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Crashworthiness optimization of thin-walled tubes using Macro Element Method and Evolutionary Algorithm

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ABSTRACT

In this paper the workflow for obtaining the optimal shape of thin-walled tubes in crashworthiness analysis is presented. The Macro Element Method approach is applied to model large deformations and to calculate crushing parameters of thin-walled sections. The objective of the work is to determine the optimal dimensions of a tube cross-section so as to achieve the maximal energy absorption of the structure. Two optimization algorithms have been developed and coupled with the Visual Crash Studio software that simulates the response of a thin-walled beam during the impact. The first approach applies a modified version of the random search Monte Carlo method. The second is based on Evolutionary Algorithm. Square and hexagonal tubes exposed to axial load are investigated in numerical examples. The best results from both approaches are compared and discussed. The obtained solution is very close to optimal results based on the FEM models and validated by experimental tests. This study illustrates the potential of the optimization in early design stages of the vehicle development process and prepares perspectives for the optimization of complex energy absorbing systems.

1. Introduction

Thin-walled beams are widely used as structural elements in automotive engineering. The assembly in form of structural frame that includes also components designed to absorb crash energy ought to fulfill strict design requirements. The development of such structures usually involves the usage of advanced numerical methods in crashworthiness analysis. The optimal design of such systems is not a trivial task. The assessment of crashworthy design focuses mainly on the application of the Finite Element Method (FEM). In the automotive design the calculation of crushing parameters becomes faster due to increasing performance of computational units however models created for the FE analysis grow simultaneously. Consequently, a highly detailed structure with a large number of model elements increases the calculation time. When additionally the structural optimization process is taken into consideration, the time required by a complete analysis increases dramatically. The successful design of a crashworthy structure requires the consideration of various concepts and model schemes. Starting from a simplified approach for modeling of large deformations of thin-walled structures engineers may subsequently increase the complexity of simulation models. In early design stages, when the simulation model is not highly detailed and the structure undergoes frequent modifications, the Macro Element Method (MEM) can be effectively employed to enhance the engineering process. The development of the MEM was conducted by T. Wierzbicki, W. Abramowicz, N. Jones and others in late eighties of the last century [1–3]. Next, the formulation of the MEM computerized version was worked out by Abramowicz and has resulted in the development of a unique software [4]. The main benefit and advantage of the MEM is a very fast calculation time because the numerical processing for quite complex structures usually takes up to several minutes on a standard PC. The solution of an equivalent model by specialized FEM software of nonlinear dynamics frequently needs several hours. Thus the MEM approach gives the possibility of introducing the optimization procedures into the vehicle development process. The optimal design of thin walled elements has become an important problem for engineers and designers. Many procedures have been developed to maximize the strength of structural element and minimize their mass. In recent years number of studies has been devoted to the subject. The instance for optimal design is presented by Zarei and Kröger [5]. Authors used multi-objective optimization algorithms combined with FEM solver to find the best solution of thin-walled cylindrical tubes subjected to dynamic axial load. The results presented a good correlation with validation tests performed on drop hammer rig. Structural optimization problem was also identified by Shi et al. [6]. The various concepts of automotive parts machining revealed the fields where the application of optimization procedures suites perfectly. The research work by Liu [7] is close to the study presented in consecutive chapters of this paper. The

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problem definition involved the axial crushing of a rectangular cross section and the author introduced the surface response method to represent the design problem. Majority of presented papers focused on geometry and topology of thin-walled cross sections. Other features of structural design can be also considered as the objective function component. The investigation of such problem was carried out by Cui et al. [8], where authors described the procedures for the optimal material selection in crashworthy design of vehicle. The comparison of various optimization methods involving the thin-walled columns crushing is presented in the paper by Hou et al. [9]. The attention in this study was drawn to the subject of diverse cross sectional shape and tubes configuration. Presented optimization procedures described the representation of complex objective functions that handle number of crashworthy parameters. The study conducted by Marzbanrad and Ebrahimi [10] illustrates the implementation of FEM coupled with thin-walled circular aluminum tubes optimization process based on neural networks and genetic algorithm. The optimization of functionally graded thin-walled structures is studied by Sun et al. [11]. The research depicts crashworthiness optimization process combined with Non-dominated Sorting Genetic Algorithm (NSGA-II). The optimization works conducted by Tran et al. [12] use simplified Super Folding Element theory to estimate the level of dissipated energy in thin walled triangular tubes subjected to axial load. The unique shape of tubes is optimized using multi-objective Deb Gupta method and surrogate models. The instance of multi-objective optimization is presented also in the research by Sharafi et al. [13]. The graph theory and the multi colony ant algorithms found the optimal topology to members of open and closed thin-walled cross sections. The research by Abbasi et al. [14] was devoted to the single and multi-objective optimization methods of thin-walled metal members. In their approach the crashworthiness performance of complex (hexagonal, octagonal and 12-edges) shape cross sections was assessed and the influence of various materials on crushing response was tested additionally. The recent study by Gao et al. [15] expanded the problem of optimization thin-walled members. The crushing behavior of foam-filled tubes exposed to oblique dynamic loading was investigated. Similar crashworthiness optimization problems were also presented in [16–19]. Its worth to emphasise that almost all (with one exception) of case studies presented above used the FEM to predict the crushing response of thin-walled structural elements. The FEM modeling demands high efficiency computing units. However, an alternative approach for calculation of crashworthy parameters of structures under consideration exists. In this work the problem related to the development of crashworthy structures and to design of energy absorption elements is investigated. The optimal dimensions of thin-walled beam cross-sections are searched in order to maximize the energy absorption during the impact. The crashworthiness analysis is carried out using the software Visual Crash Studio (VCS) [4] based directly on the MEM concepts. The VCS has been coupled with two optimization algorithms: the random search Monte Carlo method and the Evolutionary Algorithm. Square and hexagonal tubes exposed to axial load, widely used in the study of energy absorption mechanisms are investigated in numerical examples. The optimal results obtained by applied algorithms and the effectiveness of the approach are compared and discussed. Moreover, the solution is validated by comparison with optimal results using FEM models and confirmed by experimental tests described in the literature. The original contribution of this paper resides in coupling the developed optimization procedures with the VCS software, studying the problem of the optimal cross-sectional sizing to achieve the best energy absorption characteristics of thin walled tubes and investigating the efficacy of the proposed approach. This study enables us to estimate the potential of optimization in early design stages of vehicle development process and to formulate perspectives for a larger size optimization process of much more complex, real life energy absorbing systems.

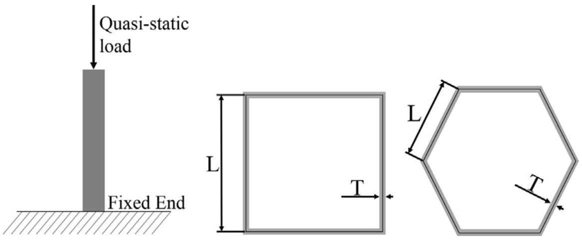

Fig. 1. Thin-walled columns exposed to quasi-static axial load and examples of square and hexagonal cross-sections.

2. Formulation of the crashworthiness optimization problem

Let us consider thin-walled tubes of a given cross-section submitted to an axial kinematic loading (Fig. 1). The behavior of these elements during a quasi-static crush will be investigated. The simulations reflect experimental conditions when prismatic column is placed in a press rig and the reaction force against the displacement is measured. A very slow deformation progress is assumed and viscous effects of the material are not taken into consideration. The geometry of the cross section is described by the length L and the thickness T. The designed structure has to absorb a maximal amount of the crush energy. This property is usually expressed by the SEA parameter (Specific Energy Absorption) which represents the total absorption energy per unit mass of the structure. In this study we intend to maximize this value thus the SEA is the optimization criteria.

A number of different factors which influence the final solution is considered. First of all, the proper crashworthy design of vehicles energy absorption zones must ensure survive conditions for occupants in the event of crash. The measure which directly quantify a save design when the deformation process occurs is the force, or directly related acceleration level with accordance to a wide range criteria. Therefore it was assumed in this study that the mean crushing force should not exceed a given critical value. Furthermore the design space is limited by geometrical dimensions. Consequently, the considered problem contains boundary values imposed on L and T. The real world energy absorbing structures are sensitive to initial imperfections. The structure collapse behavior is also influenced by material properties, load magnitude and direction. That means the progressive folding is always guaranteed for a properly designed column, equipped with a triggering mechanism. Structural elements without an appropriate preparation are much more sensitive to the boundary and load conditions. In result energy absorbing elements in the form of prismatic columns are prone to global bending. The presented numerical research is limited to ideal conditions of pure axial force. Thus, considering the former research on thin-walled columns it was assumed that the phenomenon of global collapse or non-compact folding occurs more likely below and above a certain range of L/T ratio. For that reason the constraint related to L/T ratio of the Super Folding Element (SFE) was added. The resulting optimization problem can be formulated as follows:

$$SEA(T, L) \rightarrow max \quad (1)$$

$$P_m(T, L) \leq P_{ref} \quad (2)$$

$$T_{min} \leq T \leq T_{max} \quad (3)$$

$$L_{min} \leq L \leq L_{max} \quad (4)$$

$$(L/T)_{min} \leq L/T \leq (L/T)_{max} \quad (5)$$

where: SEA - is the Specific Energy Absorption (i.e. the energy absorbed per unit mass of the structure); P_m - mean crushing force; P_{ref} - critical value of the crushing force; T_{min}, T_{max} - minimal and maximal allowable wall thickness; L_{min}, T_{max} - minimal and maximal allowable side wall length; $(L/T)_{min}$, $(L/T)_{max}$ - lower and upper limit for L/T ratio.

Two different unconstrained optimization algorithms will be applied to find the solution. Since the problem under consideration