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Optimum Design of Double-layer Barrel Vaults by Lion Pride Optimization Algorithm and a Comparative Study

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ABSTRACT

In this article, the newly developed optimization method, so-called the Lion Pride Optimization Algorithm (LPOA), is applied to optimal design of double-layer space barrel vaults. In order to demonstrate the performance of the LPOA, three large-scale benchmark optimization design problems of double-layer barrel vaults are optimized and the results are compared with those of some metaheuristics from literature. The second aim of this article is to solve these examples using three other robust metaheuristic algorithms, namely Artificial Bee Colony (ABC), Cuckoo Search (CS), and Particle Swarm Optimization (PSO). A comparative study of these algorithms shows the suitability of the LPOA for solving real-world practical spatial truss structures.

1. Introduction

A barrel vault is an effective semi-cylindrical form of the roof system, which is widespread for multipurpose facilities including warehouse, rail station, pools, sports center, airplane hangars and community centers as providing a long-span and economical roof with a significant amount of space. Barrel roofs can be used for covering rectangular structures [1]. A barrel vault, typically consists of a single or multiple braced layers of bar elements that are arched in the width direction. However, the barrel vaults usually have uniform cross-sections along their lengths. The shape of the cross-section of a barrel vault may vary along its longitudinal axis. The curvature of a barrel roof is created by a motion movement of a single or multiple layer grid along a space curve which is called a directrix. The directrix can be a circular arc, an ellipse, a catenary, a parabola or a cycloid [2]. Barrel vaults are given different names depending on the way their surface is formed [3]. There are disparate possible types of bracing that can be used in barrel roofs. But theoretically, just fully triangulated barrel vault systems can be analyzed as pin-jointed structures. The barrel vaults, having the quadrilateral or hexagonal types of bracing, must have rigid joints to be stable and consequently, their elements are under bending moments, shear forces and torques.

As a rule, the earlier types of braced barrel vaults were constructed as single-layer structures, but nowadays, double-layer barrel roofs are usually preferred by designers in the construction of long-span and support-free roofs [1,4]. Double-layer barrel vaults have better structural behavior inherently as their architectural forms. The experiments have also shown that large span single layer braced barrel vaults are prone to instability, especially under the action of heavy unsymmetrical loads and that the rigidity of joints can exert an important influence on the overall stability of the structure [5]. The single-layer barrel vaults are mainly under the action of flexural moments, the component members of double-layer barrel vaults are almost exclusively under the action of axial forces and the elimination of bending moments leads to a full utilization of strength of all the elements [3].

Turning to the procedure of optimization, it should be stated that choosing layout variables that satisfy all design constraints and declining the aggregate costs is a grave concern for structural engineers, specifically for sophisticated and complex design problems. Optimization methodologies can be powerful initiatives that offer feasible and economically good solutions for the designers.

Generally, Optimization techniques seek good feasible variable set in order to minimize or maximize single or multiple objective functions systematically considering a predefined search space and a set of constraints. These methods can be divided into two general distinct groups: mathematical gradient-based techniques and stochastic non-gradient approaches. If the objective function of an optimization problem is smooth (i.e., differentiable) and gradient information is reliable, then gradient-based optimization algorithms present an extremely powerful collection of tools for solving the problem [6]. However, in real-world structural design problems, finding the relation between the design variables, loads, and behavioral parameters such as deflections, stresses, failure modes or frequencies may not be possible or it may be difficult to compute. In addition, the implementation success of the mathematical programming methods is intensively depending on good starting point. It should be noted that some mathematical programming

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based methods have been developed for discrete optimum design problems that are not very efficient for obtaining the optimum solution of the large size practical design problems [7–9]. The objective functions of real-world structural design problems are oversensitive, non-convex, unreliable and rough. Hence, gradient-based methods are not efficient for these types of problems. In the last two decades, the researchers have proposed several stochastic methodologies to solve complicated problems. For instance: the Genetic Algorithm (GA) [10] that is conceptualized using the Darwin's natural select theory; the Simulated Annealing (SA) [11] is inspired by the annealing in metallurgy; the Ant Colony Optimization Algorithm (ACO) [12] that mimics the behavior of ants seeking a path between their colonies and food sources; Particle Swarm Optimization (PSO) [13] that is based on social behavior of fish schooling or bird flocking; the Harmony Search (HS) [14] that is inspired by the improvisation process of musicians; the Big Bang Big Crunch (BB-BC) algorithm that is inspired by big bang theory; Artificial Bee Colony (ABC) [15] that is based on the swarm intelligence of honey bees; Cuckoo Search (CS) [16] algorithm that is inspired by life of the cuckoo birds; Charged System Search (CSS) [17] method that imitate the laws of physics and mechanics; Colliding bodies optimization algorithm (CBO) that is inspired by the collision between objects [18]; Teaching Learning Based Optimization (TLBO) [19] that is based on the philosophy of learning by teaching; Mine Blast (MB) algorithm [20] that is based on landmines explosion; Dragonfly Algorithm (DA) [21] that mimics the swarm intelligence of dragonflies; Virus Optimization Algorithm (VOA) [22] that imitates the behavior of viruses attacking a living cell; and Drone Squadron Optimization (DSO) [23] is artifact-inspired method inspired by Drone Squadron in taking earth monitoring. Besides, there is a number of hybrid or modified algorithms that are proposed by researchers such as [24–31].

In the recent decades, different meta-heuristic algorithms have been developed and applied to the solution of structural optimization problems. For instance, Teaching–Learning Based Optimization (TLBO) was used for designing steel frames. Adaptive Dimensional Search (ADS) method was designed for discrete truss sizing optimization [32]. The optimum layout design of multi-span reinforced concrete beams under dynamic loadings was carried out using Ant Colony Optimization (ACO) algorithm [33]. Optimum column layout design of reinforced concrete frames under wind loading is performed by Sharafi et al. [34,35]. The graph theory and the ant colony based algorithm are combined to solve the problems of thin-walled steel sections [36]. Artificial Neural Networks (ANN) was applied to a post-tensioned concrete road bridge design problem [37]. Notably, in the field of size optimization of double-layer barrel vault frames, some studies are carried out earlier by Refs. [3,32,38–40]. Although, the dimensions of structures may be governed stringently by construction requirements, design standards, the purpose of the structure, and/or client demands, topology, shape and size optimization method can be performed concurrently. In accordance with the study of Kaveh et al. [41] this approach should be an effective way in cases when the height of barrel vaults can also be considered as a variable.

This paper utilizes a recently developed nature-inspired metaheuristic algorithm, so-called Lion Pride Optimization Algorithm (LPOA), for size optimization of double-layer barrel vault structures. To further validate the applicability of the LPOA, Artificial Bee Colony (ABC) [15], Cuckoo Search (CS) [16], and Particle Swarm Optimization (PSO) [13] are used to solve the design problems. In these algorithms the bar sections are the variables, and the design limitations are the constraints of the optimization problems. Finally, the discrete search space is a multi-dimensional area, and the number of dimensions is equal to the number of variables, and each variable is selected from the pre-defined list of sections.

The optimization procedure obtains a minimum weight of double-layer barrel roof structures subjected to the AISC-ASD [42] specifications.

The optimization variables are selected from the industrial cross sections provided by American Institute of Steel Construction (AISC) code [43] in the method. Three numerical examples are investigated to verify the robustness of the mentioned technique in finding good optimal solutions for this kind of design problems. The outcomes of the LPOA are also compared to those of some state-of-the-art optimization techniques to illustrate the efficiency of the approach.

The remainder of the paper is organized as follows: the utilized optimization approaches are presented briefly in Section 2; three practical designs of double-layer barrel vault roofs are performed and comparative study of the mentioned optimization approaches are conducted in Section 3; finally, the concluding remarks are derived in Section 4.

Table 1
The LPOA parameters selected in this study.

Parameters	Value
Number of prides	3–7
Lions in each prides	4–7
Male lions in each prides	1–2
Female lions in each prides	3–6
Territory ratio	0.5
Mating probability	0.1
Immigration rate	0.1
Diversification factor	0.1 to 0.00001

Table 2
The steel pipe sections taken from AISC-LRFD code.

Num.	Type	Nominal diameter (in)	Area (in^2)	Moment of inertia (in^4)	Gyration radius (in)
1	ST	1/2	0.25	0.017	0.2608
2	EST	1/2	0.32	0.02	0.2500
3	ST	3/4	0.33	0.037	0.3333
4	EST	3/4	0.43	0.045	0.3224
5	ST	1	0.49	0.087	0.4197
6	EST	1	0.64	0.11	0.4073
7	ST	1 1/4	0.67	0.19	0.5399
8	ST	1 1/2	0.8	0.31	0.6229
9	EST	1 1/4	0.88	0.24	0.5241
10	EST	1 1/2	1.07	0.67	0.7889
11	ST	2	1.07	0.39	0.6045
12	EST	2	1.48	0.87	0.7658
13	ST	2 1/2	1.7	1.54	0.9515
14	ST	3	2.23	3.02	1.1637
15	EST	2 1/2	2.25	1.92	0.9238
16	DEST	2	2.66	1.31	0.7018
17	ST	3 1/2	2.68	4.79	1.3369
18	EST	3	3.02	3.89	1.1349
19	ST	4	3.17	7.23	1.5102
20	EST	3 1/2	3.68	6.28	1.3063
21	DEST	2 1/2	4.03	2.87	0.8439
22	EST	5	4.3	15.2	1.8801
23	EST	4	4.41	9.61	1.4762
24	DEST	3	5.47	5.99	1.0465
25	ST	6	5.58	28.1	2.2441
26	EST	5	6.11	20.7	1.8406
27	DEST	4	8.1	15.3	1.3744
28	ST	8	8.4	72.5	2.9378
29	EST	6	8.4	40.5	2.1958
30	DEST	5	11.3	33.6	1.7244
31	ST	10	11.9	161	3.6782
32	EST	8	12.8	106	2.8777
33	ST	12	14.6	279	4.3715
34	DEST	6	15.6	66.3	2.0616
35	EST	10	16.1	212	3.6287
36	EST	12	19.2	362	4.3421
37	DEST	8	21.3	162	2.7578

ST = standard weight, EST = extra strong, DEST = double-extra strong.