A Study on Proportional Topology Optimization for Nonlinearities Material with Cyclic Load

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Abstract: This research proposes a proportional technique for updating an element density value for the topology optimization process. Fully stress design criterion for the topology optimization was combined with being one factor into the proportional function for updating the density value. An internal energy density was focused on the maximization problem and defined to the objective function with stress constraint. The cyclic load which the load value is not constant and vary by the time during the analysis process was applied to the structure that becomes dynamic analysis. For material property, the characteristic of isotropic and kinematic hardening plasticity was considered for the relationship between stress and strain of the structure. Finally, numerical examples were investigated to acquire the final layout and compared to the optimum design which obtained from the linear material properties under the static load.

Key words: Cyclic load, nonlinear material, proportional technique, topology optimization.

1. Introduction

Topology optimization is the most complex method for structural design process because the final layout is not related to the initial domain. Many researchers have been focused on optimizing the structure based on linear material properties and linear analysis [1]-[4]. The objective of linear topology optimization usually defines to minimizing structural mass based on yield stress constraint or maximize the stiffness of the structure with volume constraint.

In recent years, the topology optimization based on the nonlinear problem has been concerned into various approaches and techniques. Sequential piecewise linear programming (SPLP) was proposed to acquire the optimal layout under large displacement problem which included second order information of the objective function [5]. The element connectivity parameterization (ECP) was suggested to connect the design element for the two-dimensional of the nonlinear topology design [6], and the internal ECP (I-ECP) was implemented for the three-dimensional nonlinear problem [7]. The level set algorithm which using a level set equation to boundary the model was employed to define the optimal layout under geometrical nonlinearity problem by combining with Particle method [8] and Kreisselmeier-Steinhauser (KS) function [9] to optimize the model. Likewise, the topology optimization with the non-traditional approach was proposed to obtain the layout under the nonlinear structure. The modified ant colony optimization (ACO) [10] and artificial bee colony algorithm (ABCA) [11] were adopted to the optimization process for minimizing the complementary work of the structure with volume constraint of the design area.

Furthermore, the objective function is frequently derived to the sensitivity analysis by using the adjoint method [12]-[14] for solving the nonlinear topology optimization.

Most researches considered the nonlinear topology optimization by assuming a finite displacement of the structure based on linear analysis equation and applied the sensitivity analysis method to acquire the optimal layout. So, this research aims to employ the proportional algorithm which is a non-sensitivity technique into the structural design process under nonlinear analysis. The optimization algorithm is employed Solid Isotropic Material Penalization approach (SIMP). The structure was concerned on the characteristic of the isotropic and kinematic hardening material model while the cyclic load was applied to be an external force. The proportional method used to determine the element density value and combined with the criterion of the fully stress design into the algorithm. An internal energy density is set to the objective function to maximize while constraint the elemental stress of design variable. Eventually, the final results are also examined and compared to the optimal layout from linear material properties with the static load case.

2. Problem Statement

Structural analysis of the baseline model was first analyzed to observe the stress distribution of the whole model. The analysis model was displayed in Fig. 1 and applied the external load on the top-right of the structure. The isotropic and kinematic hardening material (Fig. 2) was assigned to the model with 285 MPa of the yield stress, and the ultimate tensile stress is 600 MPa corresponding to S275 steel. This characteristic of the material properties also used in the optimization process.

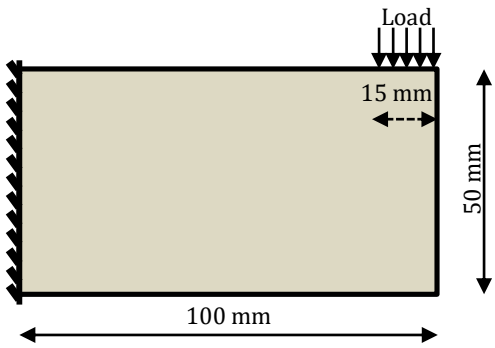


Fig. 1. The model for structural analysis.

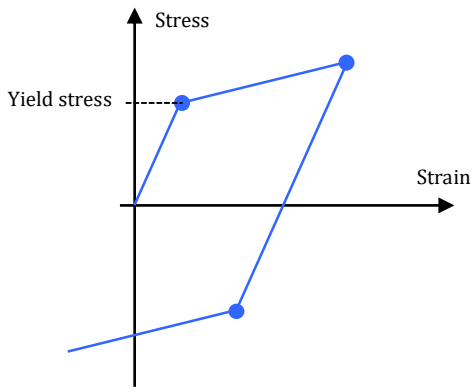


Fig. 2. Stress-strain curve for the isotropic and kinematic hardening material.

There are two cases for comparison between the maximum stress and time that are the static load and the cyclic load behavior (Fig. 3). The negative value of cyclic load demonstrated the load acted on the structure in the upward direction whereas, the downward direction was acted on the structure with the

positive value. Both cases were performed on the nonlinear analysis by using LS-DYNA software. The maximum stress of two cases was plotted in Fig. 4 which expressed by each time step. The stress of two model was different due to the load behavior. The static load caused constant stress since the first time step while the cyclic load affected stress which varied by time. So, this is an essential point for the optimization process because the stress could fluctuate in each iteration for optimization and difference from the static load.

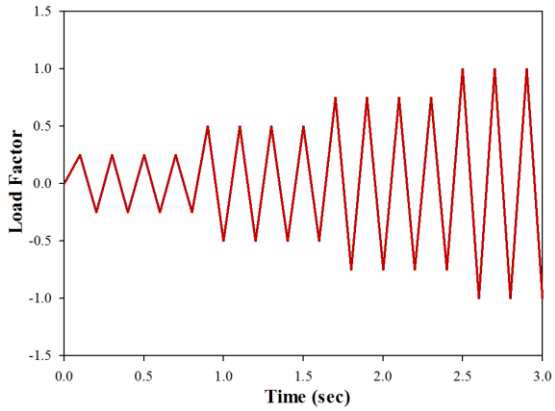


Fig. 3. The cyclic load behavior.

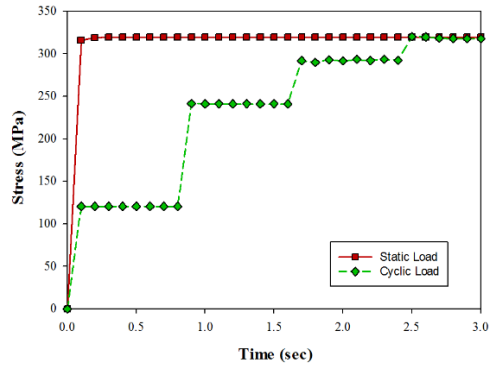


Fig. 4. Stress comparison between static and cyclic loads.

3. Topology Optimization Approach

Structural optimization based on the topology process is expected to replace the optimum material distribution on the initial design area. Firstly, the initial design is divided into discrete element and solve the discretized problem by using Finite Element Method (FEM). The final result shows the remaining area with represents by solid element and void the element is presents an ineffective area corresponding to the user-defined problem. This work used the SIMP method for the optimization procedure to find the final layout of the structure.

3.1. Solid Isotropic Material Penalization Approach (SIMP)

Each design element is assigned to be a design variable and involved in the problem. The SIMP algorithm is formulated based on the density approach with applies a penalization factor [15]. The optimal result is assigned the density value of each design element between zero to one (reference the material distribution from 0% to 100% respectively). An equation of modified SIMP approach is demonstrated in (1) and (2) where E_{min} is Young's modulus of remove material, x_e is element density, E_0 is Young's modulus of remain material, Ω is the reference domain and Ω^{mat} is the optimal subset.

$$E_e = E_e(x_e) = E_{\min} + x_e^p (E_0 - E_{\min}) \tag{1}$$

$$x_e = \begin{cases} 1, & if\ x \in \Omega^{mat} \\ 0, & if\ x \in \Omega / \Omega^{mat} \end{cases} \tag{2}$$

3.2. Optimization Formulation

The optimization is assigned the objective function to maximize an internal energy density corresponding to the application of the automotive design. The stress of each design element is considered to be the optimization constraint and should not over the stress limit. Therefore, the objective and constraint functions can be expressed by:

$$\max_{x} \quad U(x) = \sum_{e=1}^{N} E_e(x_e) u_e \tag{3}$$

$$h(x) = \frac{\sigma_e}{\sigma_{ult}} - 1 \le 0 \tag{4}$$

where U is the objective function, x_e is the element density of the eth design variable, N is the number of design variable, u_e is elemental internal energy density, σ_e is elemental stress and σ_{ult} is the ultimate tensile stress.

3.3. Density Filtering Technique

The optimization based the density approach usually causes a checkerboard pattern on the final layout and lead to the instabilities of the numerical process. To avoid the checkerboard problems, the filtering scheme was applied by using the equation from Xia *et al*. [16]. The density filtering equation displayed by:

$$\eta_e = \frac{\sum_{j=1}^{N} w_{ej} d_j}{\sum_{j=1}^{N} w_{ej}} \tag{5}$$

$$w_{ej} = \max(0, r_0 - r_{ej}) \tag{6}$$

where η_e is the filtering density of element e^{th}, w_{ej} is weight filtering of element e^{th} and j^{th}, d_j is a non-filtering density of element j^{th}, r_0 is filtering radius and r_{ej} is the distance between e^{th} and j^{th} elements.

4. Proportional Method

The density value of each design variable is updated by using the proportional method which is a non-sensitivity technique. Firstly, the target material (χ^{target}) of the design area is determined by considering the elemental stress and displayed in (7). The target material will be decreased by material movement (0.002 of the total number of element) if the stress is lower than the stress limit, whereas, the target element will be increased.

$$\chi^{target} = \sum_{e=1}^{N} x_e \pm (0.002 \times total\ number\ of\ elements) \tag{7}$$

Next, the target material is assigned to the remaining material (χ^{remain}). For the first iteration, the remaining material is assigned to zero. The optimal element density (χ_e^{opt}) is calculated by using (8) which includes a factor of the fully stress criterion [17] for the topology optimization for updating the density value.

$$\chi_e^{opt} = x_e^{prev} + \frac{\chi^{remain}}{\sum_{e=1}^{N} u_e} \left(\frac{\sigma_e^q}{\sigma_{ult}^q} \right) \eta_e \tag{8}$$

The density of the design variable from the previous iteration (x_e^{prev}) and the filtering density are used to

calculate the new value of each design density value. After that, the new remaining material $\left(\chi_{new}^{remain}\right)$ is investigated based on (9) to compare the current material amount and the first target material. The convergence criterion is set to 0.001 and defined to compare with the new material amount. The optimal layout will be acquired if the value of the new material amount lower than 0.001, whereas the inner iterative calculation for the proportional technique is required to determine the new density value until the optimization will be converged.

$$\chi_{new}^{remain} = \chi^{target} - \sum_{e=1}^{N} x_e \tag{9}$$

5. Numerical Examples

The numerical simulation consists of two calculation process: analysis and optimization processes. All nonlinear analysis is performed by using LS-DYNA software while MATLAB operates the optimization procedure. The overall process is demonstrated in Fig. 5 by the analysis results from LS-DYNA is conveyed to MATLAB by using LS-PrePost Scripting Command Language (SCL).

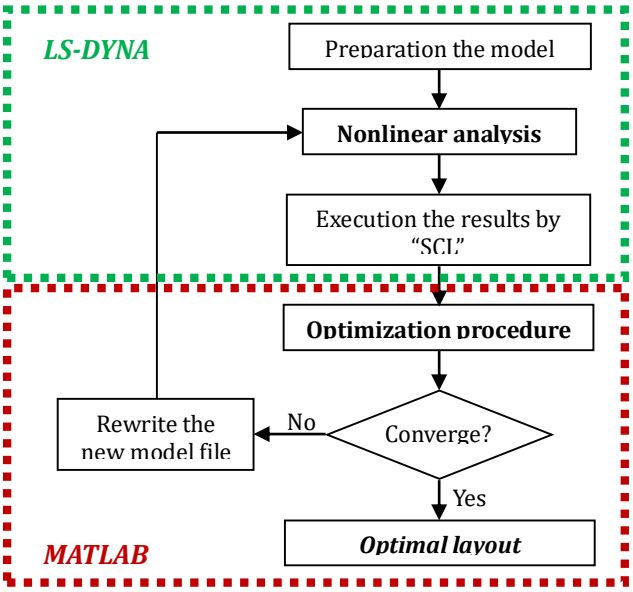


Fig. 5. Topology optimization process.

The initial design domain was the structure that displayed in Fig. 1 and applied 8 kN of the external cyclic load by following the curve in Fig. 3. The structure was divided into 100 elements for horizontal line and 50 elements for vertical line. Each design variable was assigned to 5 mm to the design thickness of shell model. For the nonlinear topology optimization, the final layout will be changed depending on the load, material properties, the objective function, etc. So, it is quite difficult to validate the model based on nonlinear optimization.

The optimization process was done with 193 iterations. After that, the optimal layout obtained and showed in Fig. 6 with the material distribution layout (Fig. 6a) and the stress distribution (Fig. 6b). The material distribution clearly represented the location of a suitable layout, and the stress of the final layout demonstrated the fully stress distribution in all members. The internal energy and maximum stress of the structure throughout the optimization process displayed in Fig. 7. The stress of 560 MPa caused a maximum value for the final layout, and the internal energy increased 256% from the baseline model. The results caused the fluctuating effect of the stress after 150 iterations until the end of the process. Commonly, the

stress raises from the beginning until the problem is converged. In this case, the fluctuate behavior responds to the behavior of the cyclic load factor and stress reduction from the characteristic of the isotropic and kinematic hardening material which included for the optimization problem.

(a) the material distribution (b) the stress distribution

Fig. 6. The final layout obtained from the nonlinear topology optimization process.

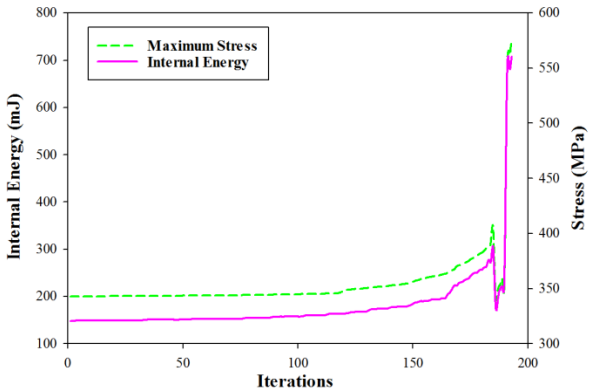
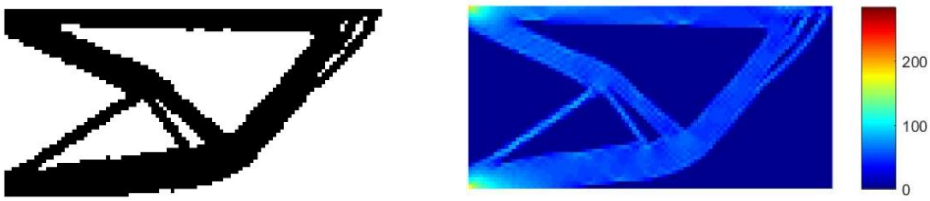


Fig. 7. Internal energy and maximum stress of the structure through the optimization process.



(a) the material distribution (b) the stress distribution

Fig. 8. The final layout obtained from the linear topology optimization process.

The maximum stress under linear topology optimization was limited to 285 MPa which is the yield stress function. The initial design and boundary conditions were identities with nonlinear optimization, but the external load was replaced by using the static load (the load has a constant value through the analysis). The optimal layout from linear topology optimization showed in Fig. 8a and the stress distribution displayed in Fig. 8b. From the results, the final layouts from topology optimization based on linear and nonlinear material properties were completely distinction on the location and layout of the structural members. So, the nonlinear optimization should be concerned when the structure causes a large deformation because the final layout is acquired depending on load behavior and material properties.

6. Conclusions

This research proposed the proportional method for topology optimization and applied to the isotropic and kinematic hardening material properties. The fully stressed criterion for the topology optimization was combined into the update function to investigate the density value in each optimization iteration. The inner-iterative calculation was required for the proportional method if the material density was not closed to the current target of material distribution. The optimal layout acquired from the nonlinear topology

optimization with caused the effect of stress fluctuating during iterative optimization. The results were clearly distributed layout to predict the locations of each structural member and fully stress distribution while the maximum stress was not over the stress limit. Linear topology optimization obtained the optimal structure members and different from nonlinear topology optimization. The nonlinear optimization should concern if the structure causes permanent deformation.

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