Influence of the evolutionary optimization parameters on the optimal topology

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Abstract Topological optimization can be considered as one of the most general types of structural optimization. Between all known topological optimization techniques, the Evolutionary Structural Optimization represents one of the most efficient and easy to implement approaches. Evolutionary topological optimization is based on a heuristic general principle which states that, by gradually removing portions of inefficient material from an assigned domain, the resulting structure will evolve towards an optimal configuration. Usually, the initial continuum domain is divided into finite elements that may or may not be removed according to the chosen efficiency criteria and other parameters like the speed of the evolutionary process, the constraints on displacements and/or stresses, the desired volume reduction, etc. All these variables may influence significantly the final topology.

The main goal of this work is to study the influence of both the different optimization parameters and the used efficiency criteria on the optimized topology. In particular, two different evolutionary approaches, based on the von Mises stress and the Strain Energy criteria, have been implemented and analyzed.

Both approaches have been deeply investigated by means of a systematic simulation campaign aimed to better understand how the final topology can be influenced by different optimization parameters (e.g. rejection ratio, evolutionary rate, convergence criterion, etc..). A simple case study (a clamped beam) has been developed and simulated and the related results have been compared. Despite the object simplicity, it can be observed that the evolved topology is strictly related to the selected parameters and criteria.

Keywords: Topology optimization, Evolutionary optimization, rejection ratio, FEM, efficiency criteria.

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1 Introduction

The improvements in the design of structural components are often reached by an iterative approach driven by the designer experience. Even if this represents a key aspect of the design process, an approach that is completely based on experience, usually, can lead to only marginal improvements and would take quite a long time. A complementary approach is what makes use of structural optimization methods [1,2] to determine the optimal characteristics, topology and/or shape of an object.
In the recent years, structural optimisation has considerably developed and the interest concerning its practical applications is steadily growing in many engineering fields [3-8]. Of course, the improvements of the information technology tools have strongly contributed to the spreading of the numerical analysis methods, like FEM or BEM, which can be effectively used during the optimization process of a structure. In the past, many research activities related to the optimization methods were focused primarily on mathematical aspects of the problem, trying to adapt the available analytical and numerical methods to solve particular structural problems. These kinds of problems, in fact, are quite difficult to solve making use of non-convex functions with several variables (continuous and discrete). Practical applications of these optimization methods usually forces the designer to simplify the problem, often dramatically, with a consequent lost of reliability.
Therefore, in the engineering field, the need for new optimization procedures (alternative to classic mathematical approaches) has arisen during years. These alternative approaches would allow maintaining some generality and accuracy in the description of real complex problems, but leading to solutions reasonably similar to those considered rigorously optimal. Consequently, since the early 1990s, different new optimization methodologies, based on numerical approaches [3, 8, 9], have been proposed. In this scenario, the Evolutionary Structural Optimization (ESO) has become one of the most interesting and known technique [6, 10, 11]. Following the ESO approach, the optimal solution is searched basing on heuristic rules. Unlike traditional methods, the evolutionary strategy has shown a high degree of efficiency for different typologies of structural problems [11]. The solutions found using the ESO approach, however, might be influenced by the chosen optimization parameters [10, 11]. Although several papers are found in literature concerning the ESO approach, to the authors knowledge, much little information is available regarding the effect of the parameters on the optimal solution.
In this work, it has been investigated how the main control parameters, used in an evolutionary optimization process, can affect the result. One of the main advantages of the proposed approach concerns the comparison between two of the most commonly used efficiency criteria. The goal is to provide useful guidelines that can lead designers to obtain the best result for every (particular) optimization problem.

2 Evolutionary Structural Optimization

The ESO method represents one of the most efficient and easily implemented approach. The working principle of the evolutionary technique requires to gradually eliminate parts of inefficient material from an assigned domain. In this way, the topology of the structure evolves toward an optimal configuration. The initial domain is typically divided into Finite Elements (FE) and the removal of material is based on particular efficiency criteria. An evolutionary optimization procedure is generally structured as follows [12-14]. At first, the whole domain is meshed using finite elements; then the boundary conditions (loads and constraints) are imposed and a numerical FEM analysis is performed. As soon as the solution is found, the obtained numerical results are sorted on the basis of the chosen efficiency criterion (e.g. von Mises stress, strain energy, displacement, etc..). The values of the chosen parameter of each finite element are then compared with a reference value; if the FE value is lower than the reference one, the finite element is removed. The reference value is usually a percentage of the maximum parameter value found in the structure. As an example, if the von Mises stress efficiency criterion is used, for each finite element the following inequality is checked:

$$\sigma_j^{VM} \leq RR_i * \sigma_{max}^{VM} \qquad (1);$$

where:

- σ_j^{VM} is the von Mises stress of the j-th element;
- $RR_0 < RR_i < RR_f$ is the Rejection Ratio during the i-th iteration;
- RR_0 and RR_f are, respectively, the initial and final Rejection Ratios;
- σ_{max}^{VM} is the maximum value of the von Mises stress calculated in the structure at the i-th iteration.

As soon as all elements that verify the inequality (1) during the i-th iteration are removed, a steady state is reached. Consequently, the rejection ratio must be increased to further improve the structure. It can be done according to the following formulation [12,14]:

$$RR_{i+1} = RR_i + ER;$$

where ER represents the Evolutionary Rate.

So that, a new FEM analysis is performed, the von Mises stress values are updated and all the finite elements verifying the efficiency criterion (1) are removed. The procedure is recursively repeated and it stops as soon as the convergence criterion [12, 15] is verified (e.g. when the final value of the rejection ratio, RR_f, is reached or the Maximum Reduction of Volume, MRV, is obtained). The initial rejection ratio is usually defined in the range $0 < RR_0 < 1\%$ but, in some cases, values higher than 1% can be considered to avoid absence of elements to be removed (since the inequality (1) is not verified). The ends values (initial and final) of the rejection ratio are usually empirically defined basing on the experience of the designer. A suitable choice of these values [11, 15] can assure a progressive removal process of the elements.

3 Implementation of the procedure

In this study, two different efficiency criteria, based respectively on the von Mises (VM) stress and the Strain Energy (SE) [9 - 11], were investigated. In the first case, as described in the previous section, the elements removal is based on the value of the von Mises stress of each element, compared with a percentage of the maximum stress value, σ_{max}^{VM}, calculated in the domain. Through this approach, a homogeneous equivalent stress level structure can be obtained (uniform strength structure).
The approach based on the second efficiency criterion, instead, removes the elements having the lowest values of strain energy.
Both optimization procedures have been implemented using the Ansys Parametric Design Language (APDL) and the Ansys software as finite element code.
In order to ensure a more gradual evolutionary process, a new control parameter, called RER (Removed Element Rate), has been introduced. The RER parameter takes into account the number of elements removed at each iteration. In particular, if before reaching the steady state of the i-th iteration, the number of removed elements exceeds the value RER, the iteration is interrupted, the rejection ratio is updated and a new iteration starts. If the rejection ratio value is erroneously too large, the use of the new parameter avoids to remove too much material during a single iteration and, consequently, it ensures more accurate and reliable results. Independently from the efficiency criterion, the optimization procedure is structured [16-17] as shown in Figure 1.

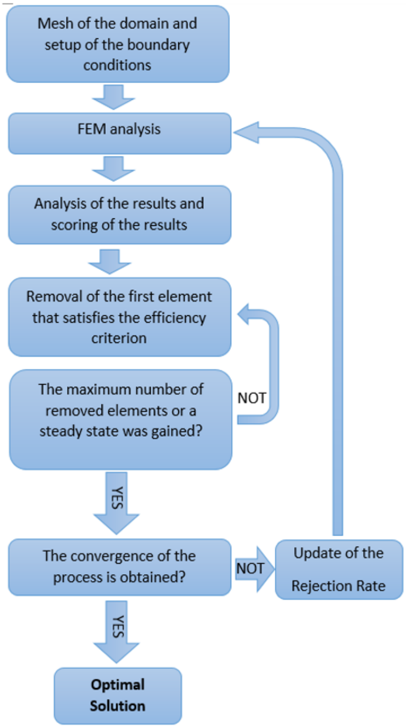

Fig. 1 Workflow of the implemented ESO procedure

4 Case Study

In order to better understand the influence of the described parameters on the final topology, a clamped steel beam has been used as a case study. A vertical load of 100 N has been applied to the free end. The main dimensions and the FEM model (meshed with 8-node brick elements) of the beam are shown in Figure 2.

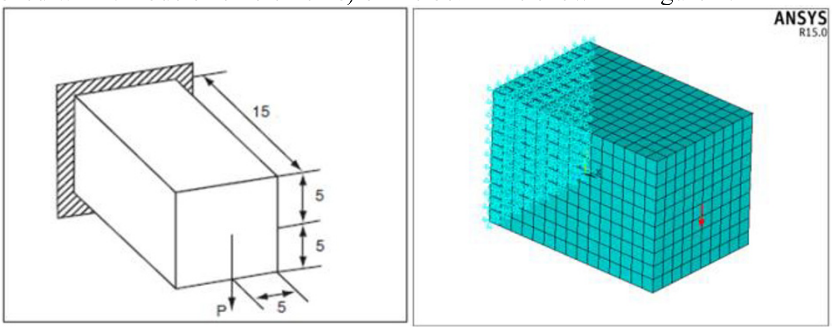

Fig.2 Dimensions (left) and FEM model (right) of the case study.

Table 1 – Range values of the main optimization parameters.

	Efficiency Criterion	
Parameter	**von Mises Stress**	**Strain Energy**
Initial Rejection Ratio – R_0	1% ÷ 6%	1% ÷ 6%
Final Rejection Ratio - Rf	5% ÷ 30%	5% ÷ 30%
Evolutionary Rate - ER	0.5% ÷ 2%	0.5% ÷ 2%
Maximum Reduction of Volume - MRV	60%	60%
Removed Elements Rate - RER	10 ÷ 20	10 ÷ 20
Number of Finite Elements	1500 - 3920	1500 - 3920

Table 1 shows the values ranges of the main parameters for a given 60% of MRV. According to Table 1, a deep investigation has been carried out aimed to find the influence of the described parameters on the final topology. In the following, the main interesting results will be highlighted and discussed.

5 Results

Figure 3 shows the results obtained using the von Mises efficiency criterion with different values of ER (1% - 2%) and without any check on the number of elements removed at each iteration (no RER control imposed).

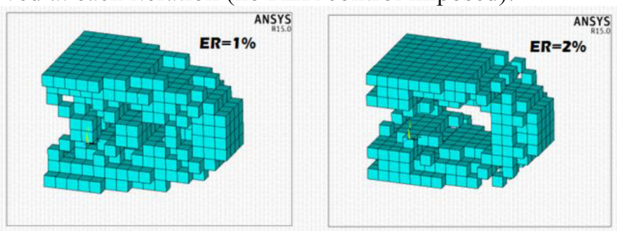

Fig. 3 – VM criterion: influence of the ER parameter on the optimized solution.

Introducing the RER parameter in the VM efficiency criterion, for a given constant value of ER (equal to 1%), different results have been obtained. In particular, figure 4 shows how the optimal topology is remarkably affected when the RER parameter changes from 10 to 20.

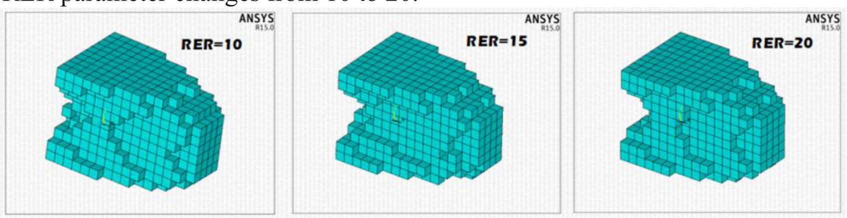

Fig. 4 – VM criterion: influence of the RER parameter on the optimized solution

Figure 5, instead, shows that using the VM efficiency criterion, the final topology slightly changes by varying the mesh size.

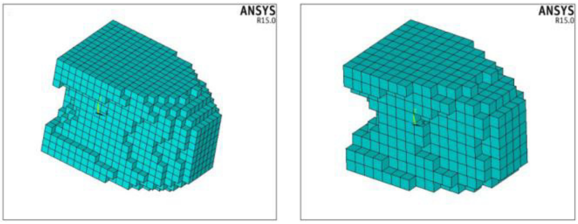

Fig. 5 – VM criterion: influence of the mesh size on the optimized solution

Finally, the plot in figure 6 shows that the final rejection ratio (RR_f) does not affects considerably the maximum von Mises stress value while, on the contrary, it has a significant influence on the minimum value on the optimized structure.

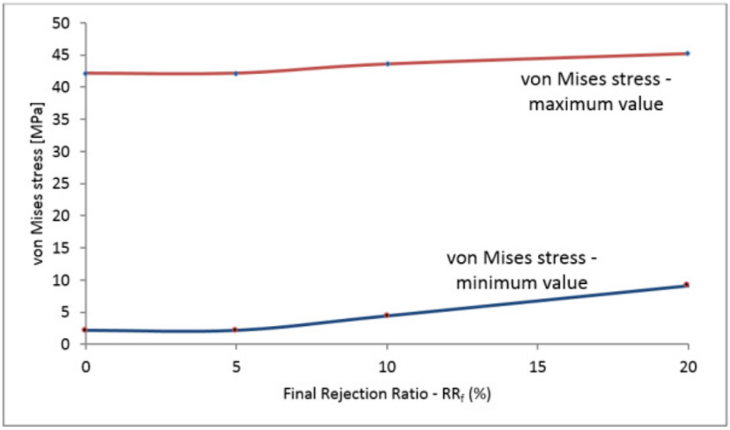

Fig. 6 – VM criterion: influence of the RR_f on the von Mises stresses

Results of the optimization process based on the strain energy criterion are influenced in a similar way with respect to the von Mises stress criterion. Figure 7 shows how the RER parameter affects the optimal topology obtained using the SE efficiency criterion. These results have been obtained considering constant values of RR_0 (1%) and ER (0.5%).

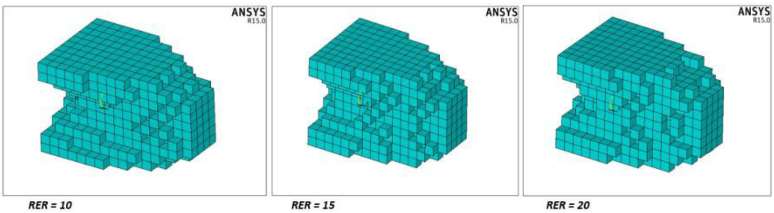

Fig. 7 – SE criterion: influence of the RER parameter on the optimized solution

Moreover, a comparison of the optimized structures obtained with both the criteria is shown in figure 8. One can notes many details that differentiate the optimal topologies.

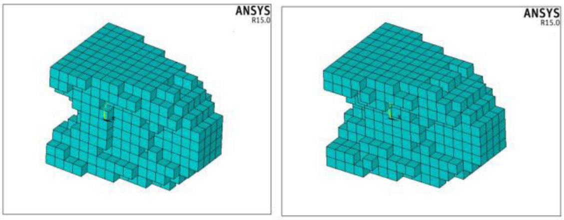

Fig. 8 – Optimized structures using the von Mises (on the left) and the Strain Energy (on the right) criteria

Finally, as it can be noticed from figure 9, the criterion of the strain energy allows to obtain higher volume reductions than the von Mises stress criterion for a given value of the final rejection ratio.

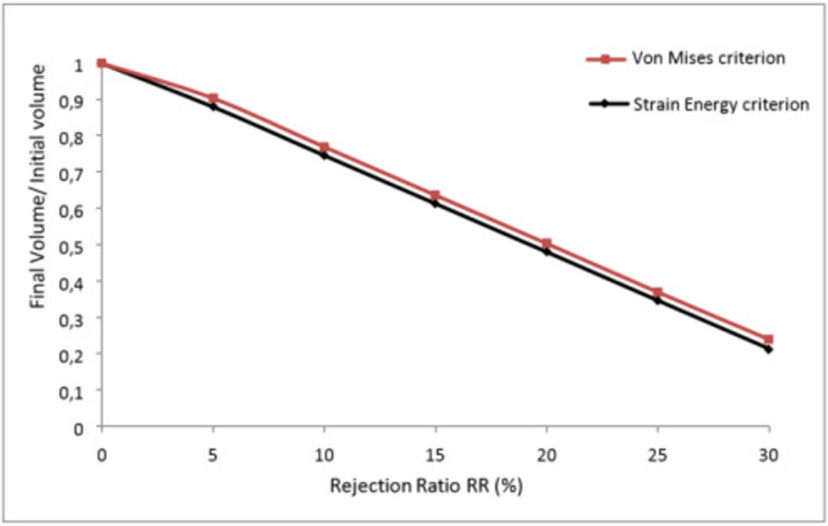

Fig. 9 – (final volume/initial volume) vs final rejection ratio.

6 Conclusions

Topology optimization methods allow to obtain high-performance structures with significant reductions in overall dimensions and masses. In this scenario, the ESO method represents one of the most effective approach to solve large-scale topological optimization problem. The designer, however, is not always able to choose a priori the most suitable parameters set of the ESO optimization process to obtain the best result in the shortest time. In this work, two different efficiency criteria, commonly used in the evolutionary optimization processes, have been investigated. In particular, the von Mises stress and the strain energy criteria have been implemented and a systematic numerical campaign has been performed aimed to better understand how the optimization parameters can affect the ESO-based solutions. In this contest, a new parameter, called RER – Removed Elements Rate, has been introduced by the author for the first time. The obtained results have shown the remarkable influence of the efficiency criteria on the optimal topology in terms of material distribution and volume reduction. Moreover, the new parameter RER allows a more accurate control of the elements removal process and a better solving of the optimization problem. The study can provide useful guidelines for a better understanding and foreseeing of the results of an ESO-based optimization process, so contributing to a larger spreading and use of this methodology during the design of high-performances structures.

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