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Determination of penetration depth at high velocity impact using finite element method and artificial neural network tools

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Abstract

Determination of ballistic performance of an armor solution is a complicated task and evolved significantly with the application of finite element methods (FEM) in this research field. The traditional armor design studies performed with FEM requires sophisticated procedures and intensive computational effort, therefore simpler and accurate numerical approaches are always worthwhile to decrease armor development time. This study aims to apply a hybrid method using FEM simulation and artificial neural network (ANN) analysis to approximate ballistic limit thickness for armor steels. To achieve this objective, a predictive model based on the artificial neural networks is developed to determine ballistic resistance of high hardness armor steels against 7.62 mm armor piercing ammunition. In this methodology, the FEM simulations are used to create training cases for Multilayer Perceptron (MLP) three layer networks. In order to validate FE simulation methodology, ballistic shot tests on 20 mm thickness target were performed according to standard Stanag 4569. Afterwards, the successfully trained ANN(s) is used to predict the ballistic limit thickness of 500 HB high hardness steel armor. Results show that even with limited number of data, FEM-ANN approach can be used to predict ballistic penetration depth with adequate accuracy.

Keywords: Finite element method (FEM); Artificial neural network (ANN); Multilayer perceptron (MLP); Generalized feed forward (GFF); Ballistics; High hardness armor

1. Introduction

The ballistic penetration modeling has become of prime importance in development of armor solutions and continues to be a challenging research field for engineers. Due to its complexity, in investigation of ballistic penetration problems, three modeling approaches are quite popular. These are experimentally derived empirical formulation, analytical model derivation and numerical simulation. Numerous empirical formulations were derived with the tests conducted in laboratory environment and used in solution of ballistic problems [1]. In contrary to straight forward methodology of deriving empiric formulation, their limited applicability to various cases is a bottleneck for widespread usage. Analytical models are quite useful due to their direct applicability on various problems but derivation always requires simplified assumptions in governing equations which results in deviation from realistic outcomes [2,3]. It is inherent that, empirical and analytic approaches cannot capture the complex nature of impact phenomenon, thus numerical simulation has become a necessary tool for the study of ballistic penetration. Numerical methods and subsequent computing technologies have been developed to the level where mentioned complex penetration behavior can be truly estimated. A review of the impact simulation literature shows that the researches under this topic

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have been focused on the implementing explicit hydro-codes [4–8].

Although FE analysis is a powerful tool, due to the difficulty of development procedure and high computational cost, easy to apply approaches are always valuable for armor development studies. Especially, a computational tool which is based on limited data will decrease the number of computationally high cost numerical simulations and physical tests. The neural network approach is one of the most powerful computer analysis techniques which is based on the statistical regression. The neural network is currently used in many fields of engineering especially for modeling complex relationships which are physically difficult to explain. One of the distinguishing characteristic of neural networks is their potential to gain knowledge of problems by means of training and, after sufficient training to be able to solve problems of the same class.

Artificial Neural Networks (ANNs) have been developed over last three decades, started with the modeling of the functions of human brain by McCulloch and Pits [9] and have been used in solution of many problems in science and engineering [10–12]. In some of the studies, neural network models were not used to predict only the system behavior but also inverse form of ANNs were developed to optimize performance of complex engineering systems by finding best input parameters [13]. In the recent studies, there is a significant attempt to use ANN(s) with FE simulations especially to reduce computational time where extensive number of FE simulations required. Arndt et al. [14] was implemented a FEM-ANN approach to an optimization problem from groundwater engineering. The proposed approach simply uses the FE results in training and testing of the developed ANN, and the trained ANN is used for further predictions to perform optimization loop. In that case, the process time was decreased by 60% when compared with simulation based solution. Similar approach has been used successfully by a few more researchers [15–20]. Hambli (et al.) [15,16] used FEM-ANN approach in various applications in mechanics. Gudur and Dixit [17] developed a hybrid model consist of radial basis neural networks, which was applied for the modeling of cold flat rolling process. The required training, testing and validation data have been prepared by using finite element code. Shabani and Mazahery [18] developed neural network modeling in order to predict the mechanical properties of A356. Haj-Ali et al. [19] presented a FEM-ANN modeling approach to characterize the indentation behavior of inelastic and nonlinear materials. Literature survey on FEM-ANN method shows that, it is significantly beneficial in replacing time consuming repeated FE simulations.

When ballistic penetration limit of an armor solution is required for various impact velocities and thicknesses, it is impractical to simulate all combinations to find an accurate value due to computational cost. FE simulation of such a complex ballistic problem requires high level computational sources. The integrated FEM and ANN methodology proposed in this study can predict the ballistic limit thickness for various cases. Fig. 1 presents the framework of the methodology for the process of penetration depth determination. From Fig. 1, it can be seen that, the preliminary study starts with a reliable FE model preparation. After reasonable correlation achieved between tests and FE simulations, data generated for ANN model. With a well trained ANN, the required number of prediction can be easily produced with a simple personal computer in minutes to find ballistic penetration limit for a given velocity.

In this paper, ballistic limit thickness of 500 HB hardness armor steel, (Secure 500) was determined against 7.62 mm 54R B32 API ammunition by using FE and neural networks. In order to eliminate memorizing behavior of ANN, the data set for training and test are intentionally chosen from 450 to 750 m/s speed range and trained model was used in prediction penetration depth at 854 m/s bullet impact velocity. The network trained with FE generated data shows significant ability to predict penetration depth, thus ballistic limit thickness was found with reasonable error.

2. Data generation with FE simulations

2.1. FE model establishment

In ballistic performance studies, it is important to use well defined threat identification both in test and simulations. For ballistic tests, numerous international standards have been developed to standardize protection levels according to ammunitions available for civilian and military applications. In this study a widespread standard, NATO Stanag 4569 [21] will be used. In Stanag 4569, protection level for logistic and armored vehicles specified in five classes. The kinetic energy threat subject to this study is denoted by Level-3, in which the ammunition is named as 7.62 × 54 B32 API and specified impact velocity is 854 m/s with a tolerance of +/20 m/s. The 7.62 mm armor piercing bullet geometry is shown in Fig. 2 which has a total mass about 10 g. The bullet consists of a hardened steel core which is inserted in a jacket. A cap of lead-antimony is placed in front of the core to stabilize the projectile during flight and penetration. A copper jacked is wrapped over the core, cup and lead antimony cap.

In numerical model, the material is discretized into finite sections over which, the conservation and constitutive equations are solved. The way in which this spatial discretization is used leads to different numerical methods. The most commonly performed discretizations are Euler, Lagrange, Arbitrary Lagrange Euler (a mixture of Lagrange and Euler) and SPH (Smooth Particles Hydrodynamics). Kilic and Ekici [22] presented a comparative study to demonstrate applicability of Lagrange and SPH techniques on determination of ballistic performance and concluded that, Lagrange method is more effective in visualizing target deformation pattern. In the Lagrange method the numerical domain moves with the material, which is ideal for following the motion and deformation in regions of relatively low distortion, and possibly large displacement. This formulation is extensively used because its advantages, such as being able to follow accurately material boundaries and integrate complicated material models.