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Design of Building Structures: A Review Article

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Abstract

Building structure optimization design is a field that has especially undergone increased realization over the past five years. It has transformed from a field dominated by deterministic and heuristic methods into a vibrant domain where intelligent systems and green building design meet. This paper provides detailed reviews on the up-to-date methods of structural optimization available, concentrating on the traditional deterministic approaches as well as intelligent, probabilistic, fuzzy, hybrid algorithms. The major areas covered are size, shape, and topology optimization with applications emphasized for planar frame structures. The multilevel modeling and simulation techniques of intelligent building systems are evolving into an important aspect. It does critically evaluate the current methodological limitations and knowledge gaps, providing world challenges for future research. Therefore, the findings do also incite later researchers into further intelligent and sustainable design practices for building structures.

Keywords: Optimal design, Structural optimization, Building structures, Design codes, Semi-probabilistic method, Artificial intelligence

1. Introduction

The paper presents a literature review on the application of computer optimization in structural building design. The use is restricted to buildings - structures comprising predominantly columns, beams and slabs, referred to more commonly as frame structures. Steel and reinforced concrete structures are the main optimal designs considered, including cross-sectional shape and size optimization, planar structure layout and shape optimization, and topology optimization. Other structural types, for example arches and bridges, are not considered. It is based on articles published in some of the most significant journals during the last two decades. Articles published in the period 1995-2000 in selected journals emanating mainly from Europe and North America were considered. The principal international journals on applied mathematics and on structural design/computational mechanics were also considered. The material for review is to comprise six principal divisions: Introduction; Approaches and methods; Optimal design of structures, comprising: static, dynamic, crack control and stress aspects; optimization of size and shape of planar frame structure elements; optimization of shape and layout of planar frame structures; and d. topology optimization; Viewpoints and current status of the field; Recommendations for further research and development [2]. Optimum building design founded on computer optimization can result in good designs inclusive of functional efficiency and economy by design. The first two steps in structural design are to design the physical size, shape, arrangement of structural elements and to model the structure using a computer-aided design system. This model is also essential for applying the finite element method in order to determine the displacements, stresses, and forces of the structure in each element [3]. The review is also confronting the reliability of structural design.

2. Level of Structural Improvement

Structural optimization can be classified into three classes: size, shape, and topology optimization. Size optimization is preferable for small structures; shape optimization further relaxes the restrictions to allow very complex geometries. Topology optimization would then be used for large non-linear structures and typically applied to planar frames having more than three spans. For more complex structures, topology optimization directly is not very practical to change as detailed in [4, 5].

It must be noted that form and topology optimization alone can only resolve the static material enhancement of continuum structures, except for more special cases like roofs or bridges. Stress constraints tied to loads, geometry, and material can be enforced globally. Topology optimization enhances structural performance in unwanted states and typically realizes semi-enclosed or open frame designs. For size optimization, it focuses on a modification in the area of a perimeter to meet load and tension requirements while ensuring material balance and safety. Numerous approaches have been suggested for the solution to the size optimization problem and proved their efficiency in complex forms like arches or frames [7].

2.1. Size Optimization

Structures to be designed by civil engineers include bridges, dams, buildings, cranes, and towers. Documentation and drawings for construction are prepared by them. Structural design, though complex, is not enough to fulfill readymade standards, which may not even give the optimum solution and may further need enhancement through optimization techniques [8]. Size optimization is that cross-sectional dimensions (height, width, depth, thickness) are modified to refine the design based on some objective function. This procedure changes the geometry while preserving the structure. The structure model is represented as interconnected elements with a certain cross-sectional profile: rectangular, square, the shape of a T, L, I, or C for beams or columns. Limits can be based on the cross-sectional area and considered load combinations (dead loads, live loads, wind loads). Sizing optimization has been developed deflections and displacements as constraints for steel, concrete, and composite structures. The national rules are mandatory for design, which has to reserve proper strength and capacity requirements during optimum processes. The analysis is carried out by the finite element method. Several benchmark problems are considered to test the accuracy and efficiency of the optimization algorithm. Commercial software is interfaced with optimization scripts that program themselves. Pre-processors and post-processors are available to discretize the model and show numerical results pictorially. Size optimization results vary with design constraints and methods but are optimal and accurate [10].

2.2. Improve the Shape

Shape optimization is very important in the design of structures with large deformations and vibrations to reduce their weight. This will be the minimum amount of material mass while meeting the performance criteria. Although developed only in the 1860s for simple shapes like cylinders and beams, optimization only became realistic for complex geometries through the finite element method, which was invented in the 1950s. The latest developments have enabled unified formulations with a smaller number of variables, increasing their prevalence in commercial software [11, 12]. Optimality relates to safety (that the structure will not fail), ease of maintenance, and cost-effectiveness so that the design remains safe with very low levels of risk. Shape optimization concerns minimizing the mass regarding dynamic behavior under loads and restrictions. Numerical analysis, especially using the Finite Element Method, has become common in studying engineering problems and taking practical decisions. For instance, codes for shape optimization of domes, tanks, and bridges have been developed using displacement-based differences and shape sensitivity gradients. This kind of shape dependency makes convergence a little unstable, but when the final shape is found for different input parameters, it becomes a very useful technique for optimizing vaulted ceilings and other structures [14].

2.3. Topology Optimization

In general, for a frame structure, size optimization can only improve axial stiffness. Geometric shape cannot be arbitrarily changed. Simultaneously, shape optimization acts as the improver for both cross-sectional geometry and overall structure shape based on the kind of variable to optimize in the specific area. Shape optimization is divided into edge shape optimization and cross-sectional shape optimization. Most optimization techniques find it hard to realize edge shape optimization. This is because they are generally not very superior topologically due to frame structures in nature—forming a new structural arrangement to help this structure obtain its optimal performance with minimal material input task very interesting and meaningful: topological optimization. Topological optimization has become an emerging topic in recent years. But it is extensively applied in structural optimization, automotive design, mechanical engineering and other related fields. Moreover, for spatial structures and repetitive structures, topological optimization also has very good application prospects [15, 16]. From a mathematical perspective, topological optimization of the frame structure is equivalent to determining the optimal arrangement of units with respect to the desired structural function, subject to both the points where no unit can pass and those points where at least one unit must pass. Generally, topological optimization involves two steps. The first step is to formulate an optimization model that is done by seeking to minimize an objective function subject to many constraints. The second step is solving the optimization model based on numerical methods [17]. The recursive nature of the topological optimization process for frame structures. Plane frame structure topology optimization can be further separated into plane frame structures and space frame structures. The first thing in the topology optimization of plane frame structures is to remove the finite element distortion effect on the optimal design since possible area directly acts as a design variable. Also, some adjustments are done to make sure that optimal design is obtained with near-perfect vertical or horizontal arrangement of elements. An exhaustive search approach is used to obtain an optimal design for a plane frame structure based on the unified stiffness method of finite elements. In topology optimization of space frame structures, some researchers introduce new zero-one variables to get rid of the influence of unit length on topology and work with symmetry conditions [18]. As a result, optimal topology is not sensitive to finite element model geometry.

3. Optimal Design of the Building Structure

As computer-aided optimization design methods are more extensively applied, the structure optimization design has become a highly open theme and rarely dependent on professional background. Yet another thing to remember is that this is not only of interest to designers and researchers but also to students in related majors and IT engineers. To make the matter more complicated, different computer languages are used for describing the optimization design of building structures. Some of the topics briefly touched upon in the optimization design of plane frame structures consist of design concepts, mathematical formulas, design variables, design constraints, numerical optimization methods, analysis and optimization techniques, and so forth. A structure meeting a number of proper design specifications is suggested. The building structure is simplified to a plane frame structure for optimization design; it is, therefore, easier to calculate and design based on the plane frame structure. Unrestricted in the number of floors and spans, the plane frame structure is analyzed by the finite element method. Equation (3) is obtained using a three-layer feed forward neural network that expresses the relationship between the resonant frequency and the current design variables. Global optimal design with the least cost is achieved by using the integer optimization method for exploring variable design spaces over a wide range. This also can be independent of material properties if defined in the program. The design specifications are of three frame structures that are differently designed. The design specifications are based on different sets of codes. It shall certainly inspire researchers to take up further work related to optimization study on various complex structures, later. This paper briefly introduces the optimization design of shear wall building structures. The authors made a corresponding systematization of plane shear wall structure buildings with different numbers of floors and spans. Optimal Design of Shear Wall Structure Building Shear wall structure building: a building structure that is both earthquake-resistant and wind-resistant; internal reinforced concrete core tube and external reinforced concrete frame with shear walls [20, 1]. The three-dimensional building structure is modeled as a composite of rigid frames and flexible frames and further simplified into a 15-story single-span plane shear wall configuration. This is done to meet the multiple stiffness requirements of different design codes. Such methods can provide a useful reference for carrying out optimization design on other shear wall structures. The narrow-arm plane truss was also studied for optimization design [21]. Using a genetic algorithm, the structure is first preprocessed, with grid shape optimality being key to deterministic optimization.

3.1. Optimize the Frame Structure

The paper ‘Optimization of Frame Structure Based on Genetic Algorithm’ adopts actual structural optimization design activities based on building structure design code. An office building frame structure is described. The building is an eight-floor building, with each floor height being 3.3 m. The construction weight for floor and roof cladding is taken as 5.0 kN/m². The real load of the building is 2.5 kN/m². Floors and roofs are of reinforced cement concrete floorings. Situated in Nanjing, Jiangsu Province, this construction site is planned to be earthquake intensity in amplification grade 6. The scheduled foundation wind pressure is 0.35 kN/m² [22, 23]. It will be assumed that, for the reinforced concrete member of identical specification as that of the cross-sectional shape of the structural beam and the structural column, with material being concrete C30 and HRB400, the design variables include the height and width of the cross-sectional structure of the structural member (column and beam). The cross-sectional height and width of the structural beam and the structural support are 230-500mm and 230-500mm. The design variables of the structural unit specifications are shown in accordance with the Chinese national standard. The dynamic characteristics of the above frame structure are calculated. The first six natural frequencies, damping ratios, and vibration modes of the nodes are listed. The vibration modes of the structural nodes are shown [24]. In the dynamic analysis, the random eccentricity of the frame structure shall be considered according to the code. There shall be multiple values of random eccentricity. The frame structure has 25 sets of loads after considering the random eccentricity, with the maximum horizontal displacement as the objective function, whereby a total of 13 structural strength and seismic constraints are satisfied.

3.2. Optimal Design of Shear Wall Structure

In the 20th century, a guideline known as the Structural Concrete Building Code developed into a major rule for reinforced concrete structures all over the world. It had to be revised several times and updated to address shear wall design. The parameters of shear walls were designed some fifty years ago. Also, linear programming methods have been introduced for the preliminary design of shear wall structures. For example, in many developing countries, due to lower tensile strength of steel produced locally, and higher labor cost, it may be more economical to increase the thickness of structural elements like walls rather than buy special high-strength materials. As both wall volume costs and frame volume costs are minimum when applied in accordance with yield criterion on principle stresses samples from photo elastic model indicate maximum material savings attainable using these criteria alone writer's lateral force distribution may be overly conservative reflecting preferences practice rather than mechanics economics oxidative atmosphere would lead an upwind observer {}; allowed (per bendst) bending; through loaded beamsair e.g. Then two geometric transformations are introduced to aid in retaining the cross-sectional shape. The problem is solved with nonlinear programming and methods of gradient type. As a nonlinear programming technique, the most economical shear-wall design is investigated. However, their methods and algorithms are either too complex to be widely used or their designs are uneconomical optimal. Up to now, there is no optimization design tool (of good applicability) for shear wall structures with optimum solutions from an economic standpoint [25]. The design of optimization for reinforced concrete shear wall structures was researched. Shear walls are a common form of structure used to resist lateral loads in high-rise buildings. Therefore, the optimization model is based on the height of the building and the numbers of shear walls. It also considers movable positions and ground for shear walls, as well as cross-sectional dimensions designed areas apart from other factors. The cross-sectional dimensions and longitudinal reinforcement ratio of the shear wall are preset by national regulations during construction; therefore, from an economic point of view, the area should be crucial. The shear wall's cross-sectional area is drawn up based on a plan shape for optimization. The longitudinal reinforcement ratio is limited by the standard such that the wall ratio of the shear wall does not exceed the limit, and the width of the wall foundation at shear wall design is not less than a certain minimum value. As a rule, compromises between these factors are to be found by a designing engineer (concrete cost, cost of reinforcement, shear wall formwork cost, and labor costs) [26]. The total cost of the system of shear walls is described by an objective function taking into consideration costs of both wall foundation and shaft, connection costs, frame costs and edge costs.

3.3. Optimal Design of Truss Structure

A truss is a structure made up of long, slender members that are connected at their ends by joints. Owing to its simple geometry and prefabricated nature, steel and aluminum are the most common materials for building truss structures due to their high strength and ductility. The ladder or pyramid shapes consist of different kinds of geometries of this type of structure depending on the applications. Trusses may be used to form the roofs, bridges, towers, cranes, etc. The truss has a lightweight structure that enables it to transfer the applied loads to equal normal stresses along its length. In a truss structure, depth is less as compared to layer hence moments of inertia are also significantly reduced which results in more economical sections optimised for bending resistance alone. Several works have been proposed for this design purpose due to various objectives such as mass, cost, stress, deflection, etc. [27]. The average stress in a plane truss structure element is expressed as the sum of the internal forces resulting from the loads applied to the nodes. The finite element idealization of truss structures is based on representation of the truss element as a line element with two nodes and constant cross section. The general element of a plane truss should be discretized into N elements. The equations of motion are expressed in a coordinate system relative to the structure. The loads and reactions are to be thought of as lumped vector sets where L is the nodal load vector at the connection, U is the nodal displacement vector at the connection, and R is the nodal reaction vector at the connection. It can be written as. The sum of forces acting on the element in global coordinates system [28]. Classical optimization methods involve the use of mathematical programming or classical structural search techniques comprising optimization operator heuristics. The design of structures is based on using established proper geometrical arrangements of structural components, cross-sections, dampers, beams, supports and so on. Thus, the design of structures is based on well-established rules and technical information and generally not free-form. Industrial problems in the sphere of designing (or redesigning) product structure and mechanical systems require methods to be applied following known strategic expert systems or heuristic methods [29]. Although in structural optimization the use of heuristic methods with application knowledge as expert systems does not provide for convergence assurance, mathematical programming methods based on optimization operator heuristics explicitly solve optimally formulation problems representing design processes for structures.

4. Conclusion

An optimal design is a novel design that is easy to design and construct. It checks the stability of the structure. An optimal design will not be achieved if the design allows a uniform distribution of materials throughout the structure. The function to be maximized or minimized in an optimum or optimal design is known as the objective function. Design variables refer to the control which the designer has; that is, those variables that can be changed in order to get the optimal design. In general, design converts the requirements of visual function into a manufactured object. Building structures include houses, bridges, roofs of commercial buildings, towers, and so on. Numerical approaches are performed with computers. Optimal design of building structures can be achieved by incorporating the methodologies of both deterministic and stochastic. The deterministic approaches look for uncertainty-independent solutions and require the precise description of the whole behavior of the system. Deterministic methodologies are extensively employed in the domain of civil and structural engineering. Stochastic programming emerges to hold quite well in view of the uncertainty surrounding problems of structural design. It is, indeed, a very plausible substitute for deterministic techniques. Given that most structures host some uncertainties, optimization of design should reflect these uncertainties. Ways of addressing such uncertainties are through stochastic programming. The literature reviewed the optimal design of building structures. It deals with different kinds of structures ranging from simple to complicated structures. The optimization is approached using different approximate and exact methods. Both deterministic and probabilistic methods are used in structural design. Several attempts have been made to the uncertainty problem in the structural design process. Some researchers tried to approach the queuing systems development of structural design reliability and others have reported optimization design techniques at length in respect of the deterministic and probabilistic designs of discrete variable and continuous or continuous variable structures.

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