

Validation of the modified digital element approach for simulating ballistic impact against fragment simulating projectile

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Abstract. A modified digital element approach (DEA) is applied to simulate fabric perforation process under ballistic impact. The previous version of the DEA is capable of simulating ballistic impact of textile fabric using rigid body spherical and cylindrical projectiles only. Fragment simulating projectile (FSP) and real bullets are not modeled. The subject of this research is to perform ballistic penetration process against projectile of arbitrary shape and validate the modified DEA. A fabric to solid body projectile contact search and contact force calculation algorithm is established. Ballistic impact of textile fabrics against spherical and cylindrical projectiles is performed using the previous DEA and the modified DEA separately. Numerical results are compared to the well published DEA results to investigate the fabric bullet resistant performance.

1 Introduction

The strength of textile fabrics under projectile impact is of high importance to soldier protection applications. Bullet resistant body armor is designed to protect soldiers against projectile penetration and blunt trauma. Textile armor is evaluated for both penetration resistance by bullets and for impact energy transmitted to the wearer.

As the development of computer power, yarn level approach became popular in 1990s. Explicit finite element commercial simulation tools, such as LS-DYNA, ABAQUS, and AUTODYN[1-4] are used intensively in failure modeling for impact mechanism research. A damage initiation criterion for the material model, based on the fabric or yarn level constitutive relationship, was implemented in the software as subroutine, which embraces yarn failure, matrix damage, and delamination under tensile, compressive, shear, and crush loadings. Although, the use of finite element method in multiscale 3-D woven textile related mechanics research has provided insight to the fabric response under ballistic impact and failure mechanism, fiber level details of fabric microstructure are overlooked.

A near fiber-level digital element approach (DEA) for simulating impact and penetration of textiles against rigid spherical and cylindrical projectile is established by Wang and Miao[5] in 2010. In this micro-approach, each yarn is discretized into several equal length digital fibers. Digital fibers are modeled as digital chain. Digital chain, imitating the physical behavior of an actual fiber, embodied the sub-yarn scale properties of fabrics. Therefore, fiber strength, fiber-to-fiber contact and friction can be modeled[6]. Figure 1 shows three key elements of DEA and its unit-cell micro-geometry of 3-D woven textile generated by Dynamic Fabric Mechanics

Analyzer(DFMA)[7] utilizing dynamic relaxation process with periodic boundary conditions[8]. In 2016, Wang and Miao[9] implemented a Monte Carlo process to assign a unique strength to each element following a bimodal Weibull distribution function to investigate the effect of inter-fiber friction coefficient on fabric ballistic performance. Although, fiber damage propagation, fabric perforation mechanisms and their relations between inter-fiber friction coefficient are analyzed in detail, ballistic performance against FSP is never discussed at filament level.

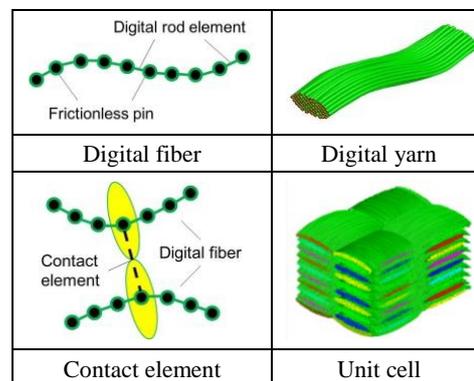


Figure 1. Basic concepts of DEA

In this research, first, the DEA is modified to simulate ballistic impact of textile fabric against solid body projectiles of arbitrary shape. Second, The contact search and contact force calculation between fabric and solid body projectile algorithm is explained in detail. Third, the impact simulation results of solid body spherical and cylindrical projectiles are compared to that of the previous DEA to test and validate the modified DEA capability. Solid conclusions are reached based on numerical results.

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2 Ballistic impact to fabric using rigid body projectile of arbitrary shape

2.1 Contact search methology

A node-to-surface contact algorithm is established to model projectile-to-fabric contact. Three steps are taken in preparation for the contact calculation: first, a projectile model is created and discretized with 8-node solid elements using commercial software. Second, elements and nodes belong to the projectile surface are extracted and sorted in structural order. Third, divide the surface elements into sub-triangles and calculate the plane equation and plane normal of each. The nodes in contact with each projectile surface element are determined using point-to-plane distance formula. Figure 2(a) shows an example of meshed FSP and Figure 2(b) demonstrates the contact model. Projectile failure due to impact is not considered at this stage.

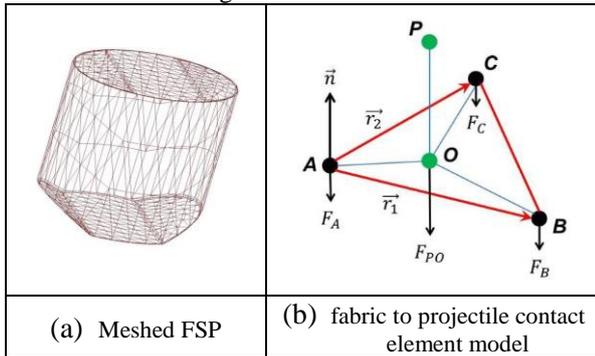


Figure 2. Contact search model

As shown in Figure 2(b), point P is a node on the fabric, triangle element ABC belongs to the projectile surface. When node P encounters triangle ABC , a virtual node O is generated to represent the physical point upon which the contact force is applied. Line PO is perpendicular to plane ABC and equals to the distance between node P and plane ABC .

To determine whether point P is in contact with surface element ABC , two conditions must be filled: 1) the distance between node P and plane ABC , calculated by equation(1), must be smaller than the digital fiber radius, 2) point O must be inside triangle ABC .

$$l_c = n_1(x_p - x_A) + n_2(y_p - y_A) + n_3(z_p - z_A) \quad (1)$$

where n_1 , n_2 , and n_3 are the x , y , and z components of the plane normal \mathbf{n} . Let vector \mathbf{r}_1 be a vector from point A to point B and \mathbf{r}_2 be a vector from point A to point C . The normal vector of triangle ABC can be calculated as $\mathbf{n} = \frac{\mathbf{r}_1 \times \mathbf{r}_2}{|\mathbf{r}_1 \times \mathbf{r}_2|}$. The direction of \mathbf{n} is determined using the right-hand rule and should always point outwards.

If l_c is smaller than the digital fiber radius, the location of point O needs to be verified through following procedure: 1) divide triangle ABC into three sub-triangles: BCO , ACO , and ABO . 2) Calculate the area of each sub-triangle a_1 , a_2 , a_3 , and the area of triangle ABC , denoted as a . 3) If $a_1 + a_2 + a_3 = a$, node O is inside triangle ABC and node P and triangle ABC are in contact. Contact force F_{PO}

is calculated and distributed proportionally onto node A , B , and C , as such $F_A = \frac{a_1}{a} F_{PO}$, $F_B = \frac{a_2}{a} F_{PO}$, $F_C = \frac{a_3}{a} F_{PO}$, and $F_A + F_B + F_C = F_{PO}$. The direction of F_A , F_B , and F_C is the same as the direction of F_{PO} . Otherwise, node O is outside triangle ABC , no contact exists between node P and triangle ABC .

2.2 The modified DEA algorithm

In a single degree system, the relationship between mass, spring elements and viscous damper can be expressed as:

$$(r_i)_e - (k_{ij})_e \times (u_i)_e - c(\dot{u}_i)_e = (m_{ij})_e \times (\ddot{u}_i)_e \quad (2)$$

where $(r_i)_e$ is the external force of element e applied to node i , $(k_{ij})_e$ is the element stiffness matrix, and $(u_i)_e$ is the relative displacement of element e with respect to its original position. Thus $(k_{ij})_e \times (u_i)_e$ is also known as the internal force. During each time step, element stiffness matrix of each element and the corresponding internal forces of each node are calculated. The nodal forces of each element are assembled to a global force vector. A central difference explicit direction integration algorithm is employed to calculate nodal velocity, acceleration, and displacement of the fabric and projectile.

$$(a_i)_n = (F_i)_n / m_i \quad (3)$$

$$(v_i)_{n+1/2} = (v_i)_{n-1/2} + (a_i)_n \Delta t \quad (4)$$

$$(u_i)_{n+1} = (u_i)_n + (v_i)_{n+1/2} \Delta t \quad (5)$$

where i is the node number; n is the number of steps; m , F , a , v , and u represent nodal mass, force, acceleration, velocity, and displacement respectively. In every iteration, a Δt smaller than critical time step is used to maintain conditional stability. For finite element (FE) meshed projectile, the internal nodal forces are calculated element by element and distributed onto each node. No global stiffness matrix is generated

2.3 Validations

To have the same numerical precondition as the DEA, only spherical and cylindrical projectiles are simulated. A set of 5 and 4 of each projectile type with different mesh density is simulated to evaluate its effect on ballistic performance. The modified DEA in simulating ballistic impact of deformable projectile of arbitrary shape is verified. Simulation details are discussed below.

2.3.1 Material properties and projectile geometry

As shown in Figure 3, the fabric used in the simulation is a 1 in. \times 1 in. rectangular Kevlar KM2 2-D plain weave generated by DFMA[5,8,9]. Projectile is positioned above the fabric geometric center, with an initial velocity of 50m/s directed towards the fabric. Fixed boundary conditions are applied on all four boundaries. Table 1 and

Table 2 list the fabric material and projectile properties which are provided by the Army Research Lab.

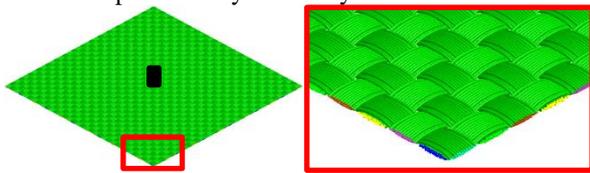


Figure 3. 2-D plain weave fabric

Table 1. Material Properties of Kevlar KM2

Type	E11 (Pa)	E22 (Pa)	Strength (Pa)	ρ (kg/m ³)
Kevlar KM2	8.46e10	1.34e9	3.88e9	1440

Table 2. Projectile Geometry

Projectile type	Sphere	RCC
Diameter(m)	5.56e-3	3.40e-3
Mass(kg)	6.92e-4	2.592e-4
Density(kg/m ³)	7689	7689
E11(Pa)	2.09e11	2.09e11
E22(Pa)	2.09e11	2.09e11
Height(m)	-	0.0037
ν	0.3	0.3

2.3.2 Simulation results and discussion

The fabric total nodes and projectile mesh density substantially affect computational time spent on calculating contact forces. In general, the higher projectile mesh density, the more accurate the results will be. In order to find the least number of projectile total nodes which produces smallest discrepancy comparing to the well-published results from the previous DEA, projectiles of varies mesh density are simulated, examples are shown in Figure 4.

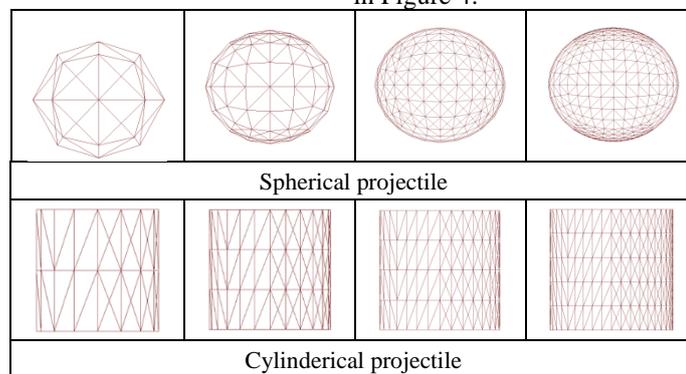


Figure 4. FE projectile with varies mesh density

Table 3 summarizes the simulation results of FE meshed spherical projectile using the modified DEA approach. The total nodes of FE meshed projectiles ranged from 53 to 2248 with a corresponding total element varying from 32 to 2037. The numerical maximum projectile force and bounce back velocity are compared to that of the previous DEA, and the discrepancies are listed below.

Table 3. Simulation Results for FE Spherical Projectiles

Test #	1	2	3	4	5
Simulation time (min)	13	88	234	318	925
# of elements	32	256	649	864	2037
# of nodes	53	321	779	997	2248
Max. projectile force (N)	793.5	950.1	992.1	990.4	994.5
Discrepancy (%)	-22.5	-7.2	-3.1	-3.3	-2.9
Rebound speed (m/s)	37.3	38.5	38.4	38.6	38.0
Discrepancy (%)	-3.0	0.28	-0.028	0.34	-1.3

Results of the maximum projectile force shows that, for spherical projectile, when the total number of nodes increases, the modified DEA simulation results more closely resembled the previous DEA results. However,

when the total number of nodes reaches 779 or more, the simulation results between the modified DEA and the previous DEA approach are almost identical. The deviation of the bounce back speed is much smaller compares to the results of maximum projectile force. Approximately 2.7% improvement is noted between Test 1 and Test 2 on rebound speed. However, as the total number of nodes exceeded 779, the discrepancy between the rebound speeds derive from the modified DEA and the previous DEA approach became bigger.

Table 4 summarizes the simulation results of FE meshed cylindrical projectile using the modified DEA approach. Similarly, simulated maximum projectile force and rebound speed are compared to results obtained from the previous DEA.

Table 4. Simulation Results for FE Cylindrical Projectiles

Test #	1	2	3	4
Simulation time (min)	35	115	296	667
# of elements	96	324	768	1500
# of nodes	171	484	1045	1926
Max. projectile force(N)	345.6	354.0	356.1	354.0
Discrepancy(%)	-4.0	-1.6	-1.0	-1.6

Rebound speed (m/s)	34.6	35.2	35.1	34.9
Discrepancy(%)	-1.0	0.67	0.29	-0.20

Likewise, similar conclusions can be reached for cylindrical projectile test results. Table 4 shows that discrepancies of both maximum projectile force and rebound speed decrease when the number of elements in projectile increases. The variation of the number of elements has a smaller effect on predicting rebound speed than it does on predicting maximum projectile force. However, the mesh density of cylindrical projectiles has significantly less effect on impact resistant performance than spherical projectiles. Less than 0.8% improvement on rebound speed is observed between Test 1 and Test 4.

Figure 5 shows the simulation time steps vs. projectile force curve for both projectile type. The red curve is derived from the previous DEA; other curves are derived from the modified DEA approach. Discrepancies between the modified DEA and the previous DEA approach were visible in Test 1. As mesh density increased, the simulation results of Test 3 to 4 and 5 closely match results from the previous DEA.

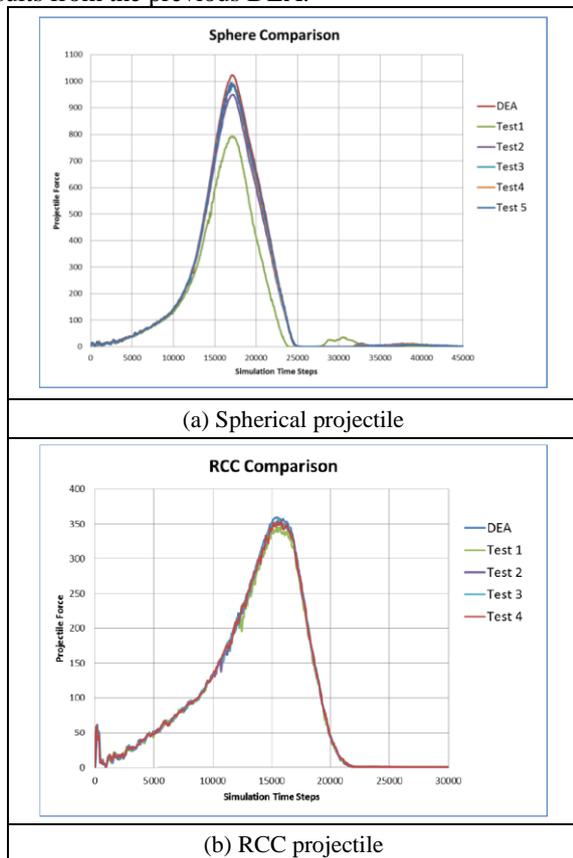


Figure 5. Projectile force comparison

2.4 Conclusion

Following conclusions are reached based on the above two sets of simulation:

1. Simulation results of the modified DEA approach using spherical and cylindrical projectiles closely resemble the results of the previous DEA. The modified DEA approach successfully replicates the results from the previous DEA and is capable of simulating ballistic impact of textile fabrics using projectiles of arbitrary

shape. The numerical maximum projectile force and bounce back speed with respect to time curves match closely that of the previous DEA.

2. General speaking, the increase of mesh density improves simulation results. However, for standard spherical and cylindrical projectile, when the projectile total number of nodes reached 1000, the improvement of mesh density on simulation results became trivial, occasionally leads to slightly less accurate results than projectiles with coarser mesh.

3. Mesh density has a greater effect on spherical projectile than cylindrical projectile.

4. Because higher mesh density consumes significantly more computational time, a total number of nodes between 500 and 1000 is recommended for time-efficient simulation.

5. The modified DEA approach analyzer provides guidance for real bullet shape impact tests simulation.

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