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Research paper

An integrated beam-plate structure multi-level optimal design framework based on bi-directional evolutionary structural optimization and surrogate model

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ABSTRACT

Lots of endeavors have been made to apply optimization techniques to real design problems for various engineering beam-plate structures, however, due to the limitation of traditional topological form and the difficulty of finding the optimal topology in numerous optional design plans, many beam-plate structure designs are not the optimal solution but only a feasible solution. This paper proposes an integrated optimal design framework for beam-plate structure based on combining bi-directional evolutionary structural optimization (BESO) and surrogate model method, which covers three optimization levels, as dimension optimization, topology optimization and section optimization. BESO is used for topology optimization. In order to deal with beam-plate structures, the traditional BESO method is improved by using cubic box as the unit cell instead of solid unit to construct periodic lattice structure. Requirements for the framework are discussed based on the features of beam-plate structure design process first. The proposed framework consists of automated finite element modeling module, structure optimization module and post-processing module. Usefulness of the designed framework is examined through a cantilever beam structure design.

1. Introduction

There are numerous engineering applications of beam-plate structures. The body of steel bridge, aircraft, ship, submarine and many other large-size steel structures are some examples with different design requirements for which evaluation of mechanical performance is very important. For example, the structural designs of various vehicles usually seek for lightest structural weight to improve the economical performance and decrease the emission level. In general, these thin-walled structures should satisfy the requirements of static strength, dynamic response, buckling strength, deformation, and so on. Thus, it is an important and meaningful task for engineers to control and optimize the mechanical performance of beam-plate structures to design optimal products.

Over the past half century, tremendous efforts of fundamental research have been made in the field of beam-plate structure optimization. Sizing and shape optimizations are two traditional techniques and have been widely employed. Ehlers [1] proposed a procedure to optimize a conceptual ship side structure from a crashworthiness point of view, where the highest energy per mass (E/M) ratio was the optimization objective and a PSO algorithm was used. The optimal solution with the highest E/M ratio can absorb 500 per cent more energy with a weight increase of 18 per cent compared with the initial concept. Elsayed et al. [2] have addressed optimal lay-up and material combination for composite elliptical submersible pressure hull, where the objective is to minimize the buoyancy factor. Klanac and Jelovica [3] presented a concept named vectorization that converts classical scalar optimization formulation which strictly separates the objective from constraints, into a vector-based optimization, transforming constraints into objectives. Based on this concept, they proposed to combine constraints within original a single-objective function to improve the computation efficiency, then implemented the optimization method to minimize weight of a fast ferry and obtained the optimal result that 10.2% better than the referenced design. Um and Roh [4] developed an optimization program based on the Sequential Quadratic Programming (SQP) using C++ programming language and decreased the weight of hatch cover of a deadweight 180,000 ton bulk carrier by about 8.5%. Sobey et al. [5] presented a method combining Navier grillage method and genetic algorithm to produce optimal panels of composite boat hull. Myung-Jin et al. [6] developed a shape-design optimization method for the thermo-elastoplasticity problems that are applicable to the welding or thermal deformation of hull structures, based on the

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modified feasible direction method, which is a gradient-based design optimization algorithm.

Since the paper by Bendsøe and Kikuchi [7], topology optimization has been developed remarkably over the last several decades in both theoretical studies and practical applications [8–12]. By redistributing the material layout and accordingly the load carrying paths, topology optimization has been recognized as one of the most promising techniques in the design of engineering structures. Meanwhile, plenty of technical difficulties highlighted in the rapid development of structural engineering promote the progress of topology optimization theories in turn. Now there exists many approaches of structural topology optimization such as solid isotropic material with penalty (SIMP) [13], evolutionary structural optimization (ESO) [14], bi-directional evolutionary structural optimization (BESO) [15], bubble method [16], topological derivative [17], level-set method [18–20] and phase filed method [21]. Among these approaches BESO is the most representative one. Many examples using BESO demonstrated the ability to find the best topological form, and the optimum usually presents a novel but highly efficient topology in contrast with the traditional topology. This indicates us to apply BESO in optimization of beam-plate structure, but it is found that satisfied results could hardly be achieved by using the conventional solid cubic design domain.

The present work proposes a multi-level optimization framework for beam-plate structure design that combines improved BESO with surrogate model method to achieve structural topology and sizing design, which makes it possible to consider both restrictions related to global dimensions and local changes in the structural topology. Automated finite element modeling (AFEM) technique is introduced to make the design evaluation more accurate and leads to design cycle time and cost savings. Different optimizations based on individual design approaches are conducted to verify the optimization efficiency of the framework. In Section 2, some basic concepts in the proposed framework are introduced. Based on these basic concepts, the proposed method of beam-plate structure optimization is presented in Section 3. In Section 4, a case study is provided to validate this proposed framework. Finally, conclusions are presented in Section 5.

2. Requirements of the beam-plate structure multi-level optimal design framework

This section describes the requirements of a beam-plate structure multi-level optimal design framework based on the nature of the beam-plate structure design practice. Those requirements and features are used as a basis for outlining the main framework of the proposed system.

2.1. Optimization for multiple levels

Generally speaking, the design process of beam-plate structure is determine the general dimension parameters (GDP) firstly, select the topological form and determine the sections of structural members. Naturally the optimization of beam-plate structure should consider three level including dimension optimization, topology optimization and section optimization. It is very important to determine the main dimension parameters because the change of them will cause the change of all downstream works and they have a great influence on design objectives. In practice, the topology optimization and the section optimization are often coupled. As the conventional topological form is concerned, change of stiffener spacing will cause a requirement of changing the section of stiffeners, because if the spacing become smaller than the amount of stiffeners must increase and the section of stiffeners can be smaller - and vice versa. There has been an increasing tendency of applying density-based topology optimization method to obtain the optimal topology directly, thus the coupling between the topology optimization and the section optimization will disappear, and the section optimization can be performed after topology optimization.

2.2. Optimization for multiple load cases

In structural optimization, optimal results are closely related to loads and boundary conditions, and there is a one-to-one correspondence between an optimal solution and the loads and boundary conditions which it applies. The optimal solution of a single load case may not be the optimal solution of other load cases, even not feasible. However, in practice, engineering structures such as ships, aircrafts bear various types of loads, which means the final optimal solution should combine features of all "single load" topologies. It is essential to study structural optimization under multiple load cases for improving practicality. Bruggi and Cinquini proposed a topology optimization method using mixed finite elements, for the design of multi-loaded structures. The method is compatible with the method of moving asymptotes reaching 0–1 and checkerboard-free final designs [22]. Guo et al. investigated robust concurrent optimization of material and structure under unknown-but-bounded load uncertainties, and found that optimal material distributions in microstructures tend to be isotropic and Kagome structure superior to other forms of microstructures [23]. Shi et al. presented an optimization model for obtaining optimal layout of multiple bi-modulus materials systems under multiple load cases (MLC), and investigated the effects of factors including the bi-modulus behavior of materials, the load directions and the weighting schemes of MLC [24].

2.3. Automatic FEA model generation

Undoubtedly, it is essential to raise overall efficiency that FEA model be generated automatically. It is also a common problem that many researchers from various fields have been developing technology such as parametric modeling, object-oriented modeling, and knowledge-based engineering [25].

Basically, the success of structure design will depend on accurate prediction of the loads applied to the structure, and the ability of structure components to withstand those loads. Therefore, besides automatic process of geometry modeling, it is also meaningful of making the determination process of boundaries and loading conditions more automatically. It is well accepted that FEA-based structural optimization problem indicates that the process of finite element modeling should be integrated into the whole optimization process to improve efficiency and enhance practicality. Rooca [26] developed a knowledge-based engineering environment by integrating CAD system and object-oriented programming, which is capable of generating structural and aerodynamic finite element models automatically and thus supporting multidisciplinary design optimization of aircraft structures. Based on knowledge patterns and Visual Basic for Applications (VBA) scripting, Sohaib [27] proposed a parameterized automated generic model in CATIA for aircraft wing structure design, which can generate the finite element mesh automatically and process any change in the shape of wing panels, wing spars or wing ribs. However, it is still difficult to change the structural topology.

2.4. Processing optimal results

The optimal results of FEA-based topology optimization describe all the presenting states of finite elements in design domain, which only provide hints as to how the optimum support structure could look and, thus, need to be "translated" to a realistic design concept. Besides, when FEA-based sizing optimization procedure is done, it would be better if the structure drawings or 3D CAD model can be generated automatically according to the optimal results. This approach enhances work efficiency and consistency. However, it is not easy to cover all the possible CAD tools for various designers or groups. Therefore, the support system should provide a data exchange interface to facilitate designer to obtain CAD models.