Finite Element Method's Application in Vehicle Safety Design

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Received November 15, 2023
Accepted February 17, 2024
Electronic access February 29, 2024

Presently, people are putting more emphasis on vehicle designs due to an average 1.3 million death caused by road traffic crashes each year. Through experiment, people aim at reducing the force acted on both the vehicles and occupants when a car crash takes place, thus mitigating the effect of collision on vehicles and increasing the human survival rate during accidents. Previous studies in the field of vehicle safety designs utilized a specific method named the finite element method. This method provide convenience to the field of engineering and ensure efficiency in many practical questions, including vehicle safety designs. The purpose of this paper is to provide an overview for the development of the finite element method including how it contributes to the field of engineering and explain how the finite element method is used for simulations in vehicle safety designs. This paper will introduce how the implementation of the finite element method in vehicle safety designs alleviates the human fatality rate during accidents, thus raises human survival rate overall. Furthermore, this paper will provide specific procedure of applying the finite element method to the area of vehicle safety designs.

Introduction

Account for 2.2% of all death globally[1] road traffic injuries are presently the major cause of unintentional injuries[2]. In order to reduce the severity of vehicle collisions, several traffic barrier systems and car designs have been improved[3]. As there is an escalating complexity in circumstances of crashes, full-scale physical testing is no longer available due to the requisite high-cost and lengthy time to simulate practical conditions. In lieu of this, numerical methods including the finite element method have become a more feasible approach to facilitate crash analysis[4]. In many of the collision models, the finite element method is implemented as a central means based on its relative affordability, easy availability, lower requirements, and comparable accuracy compared to physical vehicle crash testing[5,6]. It has solved the problems of cost and time that exist in physical testing, thus become key solutions to engineering projects that encounters difficulty because of limitation of physical testing.

Vehicle safety design plays a vital role among the several factors that account for the advancement of human safety. Well-designed vehicles can effectively reduce the impact induced by collisions and as a result, increase human survival rate and lessen the cost[7] spent on maintenance of vehicles each year. Presently, vehicle safety system is usually divided into two parts, passive and active safety applications. Active applications reduce the chance for car crash to happen, while passive applications lessen the injury made to people and the harm done on vehicles[8]. Typical examples of passive applications include road safety barriers and crumple zones. Application of the finite element method to these designs can greatly shorten the time used on simulation and improve the efficiency of accomplishing the whole process of modeling compared to testing in practical situations[5].

Finite Element Method

The finite element method is a numerical method for solving differential equations in the area of engineering and mathematical modeling[9]. It is developed due to people's aim at modeling physical incidents and refining the efficiency of engineering procedures. This method involves dividing a model into a large number of tiny sections in a process called meshing and applies specific physics theorems, such as conservation of momentum, separately to each of these sections in order to analyze physical quantities such as stress and displacement of an object. In a case where a collision between two cars happen, the finite element method is able to provide facility with estimating the force that these cars endure and the deformation that they encounter since it possesses the ability to accomplish analytic geometric and solve complex differential equations. The available computer codes of this method avoids the problems of inaccuracy during calculation and guarantees the efficiency of engineering production. With the aid of more powerful computers, the finite element method is now a major method used in engineering applications[10,11].

As shown in Table 1, the history of the finite element method can be traced back to the 1950s, when a method considered to be the earliest form of finite element method was established. In 1954, John Argyris and M.J.Turner published a paper on aerospace engineering, in which a method called Matric Stiffness Method was implemented. In this case, Turner thought of simulating the stress imposed on aircraft wings by dividing the

Time Period	Significant Events	Contribution to FEM and Vehicle Safety Design
1954	John Argyris and M.J.Turner published a paper on aerospace engineering, in which a method called Matric Stiffness Method was implemented	the prototype of the finite element method was proposed at the first time
1960	Ray William Clough published a paper relevant to plane stress analysis that coined the phrase Finite Element Analysis	the phrase Finite Element Analysis was coined
1962	Clough published a new paper about analysis of a Gravity Dam with more accurate calculation	the finite element method started to became popular and known by more people
1960s	E.L.Wilson of UC Berkeley developed the first finite element open-source software	application of the finite element method became broader
1960s	L.R.Herman evolved the mixed variation principle for incompressible solids	the precision of the finite element method was improved
1970s	T.Belytschko, K.C.Park and TJR Hughes used different time integration method with damping control to resolve nonlinear structural dynamic problems	study of an object's continuous motion was enabled and basis for inquiry into vehicle's crash behavior was provided

Table 1 Timeline for the Development of the Finite Element Method

skin of the aircraft into a finite number of triangles and placing them as the representative of the skin. Argyris then improved the method to make it suitable for engineering structures. At about the same time, this method was advanced and became proper for fragments with arbitrary shape [12]. Even though, the finite element method was not well-known until after a decade in 1960s.

In 1960, Ray William Clough published a paper relevant to plane stress analysis that coined the phrase finite element analysis. However, this paper did not invoke much attention because most of the calculations in this paper are inaccurate due to lack of computers with efficient calculating ability. Still, this paper left a strong impression on Professor O. C. Zienkiewicz, a faculty at Northeastern University, who then invited Clough to present a seminar to his students. After a few conversation with Clough, Zienkiewicz agreed to become a supporter of finite element method and a collaborator of Clough's research [13].

Along with the development of computers with more powerful calculating ability in the Berkeley campus, the invention of IBM704 [14], a computer, made it possible to model practical structure using fine meshes. In September 1962, Clough published a new paper about analysis of a Gravity Dam. Unlike the previous paper that he published, this article attracted many people to join him with the study of the finite element method because of its inclusion of more accurate data with the help of IBM704. The finite element method then became more well-known and experienced great progress during that period.

Another significant event during this time period is the development of the first finite element open-source software by E.L.Wilson of UC Berkeley. This accomplishment appends greater accessibility to the finite element method and allows widespread utilization of the finite element method in different academic fields. Along with this achievement, Oden and Best wrote the first finite element method codes at that time [12]. This expanded the application of the finite element method to simulations of more complex circumstances and increased the efficiency since the software abbreviated the procedure of writing codes in the initial application of the finite element method [15].

From Clough's second paper stemmed expeditious development in both finite element method research and its applications. The public began setting more attention on the mixed variational principle based finite element method. Among a substantial number of achievements, the most significant one is the mixed variation principle for incompressible solids evolved by L.R.Herman. This allows exploration of solids and fluids at finer scale and suits the finite element method for more precise interelement continuity requirements [16,17].

During 1970s, the focus of research were shifted onto applying FEM to objects with dynamic behavior. To enable the study of dynamic states, various time integration method were invented. This method allows for the consideration of the factor time in the process of applying the finite element method. The broad process of time integration method is to divide a period of time into finite sections and to solve the unknowns for each specific section separately[18]. The key development in this period is using different time integration method with damping control to resolve nonlinear structural dynamic problems, which is suggested by T.Belytschko, K.C.Park and TJR Hughes[19]. This allows investigation into object's action at different instants and study of an object's continuous motion over a longer time periods, thus provide a basis for inquiry into vehicle's crash behavior.

Presently, finite element method is very much favored by people majored in engineering as it simplifies the process of devising simulations which includes large amount of complicated calculation. It lowers the threshold of generating a simulation since compared with the necessity of comprehension of complex theories that lie below the physical comprehension before the invention of the finite element method, people can use the finite element method to generate a simulation once they learn to run the program[11]. Compared to modeling in practical conditions, people can obtain the results of the simulations more rapidly and more accurately with the aid of computers. In the field of engineering, the finite element method reduce the need for physical testing, which eventually leads to escalating efficiency when iterating and optimizing designs[20]. As a result, there were comments on finite element method that this method "fundamentally revolutionized the way we do scientific modeling and engineering design, ranging from automobiles, aircraft, marine structures, bridges, highways, and high-rise buildings[12]."

Among the many applications of finite element method, vehicle safety design was one area where the implementation of finite element method remarkably elevate the efficiency of conducting the simulation. Most of the constructions of vehicle safety designs involved the assistance of finite element method, including the setting up of crumple zones and the plotting of roadside barriers. Through the process of manufacturing automobile designs, the influence that the invention of finite element method imposed on the engineering field can be thoroughly reflected.

Vehicle Safety Design

The finite element method had been a central method of conducting simulations in the field of vehicle safety design for decades. Its original usage is to predict the approximate deformation of guardrails or barriers in collision with small-sized vehicles. When applying the finite element method, a complicated structure is divided into small elements while objected at calculated stress-strain relationship on each segment. Software Programs enhance the application of physical principles, such as dynamic equilibrium and the conservation of momentum. Followed by the development of computer system and technology, the calculation capability of computers are improved and nonlinear finite element analysis techniques become available for solving more complex impact problems[19]. Presently, it is more often used when analyzing road side hardware[21].

One of the major goals of most passive vehicle safety design is to lengthen the time over which a change in velocity of a vehicle occurs in collisions so that less force will be exerted on people during the deceleration process and the survival rate during collision can be ensured. The physics involved can be expressed by equation (1).

$$F = \frac{dp}{dt} \tag{1}$$

In equation (1), F is the force endured by the car during the collision, p represent momentum which can be calculated by an object's mass times its velocity, and t stands for time. According to the impulse equation, as long as the change in momentum during the process stays constant, the longer time the vehicle takes to cede its velocity to zero, the smaller the force exerted on the vehicle is. This is the role that vehicle safety designs, such as road safety barrier, play in collision: reducing the force applied to the vehicles by increasing the time during which a change in velocity occurs[22]; meanwhile, this is when the finite element method can be applied to vehicle safety design: the force that the vehicles endured can be calculated once the initial condition is inputted and the differential equation is resolved.

Another effect of passive vehicle safety designs is to dissipate the crash energy through its deformation during collisions. During the process of plastic deformation or fracture, energy absorption takes place[23]. By distributing most of the energy originally presented in the system to the transformation in shapes of objects, these designs effectively reduce the impact brought by collision on both people and vehicles.

The finite element method is often utilized in designs of structures such as crumple zones and car frames because of its high flexibility and low cost. In the process of engineering as a whole, the finite element method allows for investigation into different designs and scenarios under varying load conditions. Money and time required in vehicle collision simulation are lessen since it reduce the necessity for physical tests[24].

In the case of vehicle safety designs, the finite element method is applied by first constructing a model in one of the finite element software. Some of the common used software in crash simulation are LS-DYNA, freeFEM, freeCAD and SimScale. Among these softwares, LS-DYNA is famous for its explicit dynamic analysis; freeFEM is a free finite element analysis software known for its easy accessibility; freeCAD permits the use of external solvers such as CalculiX and OpenFoam; the platform of SimScale allows users to run more simulations[25]. The model creation process involves four steps: meshing, mesh verification, parts connection and initial penetration clean up. The generation of meshes is to split a geometric surface or volume into finite number of fragments on a very small scale. Two-dimensional surface is usually divided into triangles or quadrilaterals while three-dimensional volume is usually divided into tetrahedrons. An example for meshing of cars is shown in figure 1.

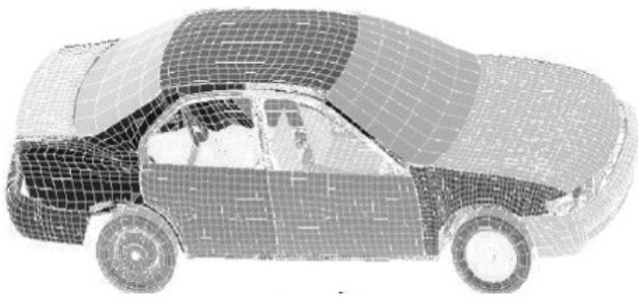

Fig. 1 example of car meshes[26]

In Figure 1, different sections of the car are tinted with disparate colors in order to make different parts of the car more distinguishable and permit more direct and precise examination when the researchers analyze this model. At parts where more complex calculation is needed, such as at junctions of two fractions or at the front of the car usually where collision happens, finer details are installed and the surface is divided into smaller elements as shown in the image[26,27]. In order to obtain results with higher accuracy, the division into hundreds of segments is required. The distribution of mass and material used shall also be inserted into the simulation, and different combination of these two factors can lead to different conclusions.

The process that follows is to deploy the model into practical depiction of events. The most frequently used method is to deposit the model into circumstances where there is a wall or a barrier that collides with the vehicle model. One example is to load the car's velocity as a variable and to calculate the force exerted on the car through the impulse equation. The calculation process will be done by computer codes. Table 2 lists the possible combinations of output used in simulation of vehicle safety designs.

Maximum deformation of the crumple zone can be estimated by the software due to distinct properties of different structures and materials. Usually, a chart or a graph is made to provide a visual representation for the data collected through simulation, and a criteria is employed to determine whether a design is qualified for use in authentic surroundings[32]. In many visualizations of vehicle impact, the darkness of colors is implemented as an indicator of value of certain variable, as shown in Figure 2.

In Figure 2, the warmness of the color acts as an indicator of total deformation. The warmer the color, which is at the front of the car, the greater the deformation. The caption at the left is a scale that corresponds different colors to different ranges of deformation.

The common errors during the process of applying the finite element method include improperly defined material, imprecise meshes and high aspect ratio. Imprecise meshes is usually referred to mesh elements with overly distorted shapes and elements too large or too small in size. They will introduce inaccurate results and excessive computation. To mitigate potential discrepancies caused by the mentioned reasons, a thorough understanding toward geometry and selection of an appropriate finite element method software and element type, such as element shape, are essential steps. Furthermore, implementation of proper mesh refinement and consistent degree of freedom should be carefully considered in order to ensure accuracy of the result[33].

Although there may still be some discrepancies as described above between computational results and practical results, the finite element analysis functions as a economical and efficient method for conducting crash tests. The large amount of calculation that is needed to be completed in the finite element analysis will be eventually accomplished by computers owing to its compatibility with computer codes, and the fact that it is simulated on computers instead of using actual material in factual condition ascribes to its low cost. The attainability of the finite element method on certain computer software contributes to the higher quality of vehicle designs, thus promotes the development of road engineering and increases human survival rate when accidents happen.

Human Survival Rate

Car accidents account for a certain portion of death per year worldwide. Every year, approximately 1.19 million people died from crash accident, while 20 to 50 million people suffered from non-fatal injuries[34]. The causes of road traffic accident can be mainly ascribed to three categories of factors: human factors, road, and vehicles, in which human factors account for 93% of the accidents, road factors account for 34% of the accidents, and vehicle factors account for 12% of the accidents[35].

Within the road factors and vehicle factors which involves interaction between people, vehicles and road environment, vehicle safety design acts as one of the fundamental system risk factors. Vehicle safety designs can be referred to several risk factors, such as crash barriers and crash protective designs. They assist with the reduction of risk and crash injury severity during collisions. The objective of vehicle engineering is to devise crash protective design that effectively protect people inside in the event of a crash, thus increase human survival rate during collisions[36]. This objective is typically achieved by reducing the kinetic energy that is being passed to passengers inside a car during collisions to the greatest extent, since the instantaneous velocity change of a person is directly related to the severity of injuries—the greater the instantaneous velocity change, the greater the severity of injuries[37].

The application of the finite element method in the simulations of vehicle crash behavior enables the calculation of more precise data on the performance of cars in real crashes. During

Object	Software Output
Road Safety Barrier[28]	• Time-ASI graph (ASI is a measure of vehicle safety severity) • Simulated visualizations of vehicle impact
Road Restraint Barrier[29]	• Simulated visualizations of the displacement of the road restraint barrier under an applied load force • Force-Displacement graph • Maximum equivalent stress
Safety Glass[30]	• True stress-Strain graph • Visualization of impact at different instants • Force-Displacement graph
Structural Crash Simulation[27]	• Side view of the model before and after impact • Time-Acceleration graph
Car Frame Frontal Crash[31]	• Calculation of boundary conditions for simulated test • Deformation of car frame at different instants • Energy-Time graph (Reflection of energy transformation) • Deformation-Termination time graph

Table 2 Software output in simulations of different objects.

simulations, an indicator of risk can be set due to several factors, such as acceleration and the force acting on passengers during collision, and the finite element method can be applied to calculate the risk level of each design. Eventually, crash protective design with the least exposure to risk can be chosen[36].

Vehicle collisions can be classified into different categories, such as head-on collisions or side impact collisions, and the indicators of risk set is dependent of the circumstance that it is being applied to. In the cases of pedestrian and cyclist crashes, the vehicle's impact speed employs as an appropriate indicator of risk. The greater the mean impact speed, the higher the fatality rate of the passengers. In the cases where two vehicle crashes, a vehicle's change in velocity is directly related to injury severity and act as a more suitable risk indicators than impact speed. As the change in velocity of the vehicles increases, the probability of suffering from severe injuries increases. In the cases of collisions with road infrastructures, the vehicle's change in velocity is relevant with the vehicle's masses, its impact speed and the angle between their paths. All of these factors are taken into consideration when deriving risk indicators[37].

When utilizing the finite element method in specific practical situations, risk indicators can be calculated due to different circumstances without physical experiments. By inserting different models into the finite element method software, the risk indicators in different circumstances can be computed. The finite element method enables the selection of the vehicle design with the lowest risk level at the lowest cost and the quickest speed, thus leads to a reduction in fatal and serious injury risk among

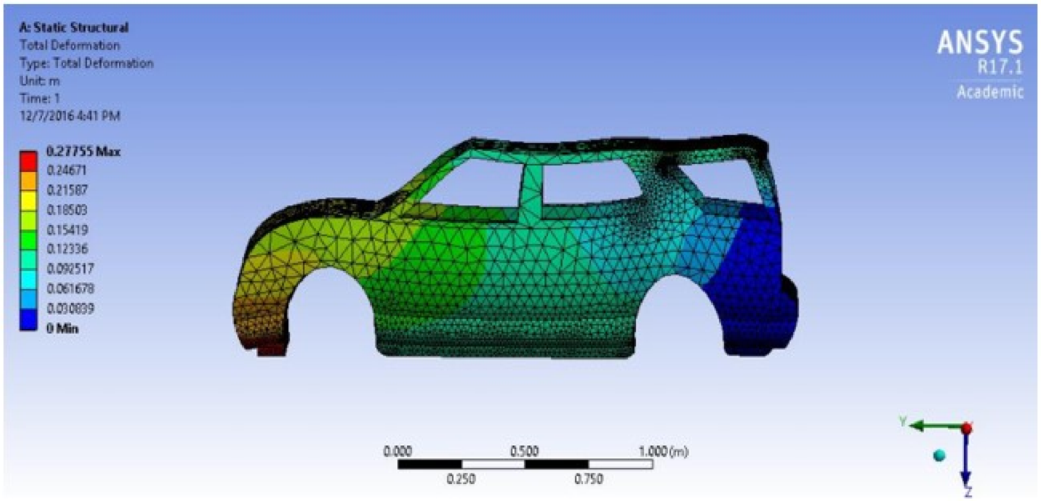

Fig. 2 Total Deformation of Stainless Steel Car[32]

car occupants.

According to statistic, from 1970 to 2021, the crash fatality rate per 100,000 population has decreased from 26.3 to 12.9, as shown in Figure 3.

In Figure 3, the green line represents the number of death caused by crash accidents each year, while the blue line represents the fatality rate per 100,000 population each year. The blue line shows a downward tendency from 1970 to 2021, meaning that there is a decline in car crash fatality rate during this period. Inside the many factors that might bring effect to the fatality rate, vehicle safety designs and road safety designs stand for a large proportion. In the field of vehicle and road safety design, the finite element method has propelled revolutionary progress, advancing the efficiency and cost of establishing simulations with the help of its computer program. Thus, the finite element method contributes to the reduction in human fatality rate during traffic accidents[38].

Conclusion

The application of the finite element method in the domain of vehicle safety design has proven itself to be a powerful tool that can be instilled into engineering problems. Its implementation in vehicle safety design gives evidence to its widespread application in the engineering field and its significance in proceeding towards the goal of vehicle engineering. One example of which is its ability of calculating the level of risk under different situation and selecting a design that best suits the engineer's objection, decreasing injury severity during collisions. Along with the development of commercial software, computers with strengthened calculation ability will be invented and the precision of the finite element method will be enhanced. Its accessibility also gets along well with the society's pursue after efficiency. Attributable to its affordability and capability, the finite element method will continue to be a major device used in engineering in the future, providing efficiency to engineers and saving lives in the events of car accidents.

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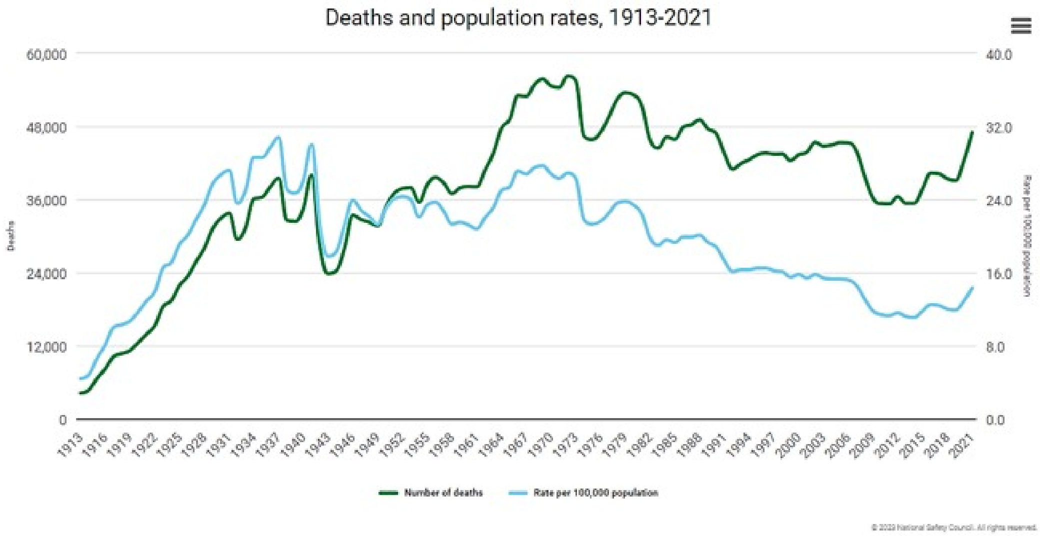

Fig. 3 Deaths and Population Rates, 1913-2021 [38]

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