ABSTRACT

Multi-storey building construction is moving at a faster rate. The tendency of a builder is to complete the construction in the shortest possible time and the least possible cost. Formwork, being an important component of reinforced concrete (RC) construction, plays an important role in the construction of a multi-storey RC building. The horizontal formwork constitutes components such as sheathing members, joists, stringers, and single-leg shores or multi-leg shores depending on the condition.

The safety of the structure during construction depends on the load transfer mechanism from slab to shores, making these components important in the horizontal formwork system. The selection of shores requires careful consideration and effective usage to ensure the safety of the structure during construction. To achieve this aim, six different objectives were identified. These are: (1) to evaluate factors for shores selection in multi-storey building construction, (2) to analyze the loads on slabs and shores-reshores in multi-storey RC building construction, (3) to optimize the time of RC work in a multi-storey building, (4) to optimize the cost of RC work in a multi-storey building, (5) to optimize the time and cost of RC work in a multi-storey building by maintaining safety during construction, and (6) to evaluate the shore loads with respect to shore spacing and shore removal pattern. Various analysis and evaluation tools such as principal component analysis (PCA), analytical hierarchy process (AHP), and genetic algorithm (GA) were used to achieve these objectives.

For shores selection, the attributes relevant to both single-leg shores and multi-leg shores were considered. These attributes were compiled from a literature review and discussion with experts. This resulted in a total of 14 attributes for single-leg shores, while 21 attributes were compiled for the selection of multi-leg shores. The application of principal component analysis (PCA) has extracted five factors from the 14 attributes for single-leg shores and seven factors from the 21 attributes for multi-leg shores selection. The five factors for single-leg shores selection were: (1) shore characteristics, (2) convenience in shore placement, (3) cost of shore, (4) availability of shore in the required quantity, and (5) reusability of shore. The seven factors for multi-leg shores selection were: (1) tower shore characteristics, (2) intrinsic characteristics of tower shore, (3) availability of tower shore in the required quantity, (4) ease of shore placement, (5) shore connection and installation equipment, (6) cost of shore, and (7) reusability of shore. These factors were further evaluated for their relative ranking using the
analytical hierarchy process (AHP). A framework was further developed to help the decision-maker in selecting the shores from among the available options.

Subsequent to the selection of a proper system of shores for a project, the analysis for the load distribution among the slabs, shores, and reshores during construction of a multi-storey building becomes important from the safety point of view. For this, a computational program was developed considering the simplified method (developed by Grundy and Kabaila (1963)) to study this load distribution. The analysis was carried out for three different geographic locations, i.e. India, USA, and Europe, as the formulae used for the concrete strength development are different here. It was observed that the strength gained by the slab with respect to the elapsed time was the highest for Europe, followed by USA, and then by India based on the type of cement, method of curing, and strength calculation equation. A graphical user interface (GUI) was also developed by considering the construction sequence for RC buildings to help the users in comparing the safety of the structure by varying the different parameters such as number of levels of shores-reshores, cycle time, stripping time, grade of concrete, etc.

The formwork needs to be removed as early as possible because it takes the major proportion of the total cost of construction and plays a key role in achieving the construction time. Hence, the developed computational program for load distribution among the slabs and shores-reshores was modified with a GA to optimize the time of RC work. The objective function was derived considering the time and safety parameters. It was found that a minimum M30 grade of concrete is required for speedy construction by maintaining minimum safety requirements. The optimization of the cost of RC work was carried out considering the construction of slabs in a multi-storey RC building by maintaining the safety of the structure. The objective function was developed with the number of levels of shores, the number of levels of reshores, the grade of concrete, and the overhead charges. The lower grades of concrete, such as M20 to M30, violate the safety condition for some combinations of levels of shores-reshores. It was suggested to use more levels of reshores than levels of shores to minimize the cost of RC work by maintaining the safety of the building. Further, the time and cost of RC work were optimized simultaneously. The previously derived functions of time and cost were combined together by the priori approach, and the optimization was carried out by assigning different priority weights to the two functions. As the cycle time increases, the required total number of formwork levels reduces, which in turn reduces the cost but increases the time of RC work.
The study was then extended to compare the shore loads for different shore spacing and shore removal patterns. The simplified method assumes the shores as rigid. 2D building models were prepared in SAP2000 commercial software to compare the load on rigid and flexible shores for different spacing. It was found that the simplified method overestimates the average loads on the shores by 12–16%, but the locations of the levels of shores with a maximum load remain the same in both the cases. Further, the increase in the shore loads during removal was studied using 3D building models with different shore removal patterns. Row-wise removal of the shores was found to be the safest way. The most loaded row of the shores should be removed first as it results in a lesser increase in the remaining shore loads and thus ensures the safety of the structure.

The study contributes in the form of models to (1) guide a decision-maker in arriving at an informed decision for the selection of shores for a multi-storey building rather than relying on intuition alone; (2) decide the number of levels of shores-reshores to maintain safety during construction; (3) optimize the time and cost of RC work by maintaining safety during construction; and (4) understand the shore removal pattern without exceeding the capacity of the shores.

The proposed approach can significantly help designers, builders, practitioners, and decision-makers (1) to select the proper shores, (2) to find an adequate number of levels of shores-reshores to optimize the time and cost of RC work, and (3) to provide guidance on the removal of shores by maintaining the safety of the multi-storey building during construction.

**Keywords:** Single-leg Shores; Multi-leg Shores; Formwork; Number of Levels of Shores and Reshores; Optimization of Time; Optimization of Cost; Shore Removal; Multi-storey Building; Principal Component Analysis; Analytical Hierarchy Process; Genetic Algorithm; SAP2000.