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Optimisation of Pre-cast Slab Systems for Large Span Floors and Roofs

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Abstract

Existing work on structural optimization do not consider all the constructability issues related to precast construction. This paper presents an optimization model for large span floor slabs and roof slabs constructed using precast technology. A case study is taken from an actual construction project of an indoor sports complex for illustrating the application of the approach. A stochastic global search algorithm called RANPAS is used for optimization. This study demonstrates the potential for optimizing large span roof and floor structures subject to the specific constraints imposed by precast construction technology. About 21% savings in the cost of material is obtained by the optimized design compared to a conventional beam and slab design.

Keywords: structural optimization, topology, precast construction.

1 Introduction

Precast construction is gaining interest because of its potential to improve productivity in the construction industry. Since many activities are shifted to factories, quality and efficiency can be increased through automation. However, transporting large precast elements in congested cities is a challenge. Also, connecting these elements with efficient transfer of forces is often difficult. These difficulties are not taken into account in traditional structural optimization. For maximizing the benefits of precast technology, it is necessary to develop an optimization model that considers transportation and constructability issues.

While structural optimization has been performed by several researchers over the last few decades, it is not being widely used in practice because many practical construction details are not modelled correctly in the optimization. This results in theoretical optimal solutions not being able to be adopted in practice. For example, a simply supported beam has a theoretical optimal depth that varies parabolically along its length. However, such a parabolic shape is difficult to construct with reinforced concrete. The construction difficulties will cause the solution to be more expensive than simple rectangular shapes. In particular, precast technology is cost effective only when large number of elements are fabricated using the same mould repetitively. Standardization of shapes and sizes help in improving the economic viability of precast construction. Optimization models should incorporate such considerations.

This paper presents an approach to optimizing a large span floor slab for precast construction. An example is taken from an actual construction project that is currently in design stage for illustrating the application of the approach. A stochastic global search algorithm called RANPAS is used for optimization. The primary research objective of this study is to evaluate the potential for optimizing large span roof and floor structures subject to the specific constraints imposed by precast construction technology.

2 Methods

Common applications of structural optimization involve a fixed set of variables whose values must be determined such that the cost function is minimised. This is commonly known as parametric optimization. However, topology optimization is a more difficult problem in which the decision variables are not predetermined. The number of variables could change during the course of optimization according to the evolution of the geometry of the object. For example, in the topology optimization of a truss structure, some solutions might have only a few nodes, while others have many, depending on the shape of the truss, even when the span is the same. These different solutions can be generated using the values of certain control variables used in optimization. If the coordinates and connectivity of truss elements are optimization variables, the solutions have varying number of optimization variables. Since the structure of the solution changes with the values of control variables, the solution space is not smooth. Genetic algorithms, simulated annealing, and other random search methods [1-3] have been used for such problems. However, such algorithms tend to be difficult to implement in the cases of problems without a fixed set of variables and values, such as in topology optimization.

PGSL [4] is another random search algorithm that has been proven to be efficient for a variety of engineering optimization problems such as design [5], system identification [6], and project planning [7]. Its performance is comparable if not better than genetic algorithms [4]. It is simple to use and does not involve any parameter tuning, all the algorithm parameters can be left to default values. Only the number of evaluations of the objective function needs to be specified, which is decided based on the time required for optimization. Because of these advantages, a version of PGSL is used in this work. This algorithm is called RANPAS (Random Parallel Sampling). In RANPAS, local search is combined with global search for faster convergence.

In the original PGSL algorithm, the best solution is obtained by randomly sampling the solution space using a probability distribution function (PDF). The PDF is updated dynamically in nested cycles such that more intense search is performed in regions containing good solutions, while avoiding premature convergence. RANPAS adopts this general scheme with an additional inner loop that performs local search within the global sampling process. This helps in faster convergence when there is reasonable order in the solution space. Local search is performed by approximating the solution space to be a quadratic function in the local neighbourhood. The quadratic surface is approximated using the values of previous evaluations.

The RANPAS algorithm proposes potential solutions by generating values of optimization variables. The values of optimization variables are used to "instantiate" a solution by constructing a complete model of the object to be designed, in this case, a finite element model of the slab system. The finite element model consists of the nodes and elements along with their geometric and material parameters. The number of nodes and elements in the finite element model will vary with the solution, since this is a topology optimization problem. The finite element model is analysed using an external program as a black-box routine. The results of the analysis are used to compute the value of the objective function (cost function) that is minimized.

The objective function that is minimized in this work is the total material cost subject to constraints imposed by the construction methodology. The material cost is the sum of the cost of concrete and the reinforcement steel. While the cost is subject to variation in market prizes, the optimal solution depends only on the relative costs of steel and concrete. The ratio of cost of steel and concrete do not vary significantly over time within a particular region or country, hence the nature of optimal solutions do not change that much.

The constraints imposed by precast construction include the following: a) the maximum size of elements that can be transported efficiently b) accessibility for connecting precast segments and elements. The second factor depends on the type of connections and the technology used. Here, manual bolted connections are considered for precast elements. Tension carrying steel rebars are connected using mechanical couplers or by welding. This requires sufficient gap between precast elements for the worker to move the tools in between the elements. It is assumed that a minimum space of 0.5 m is required for connecting rebars.

Planar elements are easier to transport since more material can be packed within the same space of the truck. Beam segments with I-sections and box sections have drawbacks in this respect. Instead of transporting segments having the whole area of cross-section, it is easier to transport the flange and web segments separately and assemble them on site. These can be easily connected through bolts and grout inserted into cavities in the precast segments at pre-defined locations. Figure 1 has a view of the cross-section showing the top flange, bottom flange, and web segments. Figure 2 shows the side view with two adjacent flange segments separated by a gap for connecting the rebars. The web is not connected to the flanges at the location of gaps in between flange segments. After connecting the rebars at site, the flange is filled with in-situ concrete. The gap in the web is retained to enable passing of electrical and mechanical ducts. The size of the gap is determined through optimization such that stresses in the flanges do not increase significantly, resulting in more material usage.

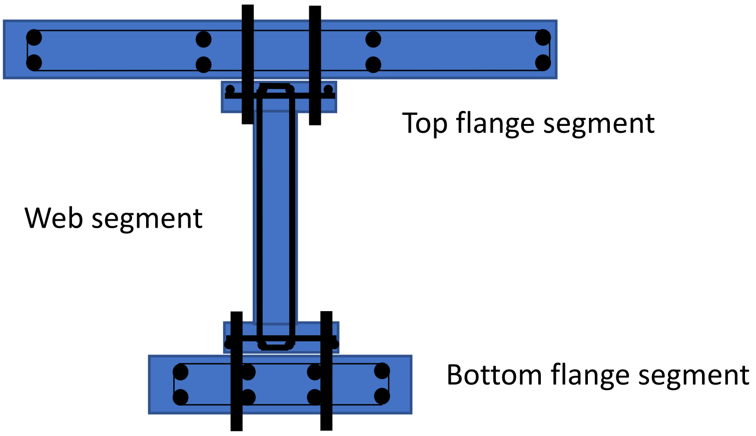

Figure 1: Cross-section of precast assembly.

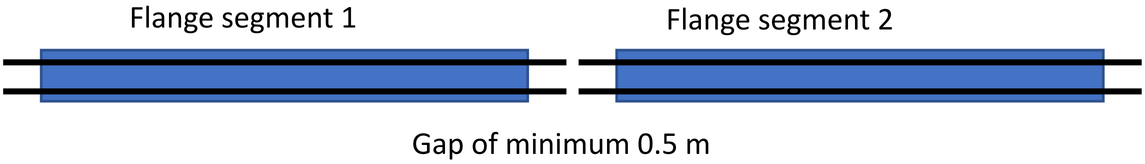

Figure 2: Connection of flange segments.

In order to accurately determine the forces in the members, the whole precast assembly is modelled as a truss system using a finite element analysis software. The reinforcement bars in the flanges and webs are represented as separate bar elements. Two layers of nodes are created in the top flange to represent the bending of the top flange. This is essential for avoiding the stiffness matrix becoming singular due to the gap in the web. Similarly, the bottom flange is also represented using two layers of nodes. These nodes are connected by horizontal, vertical and inclined elements to represent axial and shear forces in the flanges. The web is also represented by horizontal, vertical, and inclined bar elements. There are bar elements inclined in both directions to represent the diagonal tension and compression in the web segments. The results section contains examples of the meshes created using this scheme.

The number and lengths of the precast elements are taken as the decision variables in the optimization model. For each combination of lengths generated by the random search algorithm, a finite element analysis is performed, member sizes are calculated, and the total cost is calculated. This involves the following steps:

1. The total length of the segments is made equal to the total span. This is done by proportionately scaling the lengths of all the segments.
2. Alternate segments are assumed to have cavities in the web. The lengths of these segments should have a minimum value according to the accessibility constraint. In the present study, the minimum length of the gap is set to 0.5 m.
3. The finite element mesh consisting of the nodes and bar elements is generated using the scaled lengths of the segments. The input file for the finite element analysis program is generated. The FEA program is executed as an external program and the output is read.
4. The sizes of rebars are calculated from the tensile forces in the elements. The width and thickness of segments are calculated from the compressive forces as well as the required spacing between the rebars needed for developing bond strength.
5. From the quantity of steel and concrete obtained from the design, the total cost of the solution is calculated.

The total cost of material is the value of the objective function. The random search algorithm finds the best combination of sizes of precast segments such that the total cost is the minimum.

In order to evaluate the potential for savings in materials through the above optimization process, comparison is made with a conventional design, termed as the base-case. The base-case consists of an I section with solid web through out. The design of the base case is done using standard limit state procedure. The rebars are curtailed at one-third the span such that the portions of the beam near the supports have minimum reinforcement required.

3 Results

The optimization model was tested on a full-scale example of a roof structure in an academic institution. The case study involved the construction of a roof slab for an indoor sports complex. The roof slab is a beam and slab system with precast slab panels supported by the precast beams. The span is 24 m and the maximum depth of the beam and slab system is 1.5 m because of restrictions on the overall height of the building. The spacing between the beams is specified as 1.2 m according to the architectural design. When the spacing of beams is not specified by the architect, this could also be taken as an optimization variable so that the total cost of construction of the entire slab can be minimized. In this study, only the individual beams are optimized.

From the point of view of transporting precast elements, the maximum size of an element is restricted to 8 m. The minimum length of the segment is specified as 1.0 m from practical considerations. The lengths of the precast segments for the flanges and the web are the decision variables in the optimization model. A finite element model is generated for each potential solution using the values of lengths of segments proposed by the RANPAS algorithm. This is analysed using a finite element analysis program and the member dimensions are calculated according to the internal forces in the members.

The optimal design is shown in Figure 1. The bottom flanges are made of seven segments, each segment with different length and number of rebars according to the axial forces at its location. The width of bottom flange segments is kept constant to have aesthetic appearance. The web is made of 14 segments. There is at least 0.6 m gap in the web in locations where flanges are connected. This provides access to technicians for joining rebars using mechanical couplers or through welding. The gap in the web introduces additional stresses in the flanges in those regions, however, the optimization algorithm ensures that the gaps are provided such that the forces are not exorbitant, and the total cost is the minimum.

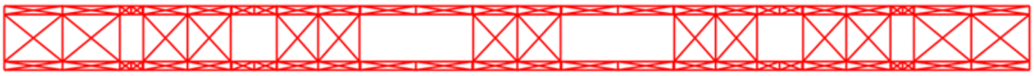

Figure 1: Optimal design of the precast beam.

A sub-optimal design generated during the course of optimization is shown in Figure 2. This design contains less area of cavities in the web. This results in more use of material. The conventional beam has continuous web with no cavities. This is taken as the base case to compare the savings in the material.

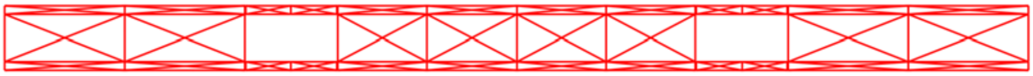

Figure 2: A sub-optimal design of the precast beam.

The material usage and savings for the optimized design and the base-case are tabulated in Table 1. There is about 21% savings in the amount of concrete as well as the total cost.

Design solution	Weight of concrete (kg)	Weight of steel (kg)	Cost (INR)
Base-case	31,476	1001	217,000
Optimal design	24,787	1477	276,000
Savings			21.2%

Table 1: Savings through design optimization.

4 Conclusions and Contributions

This paper presented a modelling approach to optimize precast construction of large span floor slabs. The optimization model included factors that enable fast assembly of precast elements at high elevations where work quality is difficult to achieve. Previous research on structural optimization have not adequately incorporated constructability issues. A stochastic global search algorithm was used to search for optimal solutions. In the case study example presented in the paper, a savings of 21% in the weight of material was obtained compared to the conventional design. The primary reason for the reduction in the material is the introduction of cavities in the web where internal forces are minimal. In addition, each precast segment has different amount of reinforcement as obtained through finite element analysis. The width and thickness of flange segments are maintained constant so that the same moulds could be used for the fabrication. The gaps provided in the web at the locations of flange joints permit easy access for workers to perform in-situ connection work. Thus, constructability issues have been incorporated in the optimal design.

The RANPAS algorithm could efficiently identify the optimal solutions, even though the solution space is not very smooth. Since solutions have different number of variables, standard parametric optimization techniques are not effective in this case. Conventional optimization algorithms have difficulties in solving such problems.

The primary contribution of this paper is the optimization model for precast construction of large span roof slabs. The results show that significant savings in material could be achieved through optimization. The model could be used for the optimization of other structural elements as well.

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