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Role of global buckling in the optimization process of grid shells: Design strategies

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ABSTRACT

The aim of the paper is to propose a new approach for the optimization of grid shell structures based on a mixed sizing/topologic process, which specifically accounts for the global buckling behavior. The approach consists of merging a sequence of sizing and topological optimization processes where local and global buckling phenomena are opportunely introduced. Indeed, in addition to the removal of some members and the increase/decrease of the cross section size of the remaining ones, the proposed approach accounts for the possibility to convert some of the elements composing the grid shell structure, generally trusses, into beam elements with the aim of having an optimized solution also with respect to the global buckling behavior. The selection of the truss members to convert into beams is made by considering two different strategies presented in detail in the paper. Numerical analyses referring to some case studies derived from the current literature are developed by considering the proposed approach and a traditional sizing/topologic mono objective approach. The results obtained from the numerical analyses clearly underline the reliability of the proposed approach and its efficiency in comparison to traditional approaches of structural optimization.

1. Introduction

The term *grid shell* refers to structures which have the shape and strength of a double curvature shell, but which are composed of a single or double grid layer instead of a solid surface. Pier Luigi Nervi and Edoardo Torroja were probably the first engineers who successfully combined *grids* with *shells* in large roof structures. More recent fascinating examples of the use of grid shells in the form of canopy structures are those of the Smithsonian Museum and the British Museum, where it clearly emerges the complete merging between *shape* and *structure*.

Just the connection between shape and structure represents an important peculiarity to consider in the design process of grid shells, where structural optimization approaches finalized to obtain efficient and light solutions in terms of architectural and structural requirements are currently used.

Indeed, the structural optimization is a process generally aiming to the search of the optimal configuration (shape optimization), optimal cross sectional dimensions (sizing optimization) and optimal connectivity of structural components (topology optimization). This process involves the optimization of some objectives, particularly in terms of minimal weight and design constraints, which often include material volume, displacements, stiffness, stress and buckling loads, etc.

The studies available in the current literature propose new algorithms and techniques for the optimization of structures. In particular, they both concern the process of form-finding and the process of sizing/topologic optimization. In Refs. [1–3] numerical form-finding techniques based on the force density method and the dynamic relaxation method are applied to weightless systems by setting the shape on the basis of the level of internal pre-stress and boundary support conditions.

In Refs. [4–6] techniques based on the use of genetic algorithms for the structural optimization are presented: here the attention is mainly focused on the parameters to account in the minimization process (bending moments, stresses, deflection, weight, etc.).

Innovative approaches for the optimal design of grid shell structures based on the combination of form-finding and sizing/topologic optimization techniques have been recently proposed. In [7] a two-phase design approach of grid shells carried out by combining form-finding followed by a refinement of the grid configuration is presented. The numerical applications presented in the study clearly show the potentialities of this approach with respect to traditional ones based on the use of form finding techniques or optimization strategies separately applied. In [8,9] an efficient optimization approach obtained by combining form finding, sizing optimization and topologic optimization

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strategies throughout a multi-level process where the design variables and the constraint conditions are opportunely selected, is proposed. In the study the authors underline the potentialities in combining different optimization strategies and, at the same time, they also emphasize the importance in managing the design parameters in terms of variables, constraints and objective functions of the mathematical optimization problem.

In this context, it is important to underline that the research of light structural solutions could lead to grid shell structures particularly susceptible to local and global buckling phenomena ([10–13]). This requires to introduced in the structural optimization process these phenomena by opportunely treating them as additional constraint conditions and/or objective functions.

The present paper aims at proposing a new approach for the optimization of grid shell structures based on a mixed topologic/sizing process, which specifically accounts for the global buckling behavior. Indeed, in addition to a sequence of sizing and topologic optimization processes, the proposed approach accounts for the possibility to convert some of the elements composing the grid shell structure, generally trusses (i.e. characterized by forces and deformations along the axial direction only), into beam elements (i.e. including also the bending component) with the aim of having an optimized solution also with respect to the buckling behavior. The selection of the truss members to convert into beams is performed by considering two different strategies here presented in detail.

Numerical analyses referring to some case studies derived from the current literature are reported in the paper in order to assess the reliability of the proposed approach and its ability in providing lighter structural solutions in comparison to the ones derived from traditional optimization approaches.

2. Proposed approach and strategies

The structural optimization of grid shells is often influenced by local and global buckling phenomena, which affect the design process and, at the same time, it requires the development of nonlinear second order analyses. Global and local phenomena of instabilities are a central theme in the mechanics of structures as testified by many historic contributions providing valuable theoretical treatments of the problem, among them ([10,14–16]) and also by more recent research works which have specifically treated the interaction between different equilibrium paths because considered, in some cases, a cause of critical load reduction and imperfection sensitivity ([17,18]).

Within an optimization design process, a common approach consists in performing the global buckling check at the end of an optimization process and, generally to increase the cross section size of members until the buckling check is satisfied. This approach could lead to oversized solutions which completely loose the efforts and advantages of the structural optimization process.

The approach proposed in this paper consists of including the buckling within the structural optimization process with the aim of having an optimized solution also with respect to the global buckling phenomenon. In particular three strategies are analyzed.

The first named *sizing/topologic mono objective* (STMO) is based on a sequence of sizing/topologic optimization phases where the global buckling check is also performed (Fig. 1a) and truss elements are assigned to the canopies.

The other two strategies are based on the idea to convert some of the truss elements of the grid shells structures, into beams until the global buckling check is satisfied. The conversion of these elements has the objective to obtain light canopies while avoiding global buckling phenomena: indeed, beam elements provides a bigger stiffness to the structure, preserving it from global buckling phenomena with lower sections, compared with the use of truss elements. On the other hand, beams elements are more demanding from a constructive point of view, because they require rigid nodes. These considerations lead the authors to seek solutions that would optimize the weight of the structure together with the number of beam elements to be used.

In particular, the first strategy, named *mono objective buckling loop, MOBL*, consists of including into the optimization process a loop specifically developed on the basis of the global buckling behavior as shown in the flowchart of Fig. 1b. The flowchart underlines that, after the first phases of sizing and topological optimization, which are typical of a traditional optimization approach, a sub-process internal to the global optimization process and denoted in the following as *buckling loop*, is specifically introduced. The *buckling loop* converts some of the truss elements composing the initial configuration of the grid shell into beam elements. The selection of the members to convert into beams is based on the shape of the buckling mode. To this aim, during the application of the buckling loop, a second order analysis of the grid shell is performed in order to evaluate the buckling factor BF (i.e. the ratio between the buckling load and the external applied load) and, if necessary, the corresponding shape of the buckling mode. In particular, if $BF > 1$, i.e. the grid shell is safe with respect to the global buckling, the buckling loop is not performed or it is stopped. On the contrary when $BF < 1$ the buckling loop activates and an exam of the shape of the buckling mode is performed for selecting the trusses to convert into beams. Indeed, this exam aims at pinpointing the nodes of the grid shell characterized by disproportionate out of plane displacements with respect to the average value of displacements of all the nodes of grid shell (Fig. 2). In this case, the subroutine characterizing the *buckling loop* provides to convert the truss elements of the grid shell that just converge in these nodes into beams elements (Fig. 2). A subsequent second order analysis is developed by considering the updated scheme of the grid shell and a check on the BF is performed again. The buckling loop continues until $BF > 1$.

The second strategy, named *multi objective buckling, MUOB*, is shown in Fig. 1c. It consists of adopting a multi objective approach where the global buckling is introduced as an additional constraint of the optimization process and the number of truss elements to convert into beams (n_B) is introduced as a further objective function to minimize together with the weight. Here the number of the elements to convert into beams is also treated as an additional variable of the optimization problem without introducing the buckling loop.

In the following sections the proposed strategies are compared and their effectiveness in guaranteeing light and safe structural solutions are discussed with reference to some case studies.

3. Numerical analyses

The numerical analyses here presented aim at showing the reliability of the proposed optimization strategies and their ability in providing lighter structural solutions in comparison to strategies based on common optimization approaches. In particular, considering case studies derived from the current literature, the numerical analyses are here developed through the commercial software Karamba ([19]), a finite element plug in developed for Grasshopper [20] and fully embedded in the 3D modelling software Rhinoceros [21]. The use of this software allows to interactively calculating the response of three dimensional structures by considering the parametric environment of Grasshopper. A further important peculiarity of this software is the possibility to introduce user-subroutines specifically developed for the accounted problem. This peculiarity has been used in the present paper where subroutines devoted to pinpoint the members to convert into beams on the basis of the buckling mode have been developed and introduced into the optimization process (buckling loop).

The numerical analyses are performed firstly by considering the STMO approach in order to emphasize the influence of the global buckling on the structural weight of solutions obtained through a sequence of sizing/topologic optimization phases. Then, the proposed approach is considered by selecting the other two accounted strategies (MOBL and MUOB).