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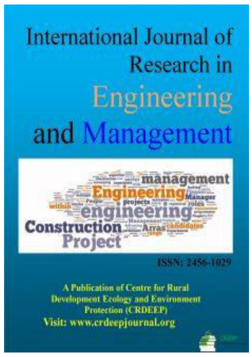

Full Length Research Paper

Application of Optimization Techniques in the Pedestrian Bridges Systems

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ABSTRACT

Throughout the years, the need for more pedestrian bridges has been growing. In addition, the construction of roads, motorways, and railways has been stepping up rapidly in recent years, resulting in the need for more pedestrian bridges. Nowadays, construction methodologies have been changed widely, and sophisticated machinery is introduced, making the labor input a minimum. But the overall construction cost is high—the best way to cover this point is by implementing optimization techniques, particularly in the planning and design stages. The literature review provides that these problems are not covered yet. It needs more works to develop optimization techniques for better performance. Therefore, it is highly beneficial to focus on design functions, construction objectives while simultaneously assessing how the budget can be sustained and standards for quality and performance can be met. The contribution of this study is to present a decision making to help select the best system for the pedestrian bridges considering project priorities, configurations, and site conditions. Furthermore, it will be present the economics of pedestrian bridges according to cost efficiency during the life cycle costing (design, fabrication, and construction) related to the pedestrian bridges systems.

Introduction

Pedestrian bridges serve many users, including bicyclists and pedestrians who are either non-disabled or physically challenged. These facilities may be one of the most critical components of a non-motorized transport network in a city. Overcrossing provides essential links to the pedestrian system by joining areas separated by various barriers, including deep canyons, waterways, or significant transportation corridors. These are established at locations where high vehicle speeds and heavy traffic volumes exist, where there are dangerous pedestrian crossing conditions, such as in areas with little to no traffic gaps, disputes between motorists and pedestrians, and in places where large numbers of school children cross busy roads. During the past decades, various systems have been applied to build several methods for the bridges and roads in the world. A considerable amount of money is consumed on these projects. A lot of money, usually consumed with no extra benefits, cost optimization is essential to solve problems and identify and eliminate unwanted costs while improving function and quality. The optimization problem for steel structures can be expressed as a problem of weight minimization. Just a limited percentage of the hundreds of papers written on steel structure optimization deal with cost optimization; the vast majority deal with structure weight minimization. A low-weight design may not be a minimal cost design. In addition to material costs, a structure's overall building cost is influenced by various other factors.(Adeli & Sarma, 2006). Optimization is a deliberate effort undertaken to increase profit margins and achieve the greatest results under certain conditions or circumstances. The optimization of time and cost is needed because it can reduce both the time and overall cost of the project. This time and cost optimization assists in achieving the greatest value. Cost optimization The Process of optimizing the expenses of cost in a project, from starting the client's idea to the completion and final payment on site (Rajguru, 2016).

Optimization is used in many fields of science and engineering, including structural engineering. For example, design objectives in structural optimization are structural criteria used to assess the merit of a design, such as maximum stiffness, minimum life-cycle cost, minimum construction cost, and minimum weight (Sahab et al., 2013). Optimization aims to optimize utility by maximizing the use of limited resources.

The optimal design aims to achieve the best feasible plan based on a predetermined measure of effectiveness. The growing realization of raw material scarcity has resulted in a demand for lightweight and low-cost structures. This demand shows the importance of structural weight and cost optimization (Kirsch, 1993). The vast majority of structural optimization papers are concerned with minimizing the structure's weight. While the weight of a structure represents a considerable part of the cost, minimizing the cost is the end purpose for optimum use of available resources. Since various materials are involved, the optimization problem for concrete structures must be formulated as a cost minimization problem. In comparison, the optimization problem for steel structures can be formulated as a weight minimization problem (Adeli & Sarma, 2006).

History of structural optimization

In 1890, Maxwell published the first analytical research on structural optimization, followed by Mitchell's further investigations in 1904. Structural optimization techniques were developed in the aircraft and space industries due to stringent requirements on minimum weight design in engineering design. The emergence of computers during the years 30-50' enabled linear programming techniques to the plastic design of frames (Tushaj, 2017). In 1960, Schmit was the first to provide a detailed definition of how mathematical programming techniques can be used to solve the nonlinear-inequality-constrained problem of building elastic structures under a variety of loading conditions. This work pioneered a new engineering design concept that was only widely adopted in the 1980s. It demonstrated the feasibility of combining finite element structural analysis and nonlinear mathematical programming to generate optimum design capabilities. The computational experience revealed that mathematical programming (MP) techniques used in the structural design were confined to a few dozen design variables. Thus, in the beginning, the applications were restricted to relatively small structures. In the late 1960s, Prager and coworkers presented an alternative approach termed Optimality Criteria (OC) in analytical form. Although this approach was mainly intuitive, it was demonstrated to be most effective as a design tool. It was independent of problem size and usually offered a near-optimal design with a few structural analyses. This feature significantly improves the number of studies required by (MP) approaches to find the solution (Kirsch, 1993). In the previous few decades, new optimization approaches have arisen. These approaches, which use probabilistic transition rules rather than deterministic ones, do not require gradient information for the objective and constraint functions. Instead, these techniques are stochastic or meta-heuristic approaches because they search for the best solution by generating random populations depending on some criteria or fitness functions. When compared to deterministic optimization techniques, these heuristic techniques have some advantages. For example, they separate domain knowledge from search, making them generalizable to a wide range of problem formulations; and there is no restriction on the continuity of the search space because no gradient information is necessary (Tushaj, 2017).

Theoretical background of structural optimization

Structural optimization is defined by (Christensen & Klarbring, 2008) as "The subject of making an assemblage of materials to sustain loads in the best way." engineers must make several technological and administrative decisions during the design, construction, and maintenance of any engineering system, with the ultimate goal of either minimizing the effort required or maximizing the desired benefit. Thus, the general nonlinear constrained optimization problem can be written as:

Min f(x) subject to $g(x) \leq 0$

which x represents the set of the variables, f(x) is the objective function and g(x) is the set of constraints.

Optimization in structural engineering

The importance of optimal structural design is growing due to limited material resources and its impact on the environment, which requires perfect performance and low life-cycle-cost structures. Optimization issues may have several objective functions. There are three different types of structural optimization problems. The first is dimensional optimization, which considers element sizing as a design variable that can change constantly or be picked from a list of potential cross-sectional dimensions. The second problem is geometric optimization, which takes nodal coordinates into account. Finally, the number of elements is considered in topology optimization (Roy & Kundu, 2020). Many ways govern optimization techniques in structural engineering—improving crew productivity is one of the most important ways to help make an optimal structural system.

In 2015, the research discussed improving crew productivity during the construction of steel structure projects. Personal interviews, a literature review, the researchers' knowledge, phone calls, and email correspondence were used to conduct the research. As a result, a Matlab model was created for measuring and evaluating the crew productivity of construction of steel structure projects based on the various factors that govern the construction of the steel structure process. It is advocated that contracting and consulting firms increase crew productivity for steel structure projects construction before and during construction (Rashid et al., 2015). In 2016, A methodology for simulating Matlab to construction performance control for steel structure construction processes was presented based on numerous factors affecting steel structure processes. The Matlab model is used to control the productivity of steel structural projects during construction. The capability of the estimating team to accurately deduce productivity for various activities will have a substantial impact on the crew cost component, project schedule, and project performance. The implementation of the Matlab model is predicted to result in cost and schedule savings for steel structure projects and cost savings for the overall project (IA et al., 2016). In 2020, Six different machine learning algorithms' predictive abilities – artificial neural network, linear regression, random forest, light gradient boosting, extreme gradient boosting, and natural gradient boosting – were compared and shown that a hybrid light gradient increasing and natural gradient boosting model delivers the best construction cost estimates in terms of accuracy metrics, uncertainty estimates, and training speed. The comparison of the projected and actual costs indicates satisfactory alignment, with $R^2 \sim 0.99$, $RMSE \sim 0.5$, and $MBE \sim -0.009$.

Furthermore, the proposed hybrid model may offer uncertainty estimates for real-valued outputs via probabilistic predictions. This probabilistic prediction approach generates a holistic probability distribution over the entire outcome space (Chakraborty et al., 2020). Second, a study aimed to present the optimal gravity and lateral systems for a multi-story reinforced concrete (RC) structure in terms of direct cost. To attain that purpose, parametric research was conducted utilizing 72 RC buildings with multiple stories ranging from 5 to 50 floors with grid spacing ranging from 6.0 to 12.0 m. The dual system is the best choice for medium and high-rise buildings, with solid slabs for short spans and ribbed slabs for medium and long spans (Elhegazy et al., 2020). Applying for value engineering benefits in construction projects, particularly multi-story buildings, was introduced in a review study. The study provided perspectives on value engineering in the context of contemporary structural engineering to frame the breadth and multiple dimensions it encompasses, summarize recent activities on selected relevant topics, and highlight possible future directions in research and implementations (Elhegazy, 2021). Third, analysis was made to learn how to employ quality function deployment in the construction industry. The study was conducted for the owners and decision-makers of an Egyptian construction firm and the owners' requirements as a sample. Using the quality function deployment technique, this study investigated the identification of the critical performance indicators influencing decision-making and value engineering for selecting an optimal structural system for a multi-story building in Egypt (Elhegazy, Ebid, et al., 2021). A study presented recommendations for the best composite flooring system for multi-story buildings to assist decision-makers in the preliminary design from total cost (materials cost and installation cost), load, span, and building function. The study makes use of data from the RSMeans Assemblies Books from 1997 to 2019. During the preliminary design stage, a simple computer model is developed to recommend the optimal composite flooring system for a multi-story building. The model can be used by the value engineering (VE) team to fulfill the abovementioned VE goals (Elhegazy, Chakraborty, et al., 2021).

Types of structural optimization

Many authors agree on the categorization of different types of optimization as follows:

A. Sizing optimization

Sizing optimization minimizes response variables (stresses, deformation, and stiffness) acting on one or more design variables. This is when x is a structural thickness, i.e., the cross-sectional areas of truss members or the thickness distribution. For example, a sizing optimization problem for a truss structure is shown in Fig. 1.

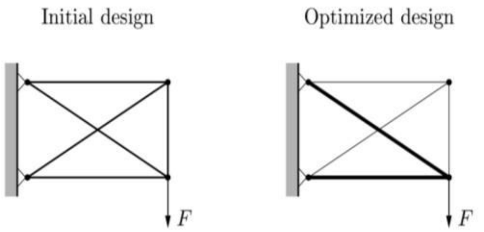

Fig.1 *sizing structural optimization problem is formulated by optimizing the cross-sectional* (Christensen & Klarbring, 2008)

Size optimization has been used in a variety of research papers. For example, in 2017, Barraza optimized frames for seismic loads. However, several other publications concentrated on designing a practical algorithm for size optimization (Barraza et al., 2017) and (Gonçalves et al., 2015) used teaching-learning-based optimization, the big bang–big crunch algorithm, and the search group algorithm, respectively, to optimize the size of various structures.

B. Shape optimization

Shape optimization seeks to determine the ideal domain shape, which is no longer fixed and has become a design variable in and of itself. This is related to the physical form of structural elements. Several researchers have used shape optimization to optimize structures. For example, (Wang et al., 2002) optimized the shape of truss structures under several displacement constraints and (Nasrollahi, 2017) optimized large span trusses shape.

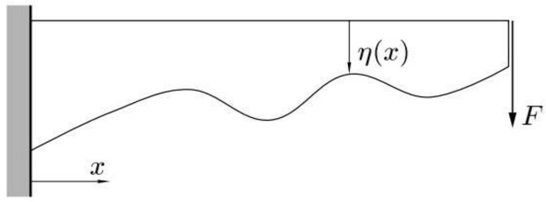

Fig. 2 *A shape optimization problem. Find the function η(x), describing the shape of the beam-like structure*(Christensen & Klarbring, 2008)

C. Topology optimization

This is the most general type of structural optimization—the number, position, shape, and topology of holes in a continuum structure. In a discrete situation, such as a truss, it is accomplished by treating the cross-sectional areas of the truss members as design variables and then allowing these variables to have the value zero, i.e., the truss's bars are deleted. As a result of the changeable connectedness of nodes, we may state that the topology of the truss changes (see Fig. 3).

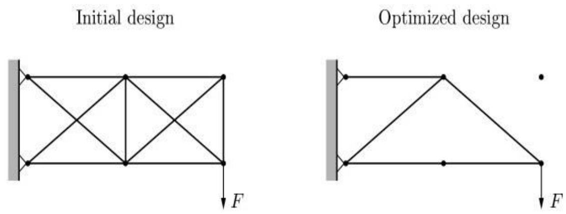

Fig. 3 *Topology optimization of a truss. Bars are removed by letting cross-sectional areas take the value zero* (Christensen & Klarbring, 2008)

A variety of research papers have used topology optimization. For example, A method developed for optimizing the structure topology by (Xia et al., 2013).

Optimization problems

Optimization problems can be categorized in many ways, as mentioned below.

Based on the Existence of Constraints

Depending on whether constraints exist in the problem, any optimization problem may be categorized as constrained or unconstrained.

Based on the Nature of the Design Variables

Based on the nature of design variables encountered, optimization problems can be classified into two broad categories. The first category's problem is finding values for a set of design parameters that minimize some prescribed function of these parameters subject to certain constraints; such problems are known as static optimization problems. The objective of the second category of problems is to find a set of design parameters, which are all continuous functions of some other parameter, that minimizes an objective function subject to a group of constraints. This type of problem, in which each design variable is a function of one or more parameters, is known as a dynamic optimization problem.

Based on the Physical Structure of the Problem

Optimization problems can be classified into two categories based on their physical structure: optimal control problems and nonoptimal control problems.

Based on the Nature of the Equations Involved

Another significant classification of optimization problems is based on the expressions for the objective function and constraints. This classification divides optimization problems into four types: geometric, quadratic, linear, and nonlinear programming problems. This classification is advantageous from a computational standpoint since several unique methods are available to solve a specific class of issues efficiently.

Based on the Permissible Values of the Design Variables

Optimization problems may be categorized as integer and real-valued programming problems based on the values allowed for the design variables. When two or more design variables in a problem are restricted to only integer values, the problem is known as integer programming. On the other hand, if all design variables may only have fundamental importance, the optimization solution is a real programming problem.

Based on the Deterministic Nature of the Variables

Optimization problems can be divided into deterministic and stochastic programming problems based on the deterministic nature of the involved variables.

Based on the Separability of the Functions

Depending on constraint functions and the separability of the objective, optimization problems can be classified as separable and non-separable programming problems.

Based on the Number of Objective Functions

Optimization problems can be categorized as single-objective and multi-objective programming problems based on the number of objective functions to be minimized (Rao, 2020).

Optimization techniques

To solve any problem, various optimization techniques are available. Optimization techniques can be classified generally; they can be divided into two broad categories, namely, classical optimization techniques and advanced optimization techniques.

Classical optimization techniques

Classical optimization techniques help solve problems with continuous and differentiable functions. These methods assume that the function is differentiable twice concerning the design variables and the derivates are continuous. Moreover, these methods are analytical and make use of differential calculus techniques to locate the optimum points. Classical optimization techniques can be used to solve problems with single or multiple variables. Some of the classical optimization techniques are given below (Shahakar & Shahakar, 2019).

- Linear programming method (LP)
- Nonlinear programming method (NLP)
- Quadratic programming method (QP)
- Geometric programming method (GP)
- Dynamic programming method (DP)
- Decomposition techniques

Advanced optimization techniques

There are numerous optimization techniques available to solve any real-world problem. However, some optimization techniques require more time and iterations and cannot produce the exact optimum solutions. Advanced optimization techniques are based on specific characteristics and behavior of biological, molecular, swarm of insects, and neurobiological systems. Newer and more advanced optimization techniques are emerging daily to handle these real-world difficulties, and some are mentioned below:

- Genetic algorithms
- Simulated annealing
- Particle swarm optimization
- Ant colony optimization
- Tabu search
- Fuzzy optimization

Review of structural systems proposed for optimization of steel bridges in previous studies

The specifications of the American Association of State Highway and Transportation (AASHTO) Working Stress Design (WSD) method and Load Factor Design (LFD) alternative are used to study a cost optimum design technique of steel bridge girders. As a result, a set of over 30 cases of steel bridges have been designed for the least cost, and comparisons with the original designs have been made (Hsu, 1989). In 1991, The application of structural optimization to the design of continuous steel plate girder bridges was presented in a study. The use of inherent structural and geometrical characteristics of structures is required to develop efficient structural optimization capabilities. Such features, particularly for bridges, can decrease the number of finite element analyses and simplify the formulation of the optimal design problem in standard form (Memari et al., 1991). In 1997, Nakib proposed a reliability-based optimization method for designing truss bridges with uncertain correlated strengths operated on by correlated random loads. The effects of material behavior on the optimum solution of deterministic truss bridges were demonstrated using inelastic structural analysis. It is determined that the behavior of component materials can have a significant impact on the optimum weight of deterministic truss bridges (Nakib, 1997). In 2010, Jin Cheng studied The optimal design of steel truss arch bridges. The weight of the steel truss arch bridge was applied as the objective function, while the design criteria of strength and serviceability were used as the constraint conditions. All design variables were treated as discrete/continuous variables (Cheng, 2010). In 2012, An algorithm was introduced for finding the best design of a cable-stayed pedestrian bridge that includes both passive and active protection. The selection of control variables in the functional structure resulted in a stable and efficient design. The algorithm determined the control parameters to adjust structural frequencies and add damping to the structure's relevant modes. For example, the damping in a passive structure depends on finding the connection's optimum damping coefficient (F. Ferreira & Simões, 2012).

In 2013, Hassan developed a significant design optimization methodology for achieving the minimum cross-sectional area of stay cables. The procedure is developed by combining the finite element method (FEM), B-spline curves, and the Real Coded Genetic Algorithm (RCGA). The proposed methodology is used to predict the optimum cross-sectional areas of stay cables in cable-stayed bridges when the bridge's self-weight, initial post-tensioning cable forces, and live load situations are all considered (Hassan, 2013). In 2014, Lonetti and Pascuzzo proposed a hybrid model based on the optimization design method and the finite element method to evaluate the optimum cable-system dimensioning and post-tensioning stress in the dead load configuration. The approach is based on a two-step algorithm that iteratively executes two different phases based on the optimization and correction moduli (Lonetti & Pascuzzo, 2014). Thus, an effort has been made to design and optimize a portable pedestrian bridge. The main focus has been minimizing the total structural member deformation by optimizing material properties, cross-sections, and weight. The structural member comprises a rectangular plate 1.5m long, 0.5m wide, and 3mm thick that is fastened to the frame of prismatic beams at the periphery and in between (Rahul & Kumar, 2014). Second, an optimization model for network arch bridge systems was presented, in which the best solution is found using an iterative approach depending on a three-step algorithm. First, the suggested process detects the initial configuration under dead loads regarding post-tensioning forces in the hangers and initial deformations in the arch and girder, reproducing the design configuration under structural and nonstructural permanent loads (Bruno et al., 2016).

The application of a constrained differential evolution-based algorithm for the optimum design of steel truss girders was investigated in 2016. The three design categories, size, shape, and topology, were considered during the optimization process. In addition, the structure's weight was supposed to be the objective function of the optimization search (Fiore et al., 2016). Another study performed the optimal design of a steel arch bridge to measure the effect of high-performance steel for bridges (HSB). The material cost of the prominent steel members was optimized using a genetic algorithm. As per the design specifications, limit stress and limit deflection were used as constraints. As a result, it was observed that the cross-sectional area of the entire structure reduced, as did the material cost of the steel members (Park et al., 2016). In 2017, Jin Cheng and Hui Jin devised and implemented a reliability-based optimization method to reduce the weight of steel truss arch bridges subject to probabilistic (overall probability of structure collapse) and deterministic (stress and deflection) restrictions. The presented method integrates the genetic algorithm (GA), the finite element method, and the first-order reliability technique (Cheng & Jin, 2017). (Cao et al., 2017) proposed a computationally efficient optimal design methodology for suspension bridges. The presented method employs a linked suspension-bridge modeling methodology that combines an analytical form-finding method with a traditional finite element (FE) model to improve FE modeling efficiency during the optimization process. To improve the computational efficiency of the optimization approach, they also employ enhanced particle swarm optimization (EPSO), which introduces a particle categorization mechanism to handle constraints instead of the commonly used penalty technique.

In 2018, (Zeng et al., 2018) presented a probabilistic-based method for optimizing fatigue maintenance of steel bridge welded joints, which is integrated with linear elastic fracture mechanics (LEFM), structure reliability, and the life cycle cost method (LCCM). In 2019, An optimization algorithm for curved cable-stayed pedestrian bridges was also provided to determine the least cost design for varying bridge lengths.

The objectives include determining the bridge geometry (tower shape, number and location of cables), cross-section sizes, control device attributes, and cable prestressing. Different bridge lengths result in varying minimum costs, stress distribution, design variables, and dynamic response. In addition, the effect of tower shape and control device attributes on optimal design is considered (Fernando Ferreira & Simões, 2019).

In 2020, To resolve the issue of substantial horizontal thrust caused by the Calatrava bridge's high rise-to-span ratio, single-objective and multi-objective genetic algorithm (GA) based optimization procedures are established. The thickness optimization of the bridge is carried out separately using the proposed design procedures and the optimization module implemented in ANSYS (Feng et al., 2020). In 2021, A study presented an effective method for optimizing the hanger pre-tensioning force of steel tied-arch bridges, containing all operational loads and their combinations depending on code specifications. The proposed method uses the particle swarm optimization algorithm to seek the optimal global design. In addition, it develops a load decoupling approach (LDA) to improve the computational efficiency of structural analysis in optimization (Cao et al., 2021).

Conclusions

In our literature review, a few studies that focused on finding the optimal structural system using optimization techniques for steel pedestrian bridges. However, the construction industry generally acknowledges the necessity of applying optimization, and our research indicates that cost optimization is recognized as an effective construction industry management tool. Respected reference books support the findings from our literature review; applying cost optimization during the early stages of a project increases its rewards. It is highly beneficial to focus on design functions, construction objectives while simultaneously assessing how the budget can be sustained and standards for quality and performance can be met. The contribution of this study is to present a decision making to help select the best system for the pedestrian bridges considering project priorities, configurations, and site conditions. Furthermore, it will be present the economics of pedestrian bridges according to cost efficiency during the life cycle costing (design, fabrication, and construction) related to the pedestrian bridges systems.

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