A few problems in the literature are solved and the result compared. The point load and the support conditions are applied over four nodes to avoid the stress concentration. The fire fly parameters are aggressiveness of random move α=1.0, attractiveness parameter β=1.0, absorption coefficient γ=1.0, levy distribution parameter λ=1.5 (Baghlani et al., 2014).

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