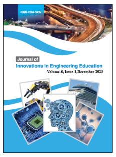

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Particle swarm optimization of star crash box

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Abstract

Crash box is energy-absorbing component to ensure the passive safety of vehicles during frontal crash. For crash-boxes - lightweight design, safety requirements absorbing energy are relevant. This research aims to determine the value of geometric design parameters in design space of star crash box optimizing specific energy absorption (SEA). The geometric modelling, meshing and finally input file for LS dyna is created using python scripting. Crash simulation is performed in LS Dyna. The energy absorption is taken from glstat of binout file and mass is taken from massout file. The particle swarm optimization is done using skopt python module. The geometric design parameters used are height (a), width (b), x-intrusion (u), y- intrusion (v) and thickness (t). For each simulation reference material Mild steel with density 7830 kg/m^3, Young's modulus 200 GPa and cowper-symond parameters c = 40s^{-1} and p = 5 is used. The impactor of 250 kg mass with speed of 15 mm/ms is used. After running simulations in batch mode, the maximum SEA of 63777.547 J/Kg is obtained at the values a = 72.291 mm, b = 75.314 mm, u = 20.162 mm, v = 4.978 mm and t = 0.985.

1. Introduction

With the increase in population, the number of automobiles is also increasing. Road traffic crashes result in the deaths of approximately 1.3 million people per year and about 93% of this case comes from middle income and low-income countries like Nepal[1]. The number of frontal collisions is significantly more than side collisions. This has increased the need of enhancing safety of the vehicle and its occupants. Crash box is important component of vehicle for passive safety of vehicle and its occupants during frontal crash. It serves as a kinetic energy absorber during collision. It is a tube shape thin-walled structure, which is located between bumper and chassis. During collision, it undergoes progressive buckling plastic deformation thereby absorbing most of the energy prior to the transfer the main cabin of a vehicle. The specific modes of deformation observed in crash box design and collapse behavior are concertina mode and diamond mode.

Concertina mode is a deformation pattern characterized by a series of accordion-like folds or wrinkles along the length of a structure, resembling the folds of a concertina musical instrument. Diamond-shaped deformation occurs when a thin-walled structure undergoes a collapse, and the resulting folds or distortions take on a pattern resembling diamond shapes. The failure of the crash box should ensure crashworthiness.

The crashworthiness of a structure refers to its ability to shield its occupants during collisions. The ultimate objective is to enhance the crash response of the structure, thus safeguarding the occupants. Crashworthiness evaluates a structure's capacity to shield occupants during impact and must meet two fundamental requirements i) It must absorb high levels of energy via controlled plastic deformation and ii) it must maintain a minimum survival space to avoid injury[2]. Along with it, lightweight and economical are the requirement of automotive industries. Hence, specific energy absorption, the ratio of energy absorbed by the structure to the mass of the structure measures the crashworthiness of crash box. Different optimization algorithms can be used for the optimized value of the design parameters in design space.

Optimization is the process of finding the best solution for a given problem within a defined set of possible solutions. the crash behavior is highly nonlinear, making it complex to find an optimized design that maximizes

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energy absorption. Population-based optimization is a type of optimization strategy that involves maintaining a population of candidate solutions and iteratively evolving this population to improve the overall performance with respect to an objective function. This approach is particularly useful for complex and nonlinear optimization problems like crash behavior of crash box.

2. Literature review

Crash box design is based on energy absorption of thin-walled structure. The mechanics and analysis of thin-walled structures dates back to 1960s. Initially J.M. Alexander studied collapse of thin cylindrical shells under axial loading during concertina mode failure [3]. The more general case of failure is diamond shape. The crumpling of thin cylindrical column under diamond pattern of deformation is studied by A. Pugsley and M. Macaulay. The empirical relation of load required to crumpled is obtained by equating internal and external work. And the critical buckling load was much below from the classical theory based on small deflection[4]. The concertina mode of failure is in thick tubes and diamond mode of failure is in thin tubes. The transition is calculated at R/t value of 45 and the transition is due to post elastic behavior [5]. T Wierzbicki and W. Abramowicz showed that the zones of extensional deformations are restricted to even smaller fraction of the total area of the shell but they always contribute to as much as one-third of the total energy dissipated in the structure. The remaining two-thirds of the energy results in equal proportions from in extensional deformations at stationary and moving hinge lines. In all types of shell, the mean crushing force depends markedly on the thickness of the shell. At the same time the dependence on the linear dimension is much weaker [6]. They later gave mean crushing load for the design of metal honeycomb as energy absorbers [7]. In 1984, W Abramowicz modified alexander's theoretical solution. He considered effective crushing distance in static crushing and influence of material strain rate sensitivity is retained in case of dynamic crushing, the experimental validated the result [8]. Then, the specific energy absorption of the foam filled structures was analyzed [9, 10]. The specific energy absorption somewhat increased in case of axial loading but in case of oblique loading result was opposite. In both cases the change from hollow wasn't significant[11, 12]. Then, [13, 14] studied the crashworthiness during oblique loading.

The material of the crash box is metal structure with light weight. But the number of researches has been in different materials. At first, thermoplastic composite was used as crash box material. The crash performance of the optimum composite crash box was compared with the optimum aluminum tube. The optimum composite crash box absorbed about 17% more energy than the optimum aluminum tube while it had about 26% less weight[15]. Number of researches were done during negative poison's ratio (NPR)[16], CFRP/aluminum hybrid material[2], auxetic core[17] as crash box material. Structural and material design was combined to improve specific energy absorption. Simulation results outline the great potential of a combining structural design and material design with a high total specific energy absorption of 27 kJ/kg. The tension parts, made of fully recrystallized HMnS, developed an outstanding specific energy absorption of 67 kJ/kg [18].

In the optimization of the crash box crashworthiness, the topology optimization was studied at first [19, 20]. Different geometrical shapes like square section with diagonal welding line, square section with middle welding line, rectangle section, hexagon section, circular section, and octagon section was studied and the square section with diagonal welding line turned out to be best according to simulation result [21]. The use of optimization algorithm was limited to response surface approximation and radial basis functions [9, 22, 23] earlier. In recent trend, the use of metaheuristic optimization models is in use due to their global search approach, iterative method, simple heuristic and less computational time. Also, these can find optimal solution in difficult and complex optimization problems [16, 24]. The objective function of the crashworthiness problem is used as specific energy absorption [18, 24], energy absorption[9, 10, 22], area in between displacement curve [24, 25], strain energies weighted at specified times [19] etc. Other objective functions suggested are internal energy, mass, maximum force, maximum acceleration and time for wall to stop [24]. The constraint can be volume [19] and maximum displacement [20]. The optimization objective of area between displacement curve and among meta heuristic optimization model, particle swarm optimization was suggested [24].

In reference to the literature, the star shape which can be made square, two honeycomb structure in its design space is selected for optimization. The PSO algorithm which works even works in the highly non-linear crushing of crash box is taken as optimization algorithm. The constraint is that the maximum displacement should be less than half of the length of the crash box. For the simplicity, the specific energy absorption is taken as the objective function.

3. Methodology

The initial design variables of the Finite element simulation are the cross-sectional dimension of the crash box. Based on the initial design variables, a LS dyna input file is created with proper meshing and simulation control in .k format. Now the simulation is run. The result of the LS Dyna file consists of binout file from where we can extract the energy absorbed and massout file from where we can extract the mass of crash box. Now in a different python file we call values of geometric parameter and we get result as energy/mass. Since we need maximum value instead of minimum, we return the negative value of specific energy absorption. Now, the PSO algorithm works and give new set of design variables which goes into FE simulation and the cycle runs till given number of iterations or the convergence criteria is met.

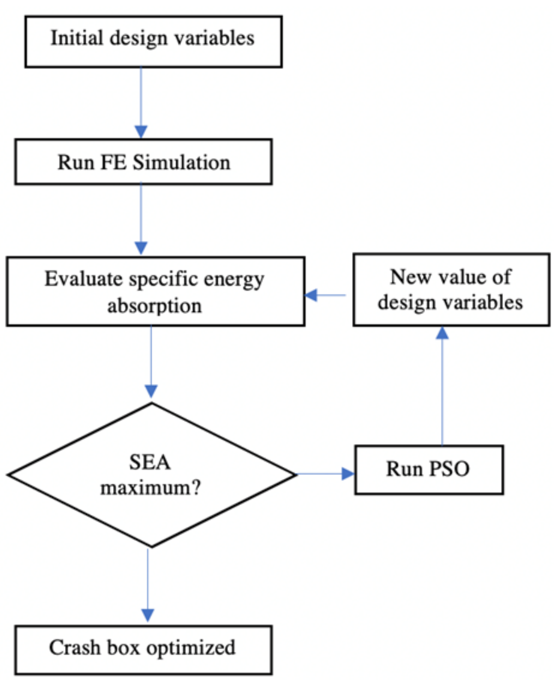

Figure 1: Flow Chart

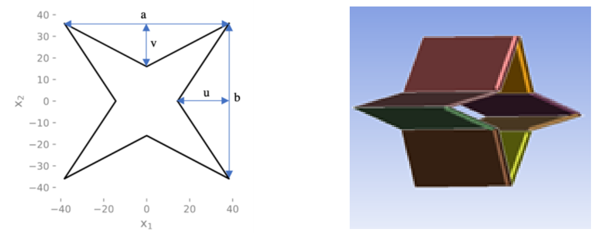

Figure 2: Geometry with parameters(left) and in LS Dyna (right)

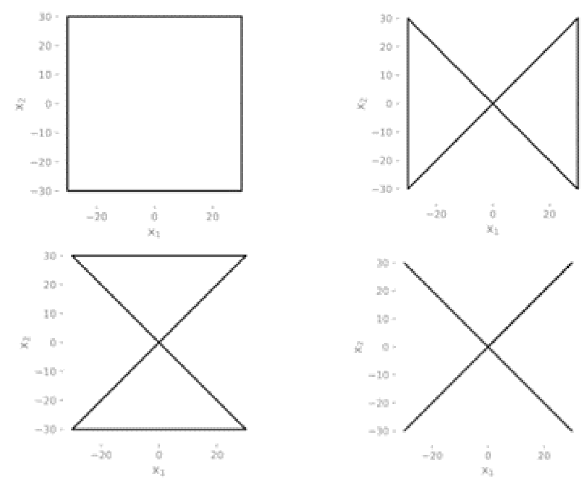

Figure 3: Degenerated star shaped geometry

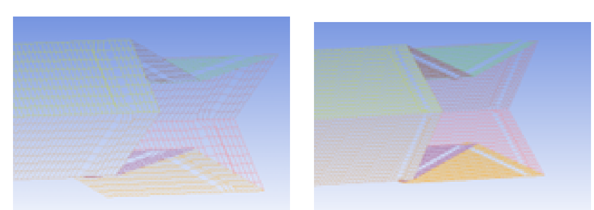

Figure 4: Mesh with size 1 mm (right) and 4 mm (left)

4. Numerical modelling

The numerical modelling step includes all the steps for numerical simulation. They are explained below.

4.1. Geometric modelling

The cross-sectional geometry of the crash box is star shaped and it is extruded to the length with a one groove near the top place. But we only deal with the cross-sectional design parameters. They are height(a), width (b), x -intrusion(u), y-intrusion(v) and thickness(t) as shown in figure 2. The intrusion in x and y direction are symmetric in both sides.

The design space of the star crash box is a = [60,120], b = [60,120], u = [0.30], v = [0,30] and t= [0.7,3]. It is wide design space which includes degenerated shapes as shown in the figure 3. The design space thus includes the square cross section, vertical and horizontal two triangular cross-sectional structure and part of honeycomb structure.

4.2. Meshing

The star crash box is meshed using Python script. Its simplified geometry allows for hex meshing on all surfaces, which reduces computational time and aids simulation convergence. The input for the mesh is the size of mesh in the code.

4.3. Material properties

Conventionally, the steel and Aluminium are used as the material of the crash box. The mild steel is used due to high tensile strength and ductility. The optimize material for the crash box is out of scope of this research. Hence for simplicity, the mild steel is taken as reference material. It has following properties.

Table 1: Material Properties

Property	Value
Density (ρ)	7830 kg/m^3
Young's modulus (E)	200 GPa
Poisson's ratio (μ)	0.3
Cowper Symond Parameter (c)	40 s^{-1}
Cowper Symond Parameter (p)	5

4.4. Boundary conditions

The boundary consists of impactor and rigid wall. One side of the crash box has the rigid wall and impactor with mass of 250 kg approaches with velocity 15 mm/ms in the other side for crashing.

5. Results and discussion

The result of the research is segregated in to optimization result, simulation result and other crashworthiness results.

5.1. Optimization results

The numerical simulation in LS dyna is combined with PSO optimization algorithm in python. After running 500 simulations in batch mode, the maximum SEA of 63777.547 J/Kg is obtained. at the values a = 72.291 mm, b = 75.314 mm, u = 20.162 mm, v = 4.978 mm and t = 0.985 mm. The PSO algorithm

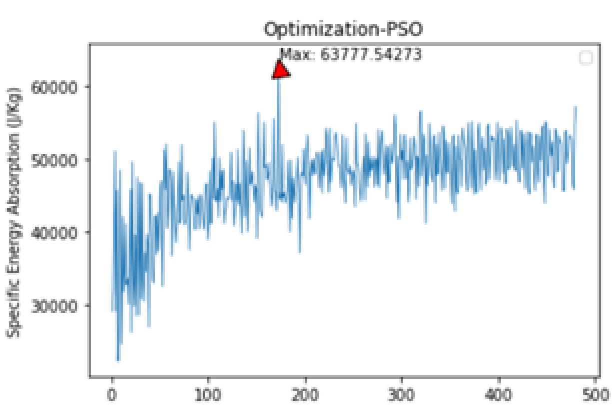

Figure 5: SEA vs No. of Iterations using PSO

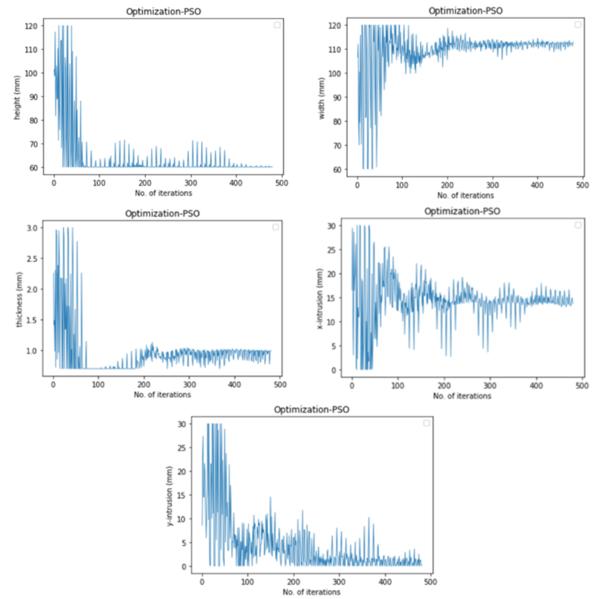

Figure 6: Geometric Parameters vs No. of iteration in PSO

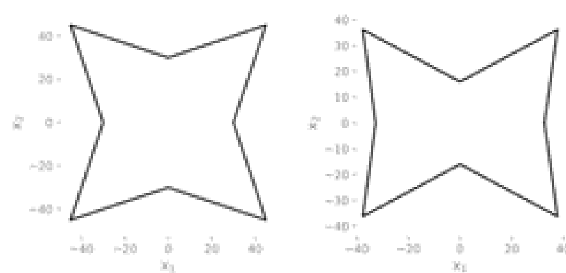

Figure 7: Baseline geometry (left) and optimized geometry (right)

don't necessarily converge for the best solution. In this case the value of SEA is about 100% more than that of baseline value. Graph of other geometric parameters vs no. of iteration is given in Figure 6.

5.2. Simulation results

The numerical simulation of crash box is done in LS dyna without optimization with baseline values. The values of geometric parameters are a= 90 mm, b = 90 mm, u = 15 mm, v = 15 mm and t = 1.85. From the simulation result, the SEA of 37948.57 J/Kg is obtained. For the optimized geometry the maximum SEA of 63777.547 J/Kg is obtained at the values a = 72.291 mm, b = 75.314 mm, u = 20.162 mm, v = 4.978 mm and t = 0.985 mm.

This shows the population-based optimization technique

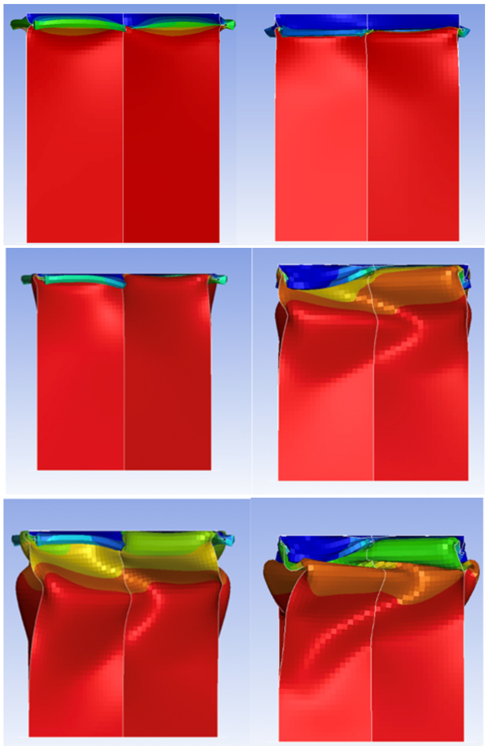

Figure 8: Baseline (left) and optimized geometry (right) at 1s (top) 2s (middle) and 3s (bottom) showing progressive buckling

can be exploited for the design of the crash box to significantly increase the specific energy absorption capacity hence increasing crashworthiness.

The energy absorbed by the crashbox depends on the geometric parameters. The optimized geometry takes the high energy in short time than the baseline in this case. The progressive bucking starts early in it as shown in Figure. Hence it absorbs more energy than the baseline geometry.

5.3. Other crashworthiness parameters

A variety of metrics are utilized to assess the crashworthiness of energy-absorbing structures. These include measures such as energy absorption (EA), specific energy absorption (SEA), peak crush force (PCF), mean crash force (MCF), and crash force efficiency (CFE). In this study, we have studied peak crush force. It is imperative to restrict and maintain PCF (Peak Crush Force) at an acceptable level in crashworthiness design, prioritizing the safety of the survival space.
In the optimized geometry, the peak crushing force is less than that in baseline geometry. Hence, the optimized geometry enhances the crashworthiness.

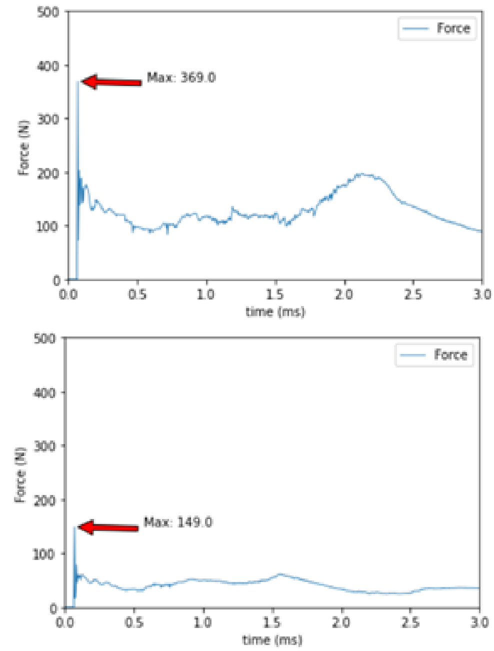

Figure 9: Force vs time graph in Baseline (top) and optimized geometry (bottom).

6. Conclusions

In this paper, the optimization of the star crash box using PSO was done. The geometric design parameters had important effect in the crashworthiness of the crash box. The values of geometric parameters in baseline geometry of star crash box were a= 90 mm, b = 90 mm, u = 15 mm, v = 15 mm and t = 1.85. From the simulation result, the SEA of 37948.57 J/Kg was obtained. Using PSO optimization algorithm, 480 simulations was run in batch mode. The maximum SEA of 63777.547 J/Kg was obtained at the values a = 72.291 mm, b = 75.314 mm, u = 20.162 mm, v = 4.978 mm and t = 0.985. The progressive bucking started early in the optimized geometry than baseline absorbing more energy. In the optimized geometry, the peak crushing force was less than that in baseline geometry. Hence, the optimized geometry enhanced the crashworthiness. So, the population-based optimization technique can be instrumental for the design of crash box which shows highly non-linear crash behavior.

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