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Fail-safe structural design using a two-level parallelization scheme

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Abstract

This paper presents an efficient parallel implementation of topology optimization of continuum structures considering the local loss of stiffness due to material failure. Considering such a loss of stiffness, we can obtain operable designs after faults, providing fail-safe structural designs minimizing safety risks. We use a local model of failure removing the material stiffness in patches with a fixed shape, whereas we consider the damage scenarios using a Kreisselmeier-Steinhauser (KS) function to approximate the non-differentiable max-operator in the min-max formulation of the optimization problem minimizing the worst-case performance. The analysis of continuum structures using this fail-safe formulation is a computational challenge due to the need for solving as many finite element problems as damage scenarios. We solve such damage scenarios using a distributed memory conjugate gradient solver preconditioned by an algebraic multigrid (AMG) method. Inter-node communications drastically deteriorate the solver performance due to network latency. Thus, we propose a two-level parallel processing scheme using intra-node communications for solving the damage scenarios and inter-node communications for computing the approximation of the min-max formulation avoiding bandwidth problems. We evaluate the performance and scalability of the proposed methodology showing good performance and scalability.

Keywords: parallel computing, fail-safe, topology optimization, multigrid methods

1 Introduction

Topology optimization aims to find the optimal distribution of material within a design domain by minimizing a cost function subjected to a set of constraints. It is a powerful tool for engineers and scientists providing innovative and high-performance conceptual designs at the early stages of the design process without assuming any prior structural configuration. However, these designs often resemble a statically determined structure in the minimum compliance problem for solid mechanics [1], being very sensitive to local failures due to the lack of redundancy. Fail-safe design philosophy allows us to obtain structural designs operable after faults minimizing safety risks [2].

Topology optimization of fail-safe structures presents serious computational challenges even for academic problems. We use a local model of failure removing the material stiffness in patches with a fixed shape, whereas we consider the damage scenarios using a Kreisselmeier-Steinhauser (KS) function to approximate the non-differentiable min-max formulation of the optimization problem minimizing the worst-case performance. We have to perform as many finite element analyses (FEA) as damage scenarios for each topology optimization iteration. Therefore, the total number of FEAs for obtaining the fail-safe design can be considerably high. Besides, the intensive use of inter-node communications can degrade significantly the performance of the iterative solver in distributed memory computing systems [3, 4]. We propose a two-level parallel scheme for the efficient analysis of the damage scenarios considering the topology of the network. We create a per-node communicator for intra-node communications and an inter-node communicator for sharing the required information between the subdomains of the computing nodes. The proposal allows us to avoid bandwidth problems degrading the performance and the efficient use of the computational resources available for solving the fail-safe problems.

The paper is organized as follows. We devote section 2 to the presentation of the basis and theoretical background of the fail-safe approach. Section 3 shows the results using the proposal scheme. Finally, section 4 presents the conclusion and contribution of the presented work.

2 Methods

We adopt the density-based approach to describe the material distribution in the minimum compliance topology optimization problem. In particular, we use the formulation of the Solid Isotropic Material with Penalization (SIMP) method, where the design variables $0 < \rho \leq 1$ are the densities penalizing Young's moduli of finite elements as follows

$$E = E_{min} + (E_0 - E_{min}) \cdot \bar{\rho}^p, \tag{1}$$

where p>1 is the penalization power, E_0 and E_{min} are Young's modulus of stiff and soft material, respectively, and $\bar{\rho}$ is the regularized and projected density using the density filter and the parametrized projection function proposed by Xu et al. [5].

Following [1], we model the local material failure modifying the stiffness as

$$E_e^i = \begin{cases} E_0 & if e \in \Omega \setminus P^i \\ E_{min} & if e \in P^i \end{cases}, \tag{2}$$

where $P^i \in \Omega$ is the patch modeling the material failure as shown in the red bounding boxes of Figure 1.

Assuming that the uncertainty related to the occurrence of local failures can be represented by an appropriate set of N patch removal scenarios, we formulate the topology optimization of fail-safe structures as a scenario-based problem where every instance of local failure is included as a worst-case formulation of minimum compliance as follows:

$$\begin{aligned} min_{\bar{\rho}} \quad f(\bar{\rho}) = max_{i=1,\ldots,N} f^i(\bar{\rho}) = max_{i=1,\ldots,N} F^T U^i(\bar{\rho}) \\ s.t. \quad K(\bar{\rho} \vee E^i) U^i(\bar{\rho}) = F \\ V(\bar{\rho}) < V^T, \bar{\rho} \in [0,1] \end{aligned}, \tag{3}$$

where V^T is the target volume.

Due to the problem (3) is non-differentiable, we approximate the max-operator in the objective function by the KS function as follows:

$$\begin{aligned} min_{\bar{\rho}} \quad f(\bar{\rho}) = log\left(\sum e^{\gamma f^i(\bar{\rho})}\right)\gamma \\ s.t. \quad K(\bar{\rho} \vee E^i) U^i(\bar{\rho}) = F \\ V(\bar{\rho}) < V^T, \bar{\rho} \in [0,1] \end{aligned}, \tag{4}$$

where γ is a regularization parameter in the KS.

Figure 1 shows the flowchart of the proposed parallel approach. We divide the problem into several subdomains to calculate the recursive stages of the topology optimization method. We use computing buffers to perform the FEA considering the damage scenarios. These buffers provide flexibility to the implementation allowing us to decouple the resources and the problem to solve [6]. We have to remark that the computing buffers only use the computational resources of their node. This computation grouping the threads in the physical node ensures that the FEA only use intra-node communications, which are much faster than inter-node communications using Ethernet/Infiniband. We perform the rest of the computation using the master node, including regularization filter, density projection, sensitivity calculation, and density update using MMA.

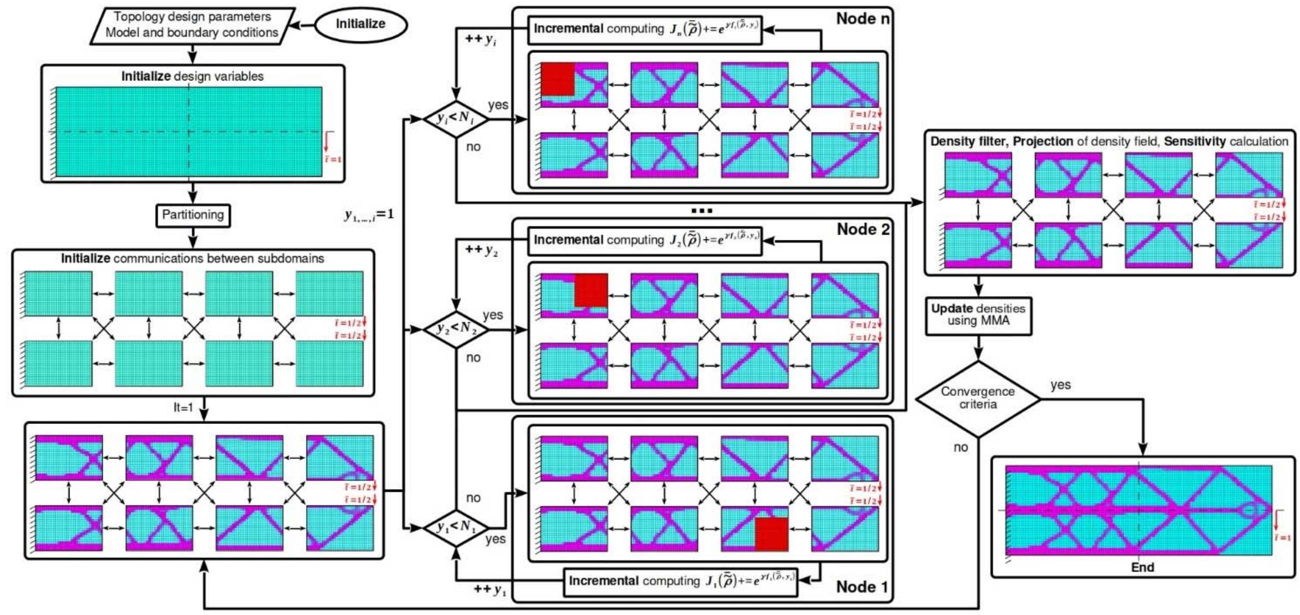


Figure 1: Flowchart of the distributed density-based topology optimization of fail-safe structures.

We also adopt the two-level parallelization scheme proposed in [7]. Such a parallelization scheme groups MPI communication for solving FEAs, and then minimizes communications by only sharing information between subdomains for computing the objective function. We use this scheme groping the computing threads into physical nodes. The underline idea is to minimize the use of inter-node communications. Figure 2 shows the MPI communication groups minimizing the communications between physical nodes.

3 Results

We evaluate the benefits and limitations of the proposed parallel implementation of density-based topology optimization for fail-safe structural designs. We use the cantilever experiment shown in Figure 3(a) for the evaluation, where we can find the geometric configuration, boundary conditions, and the set of damage cases. We model the uncertainty related to the occurrence of local failures using the set of N=10 removing material patches (red bounding boxes). We configure such fail cases allowing load paths between the application of forces and the nodes with restricted motion.

We use a mesh of 1920x640 quad elements giving rise to a system of equations of 2462722x2462722 unknowns for the FEA of the damage cases. We use a radius of 3.5 times the width of the quad elements for regularizing the density field using the density filter. We use $E_0=1$ and $E_{min}=10^{-9}$ for the material penalization of Young's modulus of stiff and soft material and p=3 for the penalization power of (1). We use an algebraic multigrid (AMG) for preconditioning the distributed conjugate gradient solver. The AMG preconditioner uses a strength threshold of 0.5 for the coarsening, a null truncation factor for constructing the interpolation operator, and an HMIS algorithm for parallel coarsening.

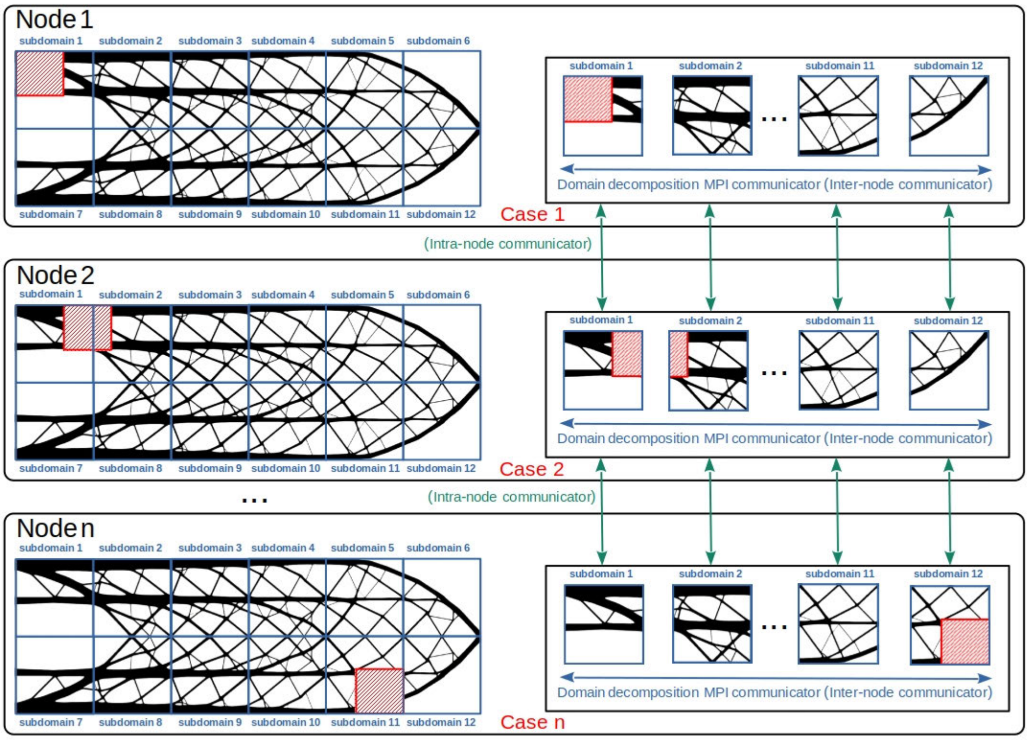
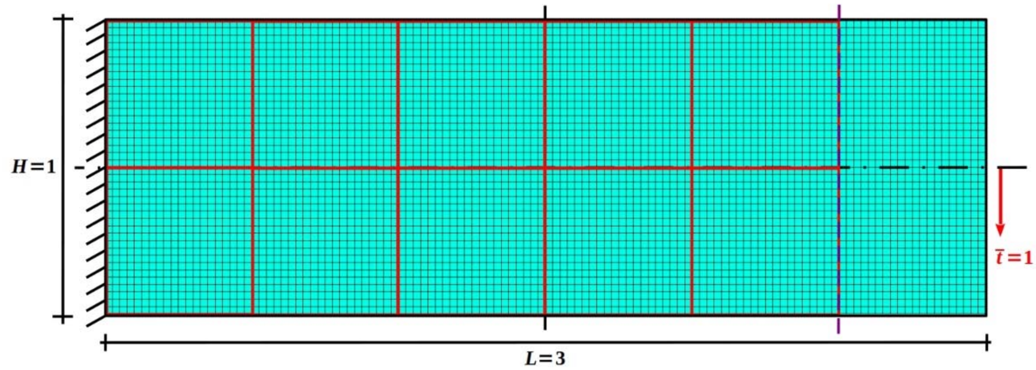


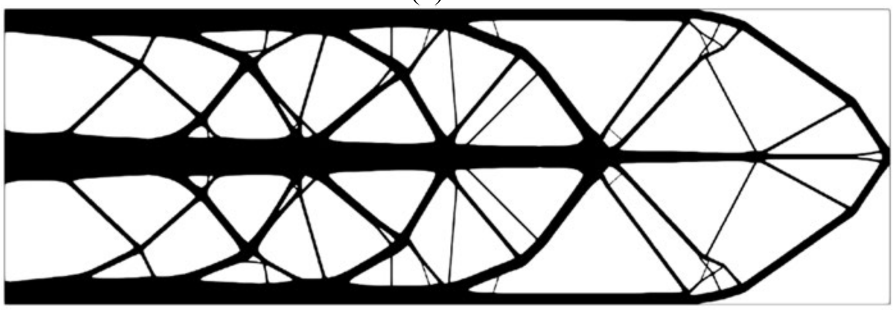
Figure 2: Two-level parallel approach for topology optimization of fail-safe structures.

We run the experiment using the AMD Rome nodes of the French TGCC (Très Grand Centre de Calcul) supercomputer infrastructure at CEA (Commissariat à l'Énergie Atomique). Such a supercomputing infrastructure has the partition Rome for regular computation with 2292 nodes with 2x64 AMD Rome@2.6Ghz (AVX2) and up to 256GB of RAM per node. The computing nodes are connected through an EDR InfiniBand network in a pruned FAT tree topology. This high throughput (100GB/s) and low latency network are used for I/O and communications among nodes of the supercomputer.

We evaluate the strong scaling for the cantilever experiment using different computational resources. Figure 3(b) shows the final fail-safe design of the cantilever experiment configuring the set of local failures specified in Figure 3(a). We run 300 iterations of the topology optimization approach showing the evolution of the objective function in Figure 4(a). We use a different number of nodes to solve the topology optimization of fail-safe structures. In particular, we solve the fail-safe cantilever experiment using one, four, five, and ten computing nodes. Figure 4(b) shows the wall-clock time for the topology optimization of fail-safe structures using different resources. We can observe that we obtain a significant benefit incorporating new computing nodes with the proposed approach.

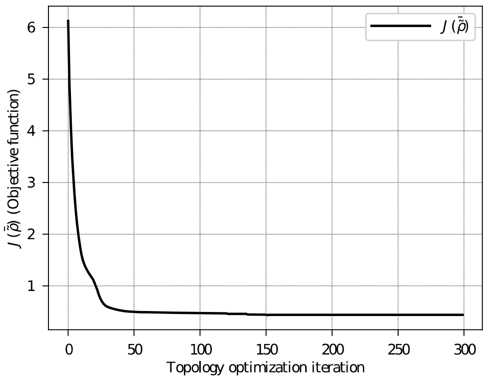


(a)

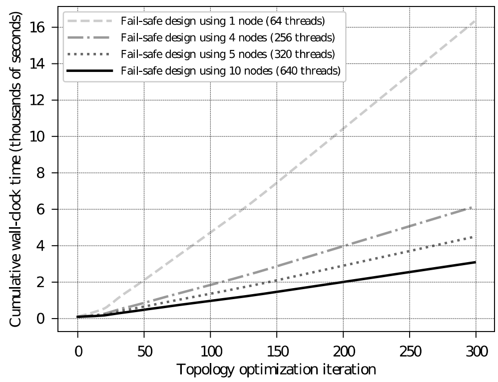


(b)

Figure 3: Cantilever experiment: (a) geometric configuration, boundary conditions, and patch removal configuration (red bounding boxes), and (b) fail-safe design structural design.



(a)



(b)

Figure 4: Cantilever experiment: (a) geometric configuration, boundary conditions, and patch removal configuration

4 Conclusions and Contributions

We have presented an efficient parallel implementation of topology optimization of continuum structures for fail-safe design. Assuming the simplified local damage model of [1], we introduce a two-level parallelization scheme considering the topology network. The underline idea is minimizing inter-node communications using Ethernet-Infiniband, which degrades the computing performance due to network latency. We achieve this goal by grouping the computational nodes by the criteria of the tasks in which they are required. Besides, we increase the flexibility and adaptability of the framework using the computational nodes as computing buffers to perform the FEA considering the damage scenarios. This scheme allows us to decouple the distributed implementation of the topology optimization problem of fail-safe structures. We evaluate the performance and scalability of the proposal using different computational resources. In particular, we use a different number of computing cores and distributed computing hosts, showing good performance and scalability for up to ten computing nodes and hundreds of computing threads.

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