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Hybrid fuzzy-genetic system for optimising cabled-truss structures

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ABSTRACT

This paper demonstrates an application of a hybrid fuzzy-genetic system in the optimisation of lightweight cabled-truss structures. These structures are described as a system of cables and triangular bar formations jointed at their ends by hinged connections to form a rigid framework. The optimised lightweight structure is determined through a stochastic discrete topology and sizing optimisation procedure that uses ground structure approach, nonlinear finite element analysis, genetic algorithm, and fuzzy logic. The latter is used to include expertise into the evolutionary search with the aim of filtering individuals with low survival possibility, thereby decreasing the total number of evaluations. This is desired because cables, which are inherently nonlinear elements, demand the use of iterative procedures for computing the structural response. Such procedures are computationally costly since the stiffness matrix is evaluated in each iteration until the structure is in equilibrium. Initially, the proposed system is applied to truss benchmarks. Next, the use of cables is investigated and the system's performance is compared against genetic algorithms. The results indicate that the hybrid system considerably decreased the number of evaluations over genetic algorithms. Also, cabled-trusses showed a significant improvement in structural mass minimisation when compared with trusses.

1. Introduction

Weight optimisation of structures is a crucial step towards achieving higher structural performance in several engineering fields. Either directly or indirectly, every structural system is designed to meet an optimality criterion, such as the lowest possible weight or cost, minimal maintenance, and maximum reliability.

In robotics and machinery, the design trade-offs inherently include a compromise between fast, accurate, and precise motions. The use of rigid but massive structural parts enhances the precision and accuracy of mechanical systems. Lighter designs, conversely, allows for performing fast large motions and using high speeds and accelerations. In civil engineering, weight optimisation plays an important role in the designing of offshore structures, where it is essential that only a minimum share of the load capacity is engaged by the structure itself. Structural optimisation is also essential in aerospace, naval, and automotive industries, where light structures help reduce fuel consumption.

Lightweight structures research is based not only on material science but also on structural mechanics, processing, and design. The combination of different structural elements and materials is critical to improve the trade-offs between rigidity and weight as it can be noticed in most of modern lightweight structures. These include, for instance, frame supported, air supported, air inflated, cable net, cable-and-strut, geodesic domes, grid shells, and tensile/tension structures [1].

One of the most traditional types of lightweight structures are the so called trusses. These structures have attracted tremendous interest since their members are arranged to transfer external loads through axial forces rather than bending. If buckling does not occur, the cross sectional area of each truss member is equally stressed, therefore the material is used efficiently and lightweight designs are obtained. Trusses present additional features such as low weight, cost, construction time, and low structural density. They also present increased portability, redundancy, deployability, and efficiency in load and mass distribution. Consequently, trusses are among the most commonly lightweight structures used in practice.

With the fast development of tension structures, tensile elements, such as cables and membranes, have been combined with truss structures to form efficient hybrid structures [2,3]. Among tensile members, cables are the most used because the tensile stresses are distributed uniformly over the cross-sectional areas of members and the material is thereby utilised in the most efficient manner. Due to their flexibility, cables have negligible bending stiffness and can develop tension only. Thus, under external loads, a cable will develop the shape that is necessary to support the load by tensile forces alone.

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The combination of trusses and cables is often performed in such a manner that cables are extrinsically positioned and form sharp angles with the truss structure. Common applications of this approach are found in civil engineering, e.g., cable-stayed towers, cable-stayed truss bridges, and roofs. In these applications, the use of extrinsically positioned cables allows changing the directions of the main loads and reinforcing the truss structure.

Despite of its advantages the extrinsic approach has limited applications in engineering fields where the structure must attend rigorous space requirement, e.g., automotive, robotics, aerospace, naval, etc. Usually, in these applications, the structure must be designed within a bounded design space, which is usually fulfilled by the truss structure; consequently, there is not enough space for staying cables. In this light, the concept of cabled-trusses is introduced, i.e., hybrid structures that are formed by the combination of truss members and intrinsically positioned pre-stressed cables.

Cables serve as essential members of cabled-truss structures [4]. Although they are only able to withstand tension forces, they maintain the stability and strength of the structural system, redistribute stresses along the structure, and decrease structural weight in comparison to trusses. The latter can be achieved by replacing truss members with cables, which have lower weight density once that they can be easily built using carbon-nanotube fibres or different materials with high tensile strength.

Planar cabled-truss structures having simple configurations and few members can be solved analytically. However, numerical procedures are required for solving complex cabled-trusses. The use of iterative procedures, e.g., Newton–Raphson method, comprises the evaluation of the stiffness matrix in each iteration until the structure is in an equilibrium state.

The optimisation of discrete structures, such as trusses, cabled-trusses, frames, and grid shells, is of great importance in several engineering branches. Similarly to trusses, lightweight cabled-trusses design aims to obtain optimal mass reduction with minimal losses in stiffness; therefore structural optimisation is essential. Nonetheless, it presents a novel optimisation problem because different structural elements can be combined to achieve optimised solutions. Furthermore, additional design variables are included in the optimisation problem since cables are pre-stressed depending on the initial strain and/or in the cross-section of elements.

Usually, the optimisation of discrete structures can be divided into size, shape, and topology optimisation, where the latter yields more material saving and greater complexity [5]. The optimal design of truss structures has been actively investigated in the last decades, and significant progress has been made in both optimality criteria and solution techniques [6–16].

Size and shape optimisation are mature areas of research that have received considerable attention [17]. Topology optimisation, on the other hand, still faces several challenges [5,15]. This is because topology variables are discrete; therefore, the direct application of the traditional gradient-based optimisation techniques is not possible [15]. The presence of discrete variables in the topology optimisation of discrete structures led to the use of stochastic search methods [18,19], such as simulated annealing [20], evolution strategies [21], particle swarm optimiser [22], ant colony optimisation [23], harmony search method [24], quantum evolutionary inspired algorithms [25], and simple genetic algorithm [26].

The performance comparisons of the most popular stochastic algorithms applied to trusses and frame optimisation are available in [27,28], respectively. The presented results show that the selection of the optimisation technique is sensitive to a large set of issues that depend on decisions and assumptions made when an optimisation model is established for a problem. Notice that new search algorithms emerge and former ones are improved year after year, comprehensive reviews of stochastic search algorithms are available in [29,30]. Whereas recent reviews are available in [31,32].

GAs have been widely employed in the optimisation of truss structures [5,13,16,33]. Hence, GAs were adopted as the basis for the proposed hybrid system. Besides vastly applied in the optimisation of discrete structures, the use of such well established algorithms allows calibrating algorithm's parameters, such as population size, number of generations, and probability of mutation. The parameters adopted in this work were adjusted based on the results from previous researchers, in particular [5,12–15].

Notice, however, that when performing truss topology optimisation, stochastic algorithms tend to have poor computational performance in terms of CPU time [34]. In addition, when compared to trusses, cabled-trusses present a larger number of design variables, thus increasing the computational cost. Furthermore, cables cannot resist compression, leading to a sharp increase in the number of kinematically instable structures during the stochastic search. Also, the solution of the nonlinear equilibrium equations requires the evaluation of the stiffness matrix in each iteration, which also yields high computational cost.

Recent researches have been focusing on improving the cost and efficiency of GAs in discrete topology optimisation by reducing the number of unnecessary calculations [15]. In this sense, two different approaches have been used for decreasing computational time. The first consists in avoiding duplicate calculations [34], whereas the second consists in avoiding the calculation of unstable solutions [12,14,33].

The computational cost of the optimisation process can also be reduced when non-suitable (but not necessarily unstable) individuals are not evaluated. This way, the inclusion of expertise-based rules to identify suitable individuals during the stochastic search represents an attractive strategy to avoid the evaluation of all individuals. Expertise rules can be included in a system by means of fuzzy logic, which simulates a natural way of thinking where linguistic expressed rules are dealt as numerical variables.

In this light, the present work proposes a hybrid system for discrete sizing and topology optimisation of cabled-trusses. The developed system is based on ground structure approach, nonlinear finite element analysis, genetic algorithm, and fuzzy logic. The latter is used to classify and filter the population generated by the GA. The classification identifies the individuals with low survival possibility before the evaluation is performed. These individuals are not evaluated, and the objective function assumes a dynamic penalty value; therefore the number of evaluations is decreased. In addition, since the optimal design of cabled-trusses depends on the structural topology and the corresponding distribution of the element cross-sectional areas and pre-stress, sizing optimisation is also performed by the hybrid system. The proposed system is applied to traditional truss benchmarks that include ground structures with 10 and 15 elements. The results from these analyses are compared against standard GA to evaluate the convergency and efficiency of the proposed hybrid fuzzy-genetic system.

2. Cabled-truss structures

Cabled-truss are formed of cables and triangular bar formations jointed at their ends by hinged connections to form a rigid framework as illustrated in Fig. 1. Although trusses and cabled-trusses are actually three-dimensional structures, most of them can be reduced to planar cases. Such approximation is adopted in this work since it reduces the computational cost and brings a deeper insight of the structure dependences.

Similarly to trusses, the planar cabled-trusses idealization is subject to five main assumptions: (i) all external forces are applied at joints, (ii) joints are considered frictionless hinges without