

Modeling of Crumple Zone for Vehicle Crash Simulation using Multi-Layers Kelvin-Voigt Model with Non-Linear Spring Optimized Using Gravitational Search Algorithm

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Abstract: This study focuses on the development of a crumple zone model for vehicle crash simulation. The proposed model employs a multi-layer Kelvin-Voigt model optimized using the Gravitational Search Algorithm (GSA). A key innovation of the proposed model lies in its representation of springs as non-linear elements. This is achieved by considering both their elastic and plastic stiffness, enabling a more realistic depiction of the material behavior. The model parameters to be optimized using GSA are damping values, elastic stiffness, plastic stiffness and the limit of elastic deformation of Kelvin-Voigt model in all layers. The objective is to improve the fidelity of crash simulations for enhancing vehicle safety design. The simulation results obtained using the developed model is compared with experimental data from vehicle crash tests in terms of deceleration and deformation characteristics of crumple zones during collisions. The simulation results shows that the model responses of both deceleration and crumple zone deformation closely follow the crash test data.

Keywords: crumple zone, vehicle crash, Kelvin-Voigt, non-linear spring, GSA and gravitational search algorithm.

1. INTRODUCTION

Road accidents are one of the leading causes of death and injury worldwide, with millions of people losing their lives or sustaining injuries each year. In recent years, vehicle safety has become a top priority for manufacturers, regulators, and consumers alike. The crumple zone is one of the key safety features in modern cars that has helped to reduce the severity of injuries in collisions. The crumple zone is a specific area of the car that is designed to deform during a collision, absorbing the energy of the impact and reducing the force of the collision on passengers [1].

The behavior of crumple zones during a collision is complex and difficult to model accurately. In order to design safer cars, researchers and engineers need to have a better understanding of the behavior of crumple zones during a collision. One way to achieve this is through computer simulations [2] that can accurately model the physics of the collision and the deformation of the crumple zone.

One of the challenges in simulating the behavior of crumple zones is the complexity of the material properties involved. The behavior of the material during deformation is highly nonlinear and dependent on factors such as strain rate, temperature, and pressure [3]. To accurately model the behavior of crumple zones, it is necessary to use sophisticated material models that can capture these nonlinear effects. There are several approaches to modeling the behavior of crumple zones in vehicle crash simulations. One approach is to use a finite element method (FEM) to simulate the deformation of the material in the crumple zone [4,5]. This method involves dividing the material into small elements and calculating the deformation of each

element under the applied loads. Another approach is to use a lumped parameter model, which is a simplified model that uses a small number of parameters to describe the behavior of the crumple zone.

In recent years, there has been a growing interest in using analytical approach to simulate the behavior of crumple zones. These models use the combination of mass, spring and damper with different properties to better capture the complex deformation behavior of the crumple zone [5, 6]. This approach has shown promise in improving the accuracy of vehicle crash simulations and designing safer cars. In this paper, a new approach for modeling the behavior of crumple zones in vehicle crash simulations is presented. The approach uses a multi-layer Kelvin-Voigt model that is optimized using the GSA. The Kelvin - Voigt model is a viscoelastic material model that can accurately capture the nonlinear behavior of the material during deformation. The key element of the proposed model is the stiffness of spring element is defined in both its elastic and plastic characteristics.

The powerful optimization technique known as the GSA algorithm allows the efficient exploration of the model parameter space to identify the optimal set of parameters that best align with the experimental data [7]. In this study, the effectiveness of the proposed modeling approach is demonstrated by comparing the simulation results with the experimental data derived from real crash tests. The results show that the behavior of crumple zones during a collision is accurately modeled, and valuable insights into the physics of the collision are provided through the approach. The utilization of this approach enables the design of safer cars and enhances the accuracy of crash simulations, ultimately contributing to the reduction of injuries and fatalities

caused by road accidents.

2. CRUMPLE ZONE MODEL FOR VEHICLE CRASH SIMULATION

The mass-spring-damper model, also known as the Kelvin-Voigt model [8], is a mathematical representation used to describe the behavior of certain physical systems, particularly those involving oscillations or vibrations. It consists of a mass connected to a fixed point by a spring and a damper arranged in parallel. In this study, the front crumple zone is modeled using a combination of six-layer Kelvin-Voigt models, with each layer having its own mass, spring stiffness, and damping parameters. The collision force is initially applied to the front-end Kelvin-Voigt layer and then transferred to the vehicle body through the remaining six layers. The proposed model is shown in Fig. 1.

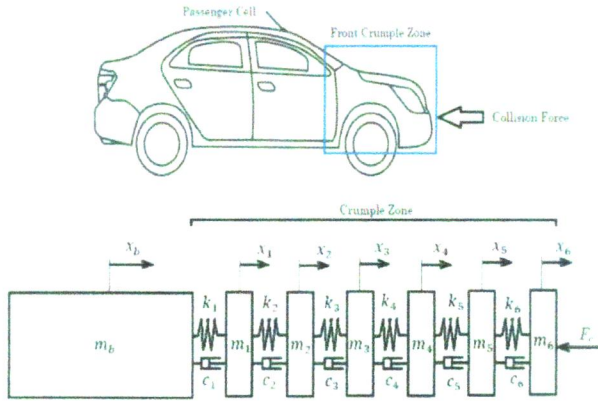


Fig. 1. Multi-layer Kelvin-Voigt for crumple zone

Equations of motion that establish the relationship between the motion of the vehicle body and the behavior of the crumple zone under collision forces are derived using Lagrange's equation with Rayleigh's dissipative function [9], as described in Eq. (1). The Lagrange function, denoted by L is defined as $L = T - V$, where T is the total kinetic energy and V is the total potential energy of the system. The kinetic and potential energy of a system depends on the coordinates of all layers are defined as $T = T(x_b, x_1, x_2, x_3, x_4, x_5, x_6)$ and $V = V(x_b, x_1, x_2, x_3, x_4, x_5, x_6)$. D is Rayleigh dissipation function, where for a single linear viscous damper, Rayleigh dissipation function is given by $D = \frac{1}{2}c(\dot{x})^2$. In this case, Q is collision force acting at the front end mass, displacement and velocity of mass in all layers are denoted as q_i and \dot{q}_i , where i is the number of layers.

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \left(\frac{\partial L}{\partial q_i} \right) + \frac{\partial D}{\partial \dot{q}_i} = Q \quad (1)$$

The equations of motion of the proposed multi-layer

crumple zone are shown in eqs. (2) ~ (8) as follows

$$\ddot{x}_b = \frac{1}{m_b} (c_1(\dot{x}_1 - \dot{x}_b) + k_1(x_1 - x_b)) \quad (2)$$

$$\ddot{x}_1 = \frac{1}{m_1} (c_2(\dot{x}_2 - \dot{x}_1) - c_1(\dot{x}_1 - \dot{x}_b) + k_2(x_2 - x_1) - k_1(x_1 - x_b)) \quad (3)$$

$$\ddot{x}_2 = \frac{1}{m_2} (c_3(\dot{x}_3 - \dot{x}_2) - c_2(\dot{x}_2 - \dot{x}_1) + k_3(x_3 - x_2) - k_2(x_2 - x_1)) \quad (4)$$

$$\ddot{x}_3 = \frac{1}{m_3} (c_4(\dot{x}_4 - \dot{x}_3) - c_3(\dot{x}_3 - \dot{x}_2) + k_4(x_4 - x_3) - k_3(x_3 - x_2)) \quad (5)$$

$$\ddot{x}_4 = \frac{1}{m_4} (-c_4(\dot{x}_4 - \dot{x}_3) + c_5(\dot{x}_5 - \dot{x}_4) - k_4(x_4 - x_3) + k_5(x_5 - x_4)) \quad (6)$$

$$\ddot{x}_5 = \frac{1}{m_5} (c_6(\dot{x}_6 - \dot{x}_5) - c_5(\dot{x}_5 - \dot{x}_4) + k_6(x_6 - x_5) - k_5(x_5 - x_4)) \quad (7)$$

$$\ddot{x}_6 = \frac{1}{m_6} (F_c - c_6(\dot{x}_6 - \dot{x}_5) - k_6(x_6 - x_5)) \quad (8)$$

In this study, the spring constants k_1, k_2, k_3, k_4, k_5 and k_6 are modelled with a more realistic approach that incorporates both the elastic and plastic behavior of materials. Fig. 2 presents a typical stress-strain curve obtained from a compression test conducted on a carbon steel material. When a compression test is subjected to relatively low pressure, the deformation completely disappears once the stress is removed. This region of the curve corresponds to the elastic behavior of the material, as indicated by the nearly straight line. However, as the stress level increases, the material surpasses its elastic limit, leading to permanent deformation even after the force is removed. This portion of the curve is known as the plastic region, where the material retains its deformed shape. For each spring, the stiffness is defined as elastic stiffness (K_{ie}) if $\Delta x \leq \delta_i$ and plastic stiffness (K_{ip}) if $\Delta x > \delta_i$.

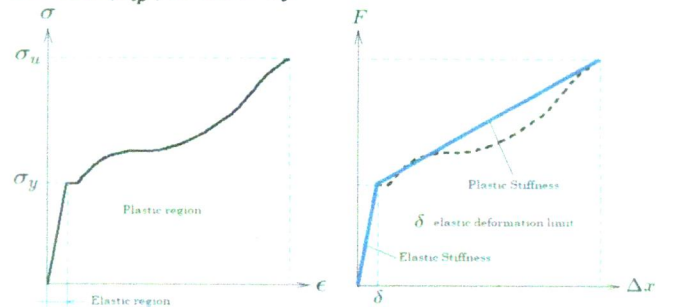


Fig. 2. Typical behavior of carbon steel under compressive load

3. GRAVITATIONAL SEARCH ALGORITHM

GSA is a metaheuristic optimization algorithm inspired by the laws of gravity and celestial interactions [10]. GSA simulates the gravitational forces among celestial objects to solve optimization problems. If there

are N agents with j -dimension, the position of the j -th agent is shown in eq. (9).

$$X_j = (x_j^1, x_j^2, \dots, x_j^d) \quad (j = 1, 2, \dots, N) \quad (9)$$

At the t -th time, the force acting on the j -th agent from the k -th agent is given by eq. (10).

$$F_{jk}^d = G(t) \left(\frac{m_k(t)m_j(t)}{r_{jk}(t)+\varepsilon} \right) (x_j^d(t) - x_k^d(t)) \quad (10)$$

where G is the current gravitational constant at time t , m_j and m_k represents the current masses of j and k agents, r_{jk} is the current distance between the two agents, x_j and x_k denotes the current position of the two agents, and ε is a small constant. By iteratively updating the positions and accelerations of solutions based on these forces, GSA aims to converge towards an optimal or near-optimal solution.

In this study, the parameters of crumple zone that will be optimized using GSA are damping values and both elastic and plastic stiffness of spring as well as the limit of elastic deformation of Kelvin-Voigt model in all layers, they are $C_1, C_2, C_3, C_4, C_5, C_6, K_{1e}, K_{1p}, K_{2e}, K_{2p}, K_{3e}, K_{3p}, K_{4e}, K_{4p}, K_{5e}, K_{5p}, K_{6e}, K_{6p}$ and δ . The parameters of GSA in optimization process are set as follows:

D (the number of dimension)	: 19
N (the number of particles)	: 80
T (the number of iteration)	: 50
G (gravitational constant)	: 40

The objective of optimization is to ensure that the response of the proposed crumple zone model closely matches the crash test data available in the literature, specifically in terms of body acceleration and crumple zone deformation [11]. To achieve this, GSA is employed, which is programmed to minimize a selected cost function. In this case, the cost function is defined as the root mean squared value of body deceleration and crumple zone deformation. By minimizing this cost function, GSA aims to find the optimal parameters or configuration for the crumple zone model that best aligns with the desired crash test data.

4. OPTIMIZATION RESULTS

During a collision, the vehicle body experiences rapid deceleration due to the forces exerted on it. These forces are primarily a result of the interaction between the vehicle and the object it collides with, such as another vehicle, a barrier, or a fixed structure. The deceleration response is influenced by various factors, including the vehicle's mass, speed, structural design, and the nature of the impact.

Immediately after the collision, the vehicle body undergoes a rapid decrease in velocity as a result of the energy transfer and deformation that occur. The crumple zones, which are designed to absorb and dissipate energy, play a crucial role in this deceleration process. As the crumple zones deform and collapse, they absorb a significant portion of the impact energy, thereby

reducing the forces transmitted to the occupants. In this study, deceleration of the body and deformation of crumple zone from the responses of the proposed model are compared with the crash test data obtained from [12].

4.1 Deceleration Response of Vehicle Body after Collision

The deceleration response of the vehicle body after a collision is depicted in Fig. 3. The figure illustrates a close agreement between the deceleration response obtained from the model and the deceleration data acquired from crash tests. Notably, the first peak at around 17g corresponds to the point at which the collision force surpasses the elastic limit of the crumple zone, resulting in plastic deformation. Subsequent peaks of more than 30g occur when the collision force exceeds the ultimate stress of the crumple zone material. Following these peaks, the deceleration response gradually returns to a stable position approaching zero.

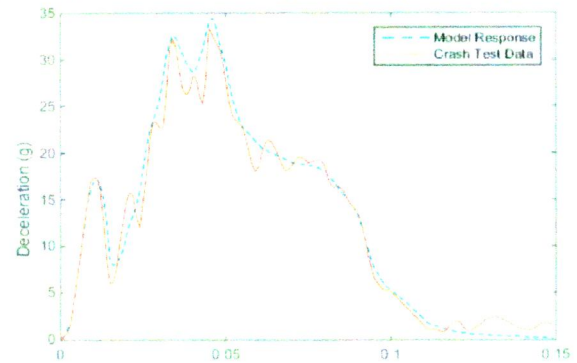


Fig. 3. Deceleration response of the model compared to crash test data during collision

4.2 Deformation of Crumple Zone

When the collision force surpasses the elastic limit of the crumple zone, it undergoes plastic deformation. This signifies that the material within the crumple zone experiences permanent changes in shape and dimensions, and it is unable to fully restore its original form after the collision. The plastic deformation enables the crumple zone to effectively absorb a considerable amount of energy, thereby reducing the impact forces transmitted to the vehicle's occupants. The deformation response of the proposed model is depicted in Fig.4, alongside the corresponding crash test data. Notably, the model's response closely aligns with the experimental data, indicating its accuracy in replicating the deformation behavior observed in real-world collisions.

4.3 Performance of GSA

Fig. 5 illustrates the performance of the GSA in multi-objective optimization, specifically aimed at minimizing the error between the model response and crash test data in relation to both body deceleration and crumple zone deformation concurrently. The results clearly demonstrate the algorithm's rapid convergence, effectively minimizing the cost function and efficiently

searching for optimal parameters. It can be seen from the figure that by iteration 35, the optimization process has already achieved convergence. It is worth noting that further enhancement of GSA performance can be achieved by increasing the number of particles and iterations. However, such improvements would come at the expense of higher computational costs.

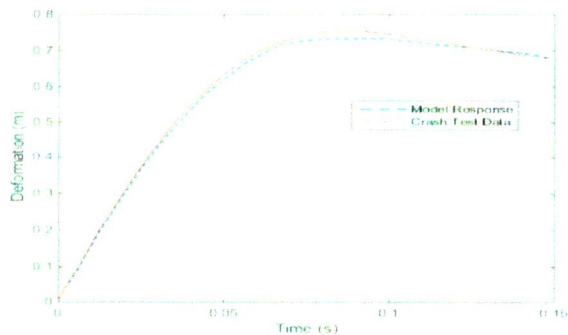


Fig. 4. Crumple zone deformation response of the model compared to crash test data during collision

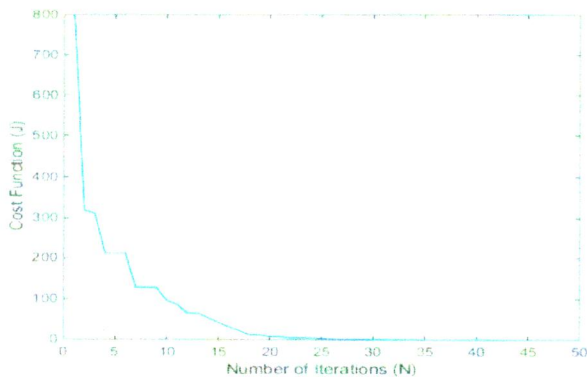


Fig. 3. Speed of convergence of GSA

5. CONCLUSIONS

In conclusion, this study successfully addresses the development of a crumple zone behavior model for vehicle crash simulation by employing a Multi-Layer Kelvin-Voigt Model with non-linear spring element optimized using the GSA. The inclusion of both elastic and plastic stiffness of spring allows for a more realistic depiction of the material properties. By comparing the simulation results obtained using the developed model with experimental data from vehicle crash tests, the study confirms the accuracy and reliability of the model. The comparison specifically focuses on the deceleration and deformation characteristics of the crumple zones during collisions. The simulation results demonstrate that both the deceleration and crumple zone deformation responses closely align with the crash test data. This indicates that the developed model effectively captures the dynamic behavior of the crumple zones.

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REFERENCES

- [1] V. Lukoševičius, D. Juodvalkis, A. Keršys, and R. Makaras, "Investigation of Functionality of Vehicle Crumple Zones Recovered after a Traffic Accident," *Applied Sciences*, vol. 13, no. 3, pp. 1686, 2023.
- [2] M.N. Bin Kamarudin, J.S. Mohamed Ali, A. Aabid, and Y.E. Ibrahim, "Buckling Analysis of a Thin-Walled Structure Using Finite Element Method and Design of Experiments," *Aerospace*, vol. 9, p. 541, 2022.
- [3] X. Jia, K. Hao, Z. Luo, and Z. Fan, "Plastic Deformation Behavior of Metal Materials: A Review of Constitutive Models," *Metals*, vol. 12, no. 12, p. 2077, 2022.
- [4] U. Idrees, S. Ahmad, I. A. Shah, M. Talha, R. Shehzad, M. Amjad, and S. S. Rahiamin Koor, "Finite element analysis of car frame frontal crash using lightweight materials," *Journal of Engineering Research*, vol. 11, no. 1, p. 100007, 2023.
- [5] A. Farokhi Nejad, R. Alipour, M. Shokri Rad, M. Yazid Yahya, S. S. Rahimian Koor, and M. Petrù, "Using Finite Element Approach for Crashworthiness Assessment of a Polymeric Auxetic Structure Subjected to the Axial Loading," *Polymers*, vol. 12, no. 6, pp. 1312, 2020.
- [6] V. Lukoševičius, R. Kersys, A. Keršys, R. Makaras, and J. Jablonskytė, "Three and Four Mass Models for Vehicle Front Crumple Zone," *Transport Problems*, vol. 15, pp. 79-92, 2020.
- [7] F. Su, C. Duan, and R. Wang, "Analysis and improvement of GSA's optimization process," *Applied Soft Computing*, vol. 107, p. 107367, 2021.
- [8] M.A. Meyers and K.K. Chawla, "Section 13.11 of Mechanical Behaviors of Materials," in *Mechanical Behavior of Materials*, Prentice Hall, Inc., 1999, pp. 570-580.
- [9] E. Virga, "Rayleigh-Lagrange formalism for classical dissipative systems," *Physical Review E*, vol. 91, p. 013203, 2015.
- [10] R. Shankar, N. Ganesh, R. Čep, R. C. Narayanan, S. Pal, and K. Kalita, "Hybridized Particle Swarm—Gravitational Search Algorithm for Process Optimization," *Processes*, vol. 10, no. 3, p. 616, 2022.
- [11] S. Kim and H. Cho, "A study on the stiffness change of a passenger car's front frame body before and after a collision accident," *Int. J. Mech. Eng. Robot. Res.*, vol. 10, no. 5, pp. 270-275, 2021.
- [12] M. Elkady, A. Elmarakbi, J. MacIntyre, and M. Alhariri, "Collision mitigation and vehicle transportation safety using integrated vehicle dynamics control systems," *J. Traffic Transp. Eng.*, vol. 4, no. 1, pp. 1-20, 2017.