Meta-model based optimization of spot-welded crash box using differential evolution algorithm

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Abstract

The objective of this study is to improve the energy absorption performance of spot-welded crash box using optimization techniques. The number of crush initiators and the number of spot welds were selected as design parameters for optimization study. Maximization of absorbed energy is selected as objective function and the upper bound of maximum initial peak force is defined as constraint. DOE study has been performed with full factorial sampling method, and then polynomial objective and constraint functions were defined to approximate the responses, such as absorbed energy and initial reaction force. The geometry was prepared using CATIA software. The finite element model of crash box and boundary conditions were prepared using Hypermesh software and the model was then transferred to Ls-Dyna in order to solve the finite element model. A Pascal code based Differential Evolution method was developed for solving optimization problem. Developed optimization software was tested with two test functions, then, optimization problem has been solved. It is concluded that, by introducing crush initiator geometries and optimization studies, performance of energy absorption of thin-walled and spot welded crash box has been improved. Not only using crush initiator geometry to control the crushing process is enough but also optimization is necessary for improving energy absorbing of thin-walled structures.

1 Introduction

Thin-walled tubular structures behind the bumpers of vehicles protect passengers and the structure during the impact. The bumper deforms first, then the following component deforms until the all energy is absorbed. Thin-walled structures absorb most of the crash energy with a progressive folding deformation. Generally, one or more crash initiators are used to initiate progressive folding of the tube. After first contact during collision, the axial force first reaches an initial high peak, followed by a drop and then fluctuates. The process is known as crushing. The reaction force has a typical plot with regular peak and valleys, each of them corresponding to the formation of a fold [1]. This force peak induces a high deceleration value that should not exceed a survival limit and that should be kept in any case as low as possible to improve the passenger safety. The mean value of the reaction force is related to the total absorbed energy by means of the total crushing length. It should be kept higher than possible to increase the energy absorbing capability of the analyzed component. The initial peak force is less important from the viewpoint of energy absorption but it should be avoided for the sake of occupant safety. For improved frontal car safety, it is necessary to design a structure that absorbs enough energy but at the same time maximum reaction force should be kept as minimum as possible. The main goal of this study is to maximize the energy absorption performance of spot-welded crash box using optimization techniques. Maximization of absorbed energy is selected as objective function and the upper bound of maximum initial peak force is defined as constraint function. Design of experiment (DOE) study has been performed with full factorial sampling method, and then polynomial objective and constraint functions were defined to approximate the responses, such as absorbed energy and initial reaction force. A Pascal code based Differential Evolution method was developed for solving optimization problem. Developed optimization software was tested with two test functions, then, optimization problem has been solved.

2 Finite Element Model

In order to find optimal crashworthiness of structure, nonlinear finite element method has been used which enables to model complex material models, large deformation and strain rates and frictional contact with acceptable accuracy. Solving crash analysis problems and performing these calculations are computationally intensive. The finite element model of crash box and boundary conditions were prepared using Hypermesh software. In this study, an explicit finite element code, Ls-Dyna was used to implement the computations. A dynamic impact model is defined as shown in Figure 1. [2]

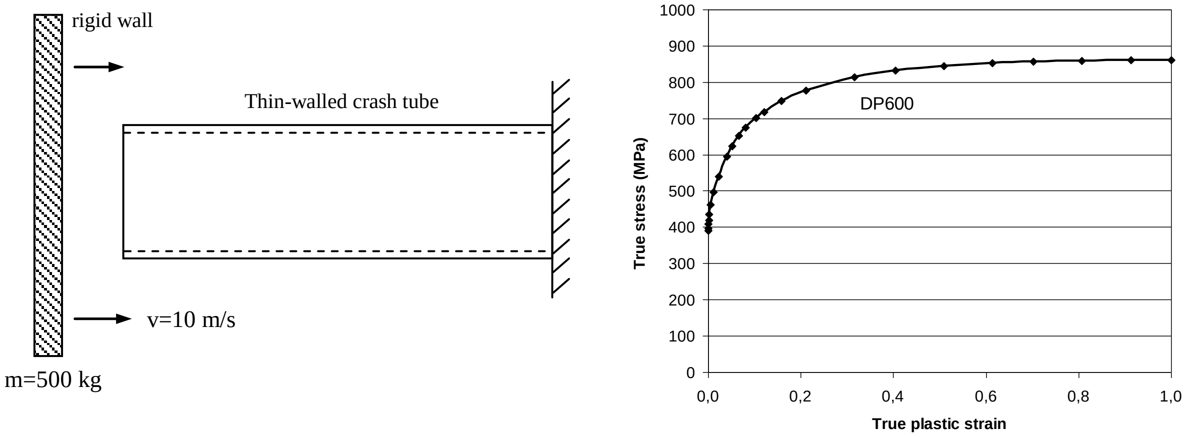

Fig.1: Impact model and true stress-strain diagram of material

The behavior of the crash tubes has been studied by simulating the impact of a rigid barrier traveling at a speed of 10 m/s with a mass of 500 kg for the crash tubes with rectangular cross-section with 1 mm thickness. The material properties of dual phase steel (DP600) were used in the analyses, i.e. young's modulus, E=210 GPa, Poisson's ratio, υ=0.3, material density, ρ=7850 kg/m3, yield stress, σy=390 MPa. One end of the tube is constrained in all degrees of freedom and the other end is free. 20086 quad Belytschko-Tsay shell elements and 20496 nodes were used to define the different finite element models. To account for the contact between the lobes during deformation, a single surface contact algorithm with friction was used. The friction coefficient is taken as 0.3. The strain-rate dependency of the material is not considered here.

The crash box consists of two sheet parts and joined with spot welds. Elasto-plastic material model based on Von-Mises plasticity MAT_100 (MAT_SPOTWELD_DAMAGE-FAILURE) was used to model the spot weld connections [3]. The diameters of the spot welds were chosen 4 mm and modeled with using 4-hexa solid elements.

Following results have been obtained with no crush initiators exist on crash box. Seven deformable spot welds per flanges defined in the finite element model. Undeformed and deformation mode are shown in Figure 2.

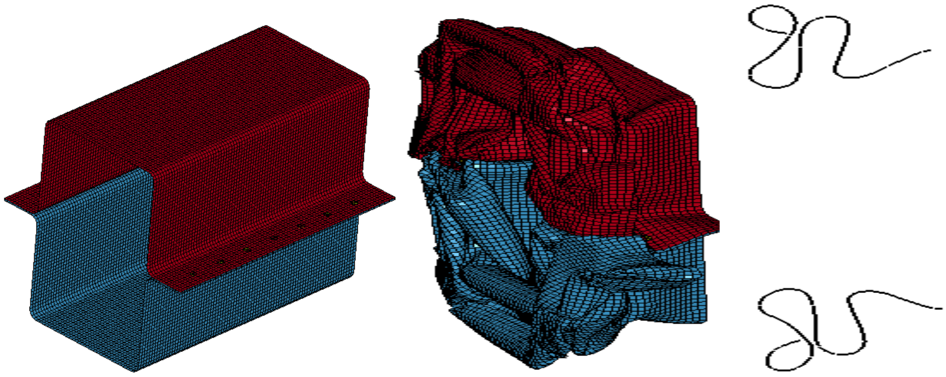

Fig.2: Undeformed, deformation characteristics and section view (deformed time=15 ms)

Time history plot for reaction force is given in Figure 3 to show some characteristics of the deformation mode.

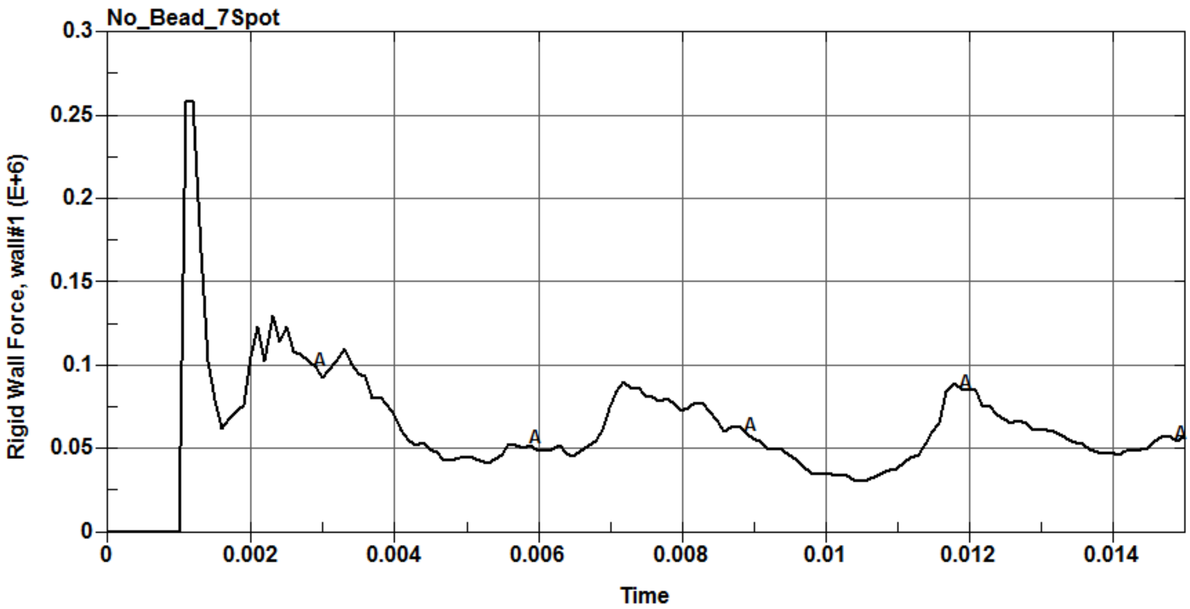

Fig.3: Time history plot for reaction force

It is clear from the Figure 3 that, the reaction force has highest value at the first contact between rigid body and the profile to start the local folding and later it continues with regular peak and valleys, each of them corresponding to the formation of a fold. Initial force peak induces a high deceleration value that should not exceed a survival limit and that should be kept in any case as low as possible to improve the passenger safety. On the other hand, the mean value of the reaction force is related to the total absorbed energy. It should be kept higher than possible to increase the energy absorbing capability of the profile. Therefore, the best crash box profile should have lower initial force peak not to exceed a survival limit and higher mean value of reaction force to absorb more energy.

In order to reduce the maximum reaction force, crash initiators are defined on the crash box. These geometries provide a stable regular folding process without a much higher peak force level to introduce the first fold. The folding process starts at the front end and proceeds towards the rear end, giving more stability. In this case, the whole length of the crash box could be used for folding lobes of the same size. An example of 3 crush initiators which is modeled using CATIA can be shown in Figure 4 used in this study.

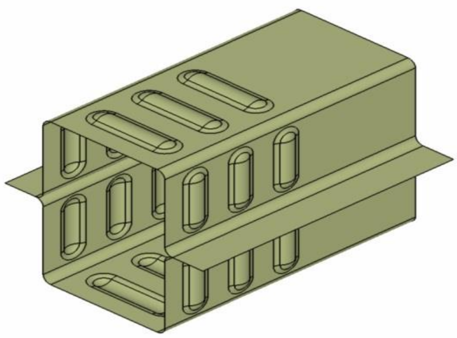

Fig.4: Crush initiators on the crash box

In the following subsections, research is described to find the optimal number of the crash initiator and the optimal number of spot welds on the crash box. Generating crash behavior databases for all possible numbers of spot weld and crush initiators is an extremely expensive task. Approximation methods such as metamodels will overcome the aforementioned problem, especially in case of crashworthiness design optimization. One of those approximation methods is the so-called response surface methodology (RSM). [4].

3 Response Surface Method

In order to define response surface to be used in place of the actual simulation models, response surfaces have been defined for absorbed energy and initial reaction force. To construct the response surface model, a Design of Experiment (DOE) simulation was conducted at 9 sampling points by the full factorial design method. This method investigates all possible combinations of the factor levels (L) and number of design variables (N). A full factorial study requires L^N number of runs. Such a design is beneficial for calculating all main and interaction effects. The use of full factorial design for a situation involving a large number of factor levels may become computationally expensive. In this study, a full factorial design is employed to decide on the analysis points in order to obtain enough information for the approximation. Three levels (3, 5, and 7) for number of spot weld on one side of crash box and three levels (1, 3, and 5) for number of beads were selected. 9 analyses have been solved to obtain the response surfaces for absorbed energy and F_{max}, DOE table and analysis results were given in Table 1.

Exp. No.	No Of Spot Welding Per Flange	No Of Crush Initiators	Absorbed energy (kJ)	Initial reaction force (kN)
1	3	1	7.105	148.236
2	5	1	7.032	148.583
3	7	1	7.426	148.997
4	3	3	7.869	139.639
5	5	3	7.624	139.67
6	7	3	8.330	139.936
7	3	5	7.986	140.738
8	5	5	7.977	140.979
9	7	5	8.308	141.438

Table 1: 9 Design sampling points and the simulation results.

Curve fitting technique is applied to find the response equation for absorbed energy and initial reaction force respect to number of spot welds and crush initiators. These approximated polynomial functions are given as follow:

$$E(x, y) = 0.07325*x^2-0.0755*y^2 +0.0000625*x*y-0.640687*x+0.678354*y+7.76135 \quad (1)$$

$$F(x, y) = 0.0216667*x^2+1.27004*y^2-0.0038125*x*y-0.0587292*x-9.4896*y+156.538 \quad (2)$$

x: Number of spot weld
y: Number of crush initiators

These functions are used to define optimization problem.

4 Optimization

The aim of the optimization in this study is to maximize the absorbed energy (E) subject to initial reaction force (F) lower than 140 kN, Design parameters are number of spot weld and crush initiators.

Optimization problem is defined as follows:
Objective function: maximum E
Subject to: F ≤ 140 kN
Design parameters: $3 \le x \le 7$
$1 \le y \le 5$

One of the main shortcomings of classical optimization methods is to stuck into local optimum instead of global optimum. Genetic Algorithm and Differential Evolution (DE) algorithms are evolutionary optimization algorithms; they were developed for finding the global optimum of the optimization problems. DE is a relatively new evolutionary optimization algorithm. Details of DE algorithm can be found at [5].

In this study, DE algorithm was selected for optimization due to following reasons;
- It finds the lowest fitness value for most of the problems,
- DE is robust; it is able to reproduce the same result consistently over many trials,
- It is simple, robust, converges fast, and finds the optimum in almost every run.

A Pascal programming language based DE optimization software was developed and validated using two test functions. After validation of the developed DE optimization software, defined optimization problem was solved. User interface and optimization results are shown in Figure 5.

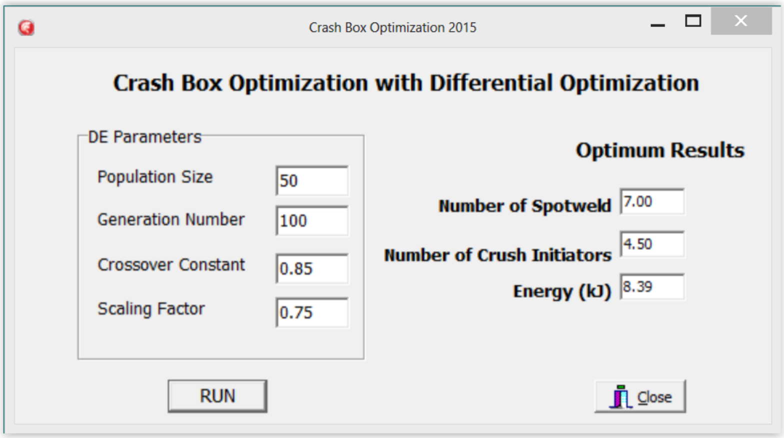

Fig.5: Optimization results

Due to DE algorithm is based on real representation of design parameters, optimum results are real values. Number of spot welds is found as 7 and number of crush initiators is 4.50. Number of crush initiators can be selected as 4 or 5. To select the best one, both alternative design have been analyzed and compared according to absorbed energy and initial reaction force. It is found that number of spot welds for 7 and number of crush initiators for 5 give best results. Alternatively, number of spot welds for 7 and number of crush initiators for 3 is another optimum solution according to Table1. For optimum design, maximum absorbed energy is 8.308 kJ. Final design undeformed and deformed crush models are given in Figure 6.

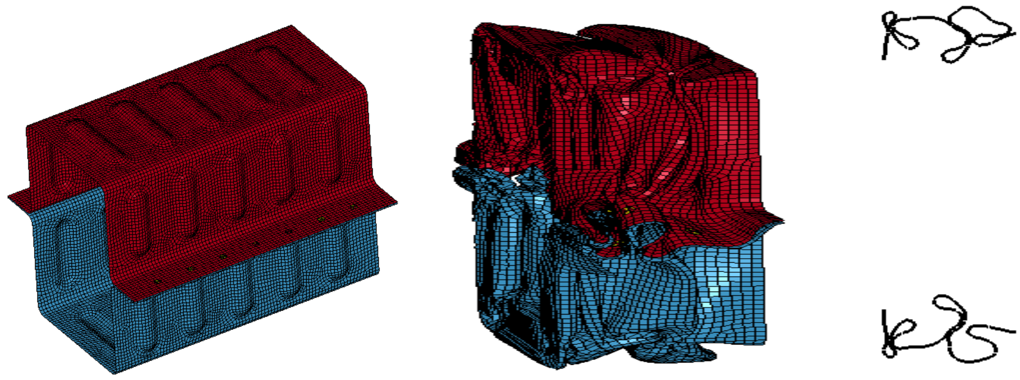

Fig.6: Undeformed, deformation characteristics and section view (deformed time=15 ms)

Reaction force time history plot is given in Figure 7.

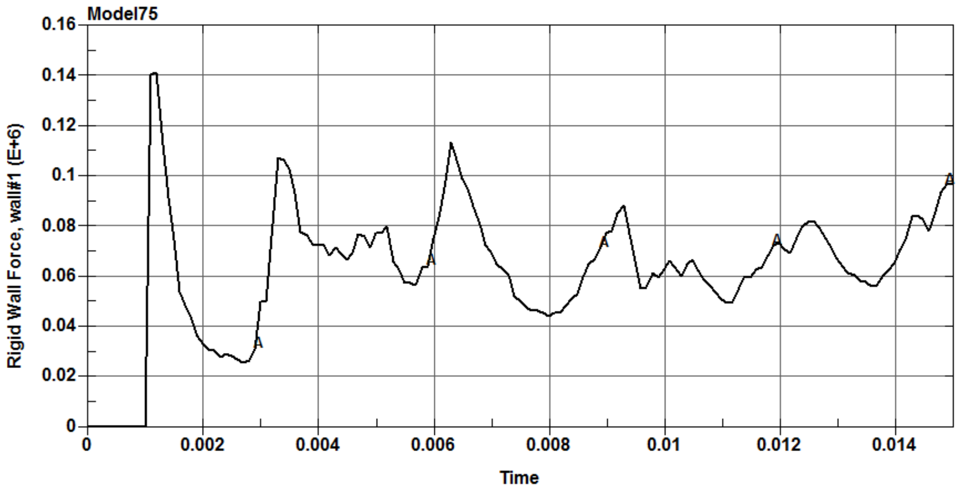

Fig.7: Time history plot for reaction force

It is revealed that with the help of crush initiators maximum reaction force is reduced from 259.38 kN to 141.438 kN as shown in Figure 7. Therefore, crush initiators geometries can be used in crash boxes to reduce the high reaction force effectively. Additionally, it is shown that, the optimization tools can help designers to select best combinations among the candidate designs.

5 Summary

The effect of the number of spot welds and crush initiators on the absorbed energy and reaction force are investigated on crash box under dynamic loading conditions. Maximization of absorbed energy is selected as objective function and the upper bound of maximum peak force is defined as constraint. DOE study has been performed and polynomial objective and constraint functions were defined to approximate the absorbed energy and maximum reaction force. Optimization problem has been defined and solved with Differential Evolution algorithm. By introducing crush initiator geometries and optimization studies, initial reaction force has been reduced without decreasing energy absorption capability of thin-walled and spot welded crash box.

6 Literature

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