Topology optimization in crashworthiness design

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Abstract

Topology optimization has developed rapidly, primarily with application on linear elastic structures subjected to static loadcases. In its basic form an approximated optimization problem is formulated using analytical or semi-analytical methods in order to perform the sensitivity analysis. When an explicit finite element method is used to solve contact-impact problems, the sensitivities cannot easily be found. Therefore, an alternative formulation for topology optimization is investigated in this work. The fundamental approach is to change the element thicknesses based on the internal energy density distribution in the structure. Within this formulation it is possible to treat nonlinear effects, e.g. contact-impact and plasticity.

Introduction

Topology optimization is usually meant to be the optimal redistribution of material within a given domain. Actually, changing the topology of a structure is associated with changing its appearance and unless holes or limbs are created during the optimization, there is no change in the topology. Topology optimization has been the subject of many investigations mainly for static, linear elastic problems, see Bendsøe and Sigmund [1] and Eschenauer and Olhoff [2] for overviews of the state of art in topology optimization techniques. Another approach to topology optimization is to utilize sizing optimization of truss or frame structures. This approach has been used in several investigations, e.g. Sigmund [3], [4] and Fredricson et al.[5].

This work has been inspired by Ebisugi et al.[6], and Soto [7],[8],[9]. These authors have investigated a method with a parameterized material law in order to determine the material distribution in a given spatial domain. They have also varied the thickness of shell elements in order to determine the optimal topology of a structure subjected to impact. The optimal structure for energy absorbtion in a vehicle design should fulfill several criteria. The main objective is to absorb energy with a minimum amount of material in a controlled way.

In this paper, a simplified topology optimization method to be used at early design stages is presented. The Internal Energy Density, IED, distribution is investigated and used as a measure on to which extent a certain finite element contributes to the total internal energy and, thus, to the importance of the element from a topological point of view. In the linear elastic case a related problem is found in minimizing the maximum stress in a structure. The optimal solution of this optimization problem is a structure with an evenly distributed internal energy density.

In the following we have studied the topology optimization of 2D plane stress problems. The methods can however be generalized to 3D.

Proposed methodology for topology optimization in crashworthiness design

The approach in this paper is to use the Internal Energy Density, IED, parameter to determine whether an element is efficient or not from an energy point of view. If it is inefficient, its thickness is reduced. On the contrary, if the element is efficient, its thickness is increased.

The basic assumption of this method is that the stress state surrounding a finite element remains the same in two consecutive iterations to motivate the thickness update. This is hardly true for all possible loading situations and all possible optimization histories.

The internal energy density is defined as

$$IED = \int_0^t \boldsymbol{\sigma} : \mathbf{D}dt$$

where **σ** and **D** are the Cauchy stress and the rate-of-deformation tensors, respectively, and t denotes time. The IED will increase with the deformation as long as the material undergoes hardening and no elastic unloading takes place.

The topology optimization problem for the method with variable finite element thicknesses is stated as

$$\min \sum_1^{n_{el}} (IED_i - IED_{target})^2$$
$$s.t. \begin{cases} M\ddot{u} + f_{\text{int}} = f_{ext} \\ \rho_{\min} \le \rho_i \le \rho_{\max},\ \mathrm{i} = 1,\ldots,\mathrm{n_{el}} \end{cases}$$

where IED_{target} is a user set target value for all elements. A volume or mass constraint for the structure can be added for a more general formulation.

Evolution of the topology

The proposed topology optimization approach does not explicitly use gradient information in order to solve the problem. Instead, the IED value in each element and in each iteration is used to determine whether this element is efficient or not for the loading cases at hand.

The initial model (ground structure) is created using TrueGrid, see Rainsberger [10] and the impact analysis is solved using the explicit FE solver LS-DYNA, see Hallquist [11],[12]. The post-processing is done using LS-PRE/POST, see Ho [13], and different Perl scripts. Perl scripts are also used to update the FE model.

A stop criterion must be given for the optimization process. Any criterion suitable for the purpose at hand can be used, e.g. a minimum change in relative thickness, a minimum change in the IED distribution, etc.

Multiple loadcases

In the case of multiple loadcases, our approach is to normalize all element IEDs with the maximum IED value found in any element for that particular loadcase. In this work, the IEDs are normalized for each loadcase and the IEDs from each loadcase are then summed for each element.

$$IED(j) = \sum_{LC} \alpha_{LC} IED_{LC}(j)$$

where IED(j) is the summed IED for element j, LC denotes the number of loadcases and α_{LC} is a loadcase weighting factor (usually α_{LC}=1). The summed IED is then evaluated and the elements are modified according to its summed IED. In the present application every loadcase is given an equal weight.

The FE model updating procedure

An algorithm controls the update of the topology. The basic idea is to set a target value for the IED. If an element has a higher IED, summed over all loadcases, the thickness is increased, and if it has a lower IED it is decreased. A range, defining the maximum element thickness change within an iteration is used. Also a factor is defined for each element

$$q = \frac{IED^i}{IED_{\max}}$$

where IED^i is the summed internal energy density of the currently updated element and IED_{max} is the maximum summed internal energy density found in any element in the structure. Depending on if q is greater or lower than IED_{target}/IED_{max} a factor f is defined as

$$f = \begin{cases} \dfrac{IED^i - IED_{\max}}{IED_{target}}, & q \le IED_{target} / IED_{\max} \\ \dfrac{IED^i - IED_{\max}}{IED_{\max} - IED_{target}}, & q > IED_{target} / IED_{\max} \end{cases}$$

and the new element thickness is set according to

$$t_{new} = t_{old} + f * range$$

where range is a user-defined parameter. Finally, if the global limits of the element thickness are violated the thickness is reset to the limit value. This kind of updating technique can be seen as a traditional panning scheme, where the global limits of the thickness define the design domain and the range defines a region of interest.

Of course, the target value of the IED will determine in which direction the optimization procedure should go. The range parameter will affect the convergence rate of the optimization problem.

Penalization of intermediate thickness values

From a manufacturing point of view, it is difficult and expensive to construct a part with too much thickness variation. Therefore, a thickness penalization formulation was investigated, in order to get a more distinct topology.

The factor f can be viewed as a linear penalization depending on the IED value. Our thickness penalization approach modifies the factor f. Each element thickness is updated using the new factor

$$f_{new} = (f_{old})^{1/p}$$

where $p \geq 1$ is the penalization parameter. If p is set to one the linear factor is retained. If $p>1$ then most of the intermediate thicknesses are set towards the limits of the range.

Volume constraint

In the previous optimization formulation, there was no constraint on the available amount of material. Hence, the total mass could increase. In order to restrict the volume material used, however, every finite element thickness is scaled with the factor (if the volume constraint is broken)

$$s = 1 - \frac{V - V_{all}}{V}$$

where V is the volume after the thicknesses have been updated with respect to the IED distribution and V_{all} is the total amount of available volume. Since some of the elements might be on the lower global limit of the thickness value, these thicknesses are reset to the limit value. Therefore, the volume limit will still be broken. In order to minimize this constraint violation, the new volume is calculated and a new factor is found. Hence, iteratively we can find the thickness distribution, which also fulfills the volume constraint.

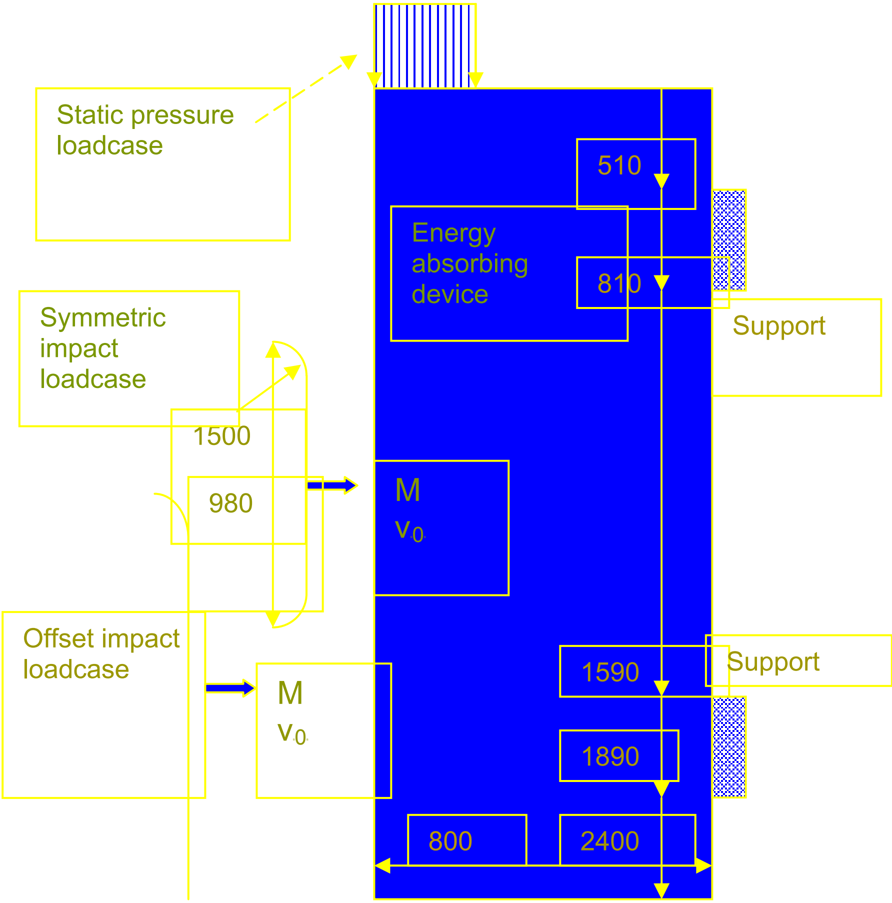


Fig.1. Ground structure of the energy absorbing device. Length unit mm.

Application problem - Energy absorbing device

The task is to develop an energy absorbing frontal underrun protection device (eaFUP) for a truck. The structure can occupy a well-defined region in space and it is fixed to the front of the truck. The ground structure and other data are given in Fig.1. The structure is subjected to three loadcases: two dynamic loadcases, i.e. symmetric frontal impact and offset frontal impact, respectively. In addition it is subjected to one static transversal pressure loadcase.

The ground structure consists of a uniformly distributed fictitious material. The main reason of using a fictitious material is to ensure that reasonable plastic deformations do occur in order to absorb the applied energy. The material is selected to behave like an elasto-plastic material.

The main advantage of modifying the thickness of an element instead of deleting it, is that an element with a small thickness is kept in the model and its thickness can grow at a later stage of the optimization process. If an element is deleted, that loadpath is removed and cannot be re-introduced.

The objective in the present optimization methodology is to find a structure with an evenly distributed IED. A target value for this IED level has to be selected. In the optimization processes presented here we have used the average value found in the initial FE model. The thickness may be altered within the interval 1 mm to 200 mm.

Results from the symmetric loadcase

The thickness distributions at four iterations of the topology optimization process are shown in Fig.2. The maximum allowed change in thickness within an iteration is set to 50 mm. After some initial oscillations the major topology is revealed. The IED target level is set to 2.12 MNm/m^3, which is the average value of the IED for the initial simulation.

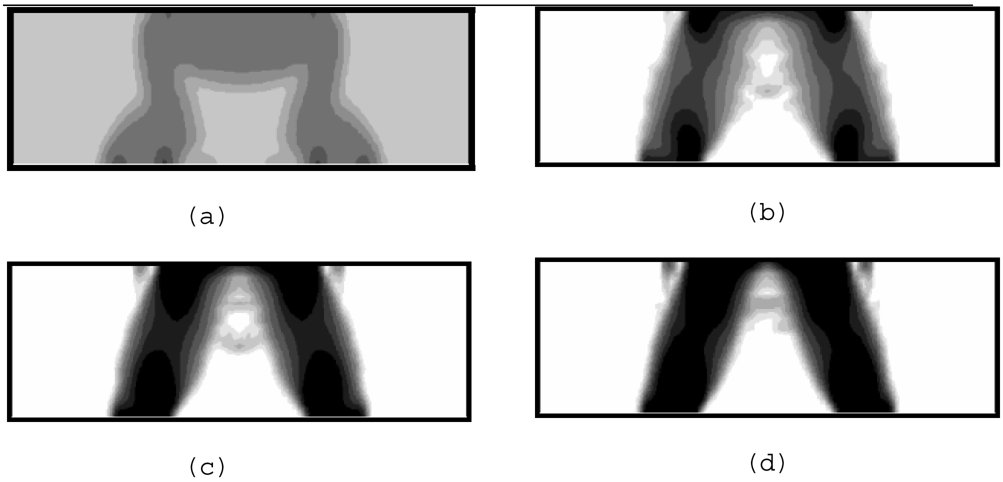


Fig.2. Symmetric impact case. Thickness distribution after
2 (a), 8 (b), 16 (c), and 26 (d) iterations

Results from the pressure loadcase

The thickness distributions at four stages of the thickness optimization of the pressure loadcase are shown in Fig.3. A maximum change of 10 mm in thickness of an element was allowed. The IED target value is set to 42.8 kNm/m^3, which is the average value of the IED for the initial simulation.

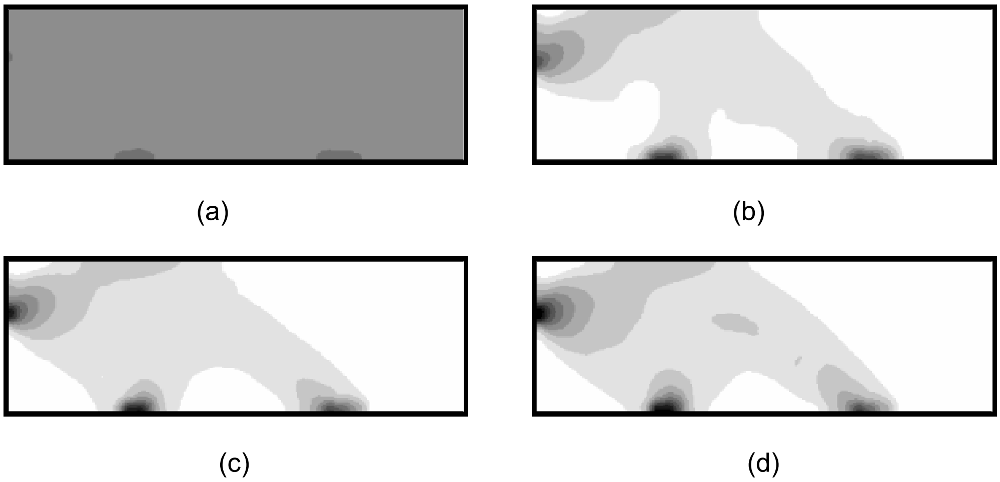


Fig.3. Pressure loading case. Thickness distribution after
2 (a), 10 (b), 18 (c), and 26 (d) iterations

Results from combined loadcases

In these optimizations, firstly, the two loadcases investigated earlier with the thickness topology optimization process, were evaluated in a combined optimization process, see Fig.4. Secondly, all three loadcases are used in a combined optimization process, see Fig.5.

The maximum thickness change in one iteration is set to 30 mm throughout the optimization process. The IED target value is set to the sum of the average IED for the individual loadcases.

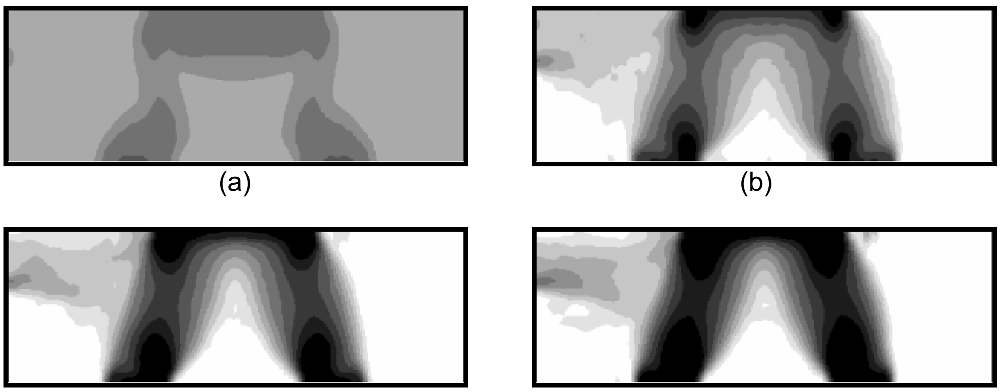
Conclusions

We have presented a topology optimization method that can be applied to nonlinear structures subjected to dynamic loading. Several different loadcases can be combined in the optimization process, even if they have different characteristics.

With the thickness update methodology there are some steering parameters to be set and some general observations can be made. The range parameter highly influences the convergence rate of the procedure. If it is set too low the topology optimization process converges rather slowly but in a linear way. If it is set too high, oscillations in the element thicknesses are observed during the iterations, which also decrease the convergence rate of the optimization process.

With the target value of the IED, the optimization process pushes the solution towards a predefined load intensity in each finite element. A proper value for the IED parameter can be determined from the material properties.

There are issued which have not been fully addressed. The influence of the range, target value of the IED, the penalty factor and the global limits on the thickness are all factors which need further investigations to make the optimization procedures more efficient.



(a) (b) (c) (d)

Fig.4. Static pressure and symmetric impact. Thickness distribution after 2 (a), 10 (b), 18 (c), and 26 (d) iterations

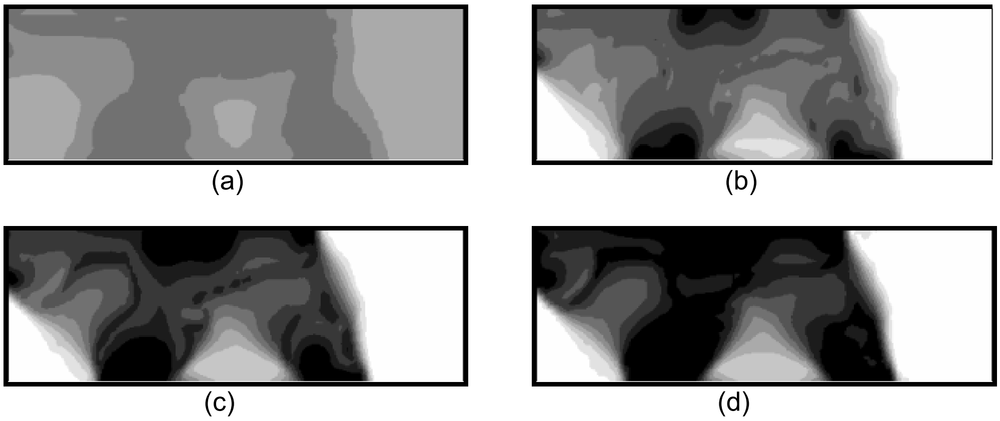


Fig.5. Static pressure, symmetric impact and offset impact. Thickness distribution after 2 (a), 10 (b), 18 (c), and 26 (d) iterations

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