Modeling of Directional Focused Fragmentation Charge (DFFC) – Investigation of Different Approaches

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1 Abstract

The aim of this study is to examine the effects of explosion-accelerated clusters of projectiles, which is in literature referred as Directional Focused Fragmentation Charge (DFFC), on target armor structures. The primary challenge in this study is to develop an accurate model for the explosive and fragments configuration, since the scenario involves a close-range explosion and fluid-structure interaction (FSI) due to the direct contact of fragments with the explosive. To find an appropriate and stable solution to this challenge, various techniques are explored for modeling both the explosive and the cluster of fragments.

In the modeling of explosive, two different approaches are considered: the structured Arbitrary Lagrangian-Eulerian (S-ALE) method [1] and the **`*PARTICLE_BLAST`** (PBM) approach [2]. In terms of modeling the cluster of fragments, the classical Lagrangian approach and the discrete element method are utilized in combination with explosive modeling techniques. Each of these combinations of methods have their own advantages and limitations which will also be discussed during the presentation of the work.

To evaluate the effectiveness of these modeling techniques, the dispersion of fragments on the target plate is compared with the one obtained in field tests. After comparison of the results, it is observed that utilizing the S-ALE approach for modeling the explosive and using the classical Lagrangian approach for the cluster of fragments yields a stronger correlation with the dispersion observed in the experiments than PBM method combined with discrete element method.

2 Introduction

The DFFC explosive has a special design, featuring a predetermined quantity of spherical fragments positioned immediately ahead of a defined explosive mass, as illustrated in Fig.1. These compact spheres, approximately 10mm in diameter, has a significant hardness which is above 60 HRC. After the detonation of explosive, these fragments undergo very high acceleration, striking the target at very high velocities (around 2.5 km/s), resulting in localized damage.

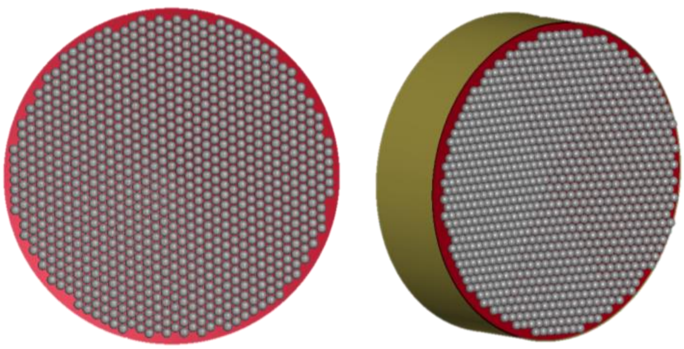

Fig.1: DFFC Explosive with fragments.

The testing of these types of threats on structures is costly. Hence simulation tools should be used to come across an effective design solution for armor packaging against DFFC threat. In this test configuration, the target plate is located around 5 meters away from the explosive. General simplified view for the set-up is shown in Fig.2.

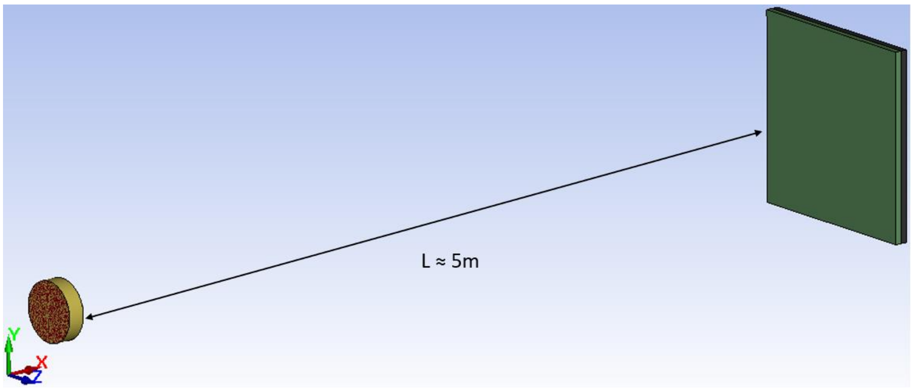

Fig.2: DFFC test configuration (simplified).

3 Modeling the Fragments

The first method used for modeling the fragments is the classical Lagrangian approach in which the fragment spheres are modelled as individual parts with using **`*MAT_RIGID`** material model. Since the basic material is steel with very high hardness for these fragments, the material properties are chosen accordingly. While using classical Lagrangian approach, two different mesh densities are applied for spheres as shown in Fig.3.

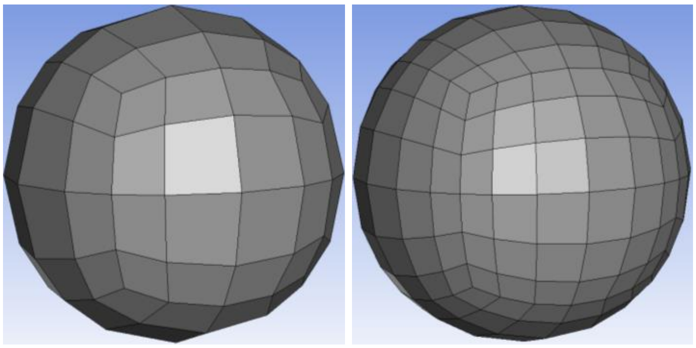

Fig.3: Mesh density for fragments.

Two different particle positioning are considered while using classical Lagrangian approach for fragment modeling. In one of the approaches the particles are positioned in such a way that the particles are modeled with exact position according to their diameter and directly used in the DFFC simulation. In the other approach, the spheres are positioned as the previous method and then loaded with gravity to have an initial contact between each other.

The second method is the discrete element method in which the fragments are modeled as a single part with **`*ELEMENT_DISCRETE_SPHERE_VOLUME`** type of elements. The contact between the fragments are determined automatically due to the nature of the method.

4 The Explosive Model

The explosive geometry is not a regular cylinder. It has a convex side on which the fragments are placed in a staggered pattern. This shape is modelled with a shell element case in which the explosive material is filled in a proper way regarding the modelling technique. The explosive shape is shown in Fig.4.

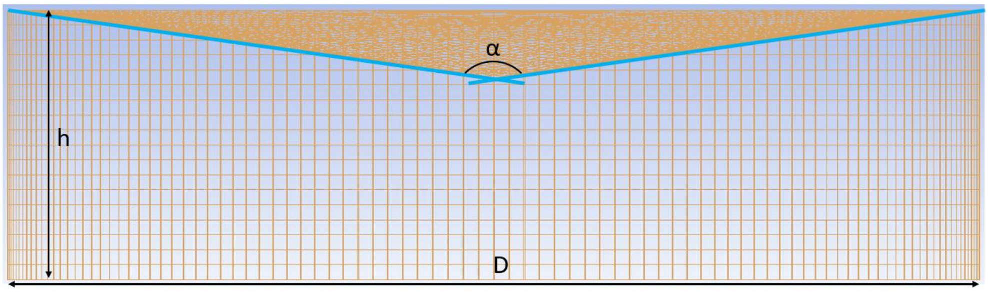

Fig.4: Explosive shape (mesh view).

The first method used for modelling explosive is the S-ALE approach [1]. In this approach, the explosive numerical model is generated with the keyword **`*INITIAL_VOLUME_FRACTION_GEOMETRY`**. The whole domain including also the air is controlled with **`*ALE_STRUCTURED_MESH`** keyword. A variable size mesh pattern is used when generating the domain. This variable mesh size pattern is controlled in the keyword **`*ALE_STRUCTURED_MESH_CONTROL_POINTS`**. The region around the explosive and the fragments are kept denser whereas the far regions are left coarse. The sample keyword is shown in Fig.5.

```
*ALE_STRUCTURED_MESH_CONTROL_POINTS
$#    cpid    unused     icase       sfo    unused      offo
         1                   1       1.0                 0.0
$#                 n                   x               ratio
                   1            -300.000
                  16            -200.000                 4.0
                 216             600.000                 4.0
                 231             700.000
```

Fig.5: Control points sample with variable mesh size.

The ICASE=1 option is used for variable mesh size of S-ALE domain in the X direction [3]. The same approach is also used for both Y and Z directions of the mesh domain. The main idea is to achieve a fine mesh around the explosive itself and coarse mesh far away from the explosive.

The interaction (FSI) between the S-ALE domain and the fragments are modeled with the new keyword **`*ALE_STRUCTURED_FSI`**. The FSI performance is controlled with only one parameter, therefore it is a very clean and lean keyword. The coupling stiffness is controlled by a load curve, the values of which is determined by trial and error. The keyword is shown in Fig.6.

```
*ALE_STRUCTURED_FSI_TITLE
$#  coupid                                                                 title
         1 structured_fsi
$#   slave    master     sstyp     mstyp                                   mcoup
       922  90000000         0         1                                 -100001
$#   start       end      pfac                          flip
       0.0      0.20      -100
```

Fig.6: FSI keyword sample.

The second method is the PBM method. This method is used in some close-range blast studies and hence is chosen as an alternative way of modeling explosion in this study [5]. In this method, the air particles are not included since the effect of them is assumed to be negligible. The fragments are used as discrete element spheres for the ease of coupling of these two methods. The coupling is automatically defined within **`*DEFINE_PARTICLE_BLAST`** keyword by defining the part number of the fragments. The sample keyword is given in Fig.7.

```
*DEFINE_PARTICLE_BLAST
$#  lagsid  lagstype     nodid   nodtype     hecid   hectype    aircid
         0         0         1         3      1001         1         0
$#    nphe     npair     iunit
    500000         0         0
$# ihetype   density    energy     gamma     covol    deto_v
         2 1.4815e-6       9.0      1.35       0.6    7500.0
$#    detx      dety      detz      tdet     btend       nid
  &detpntx  &detpnty  &detpntz       0.0       0.5
$#    bcx0      bcx1      bcy0      bcy1      bcz0      bcz1
  &salex1f  &salex2f  &saley1f  &saley2f  &salez1f  &salez2f
$#   ibcx0     ibcx1     ibcy0     ibcy1     ibcz0     ibcz1      bc_p
         0         0         0         0         0         0         1
```

Fig.7: Particle blast method sample keyword.

5 Fragments & Target Interaction

While using S-ALE method in combination with classical Lagrangian approach, interaction between fragments and target plate is modeled with **`*CONTACT_ERODING_SURFACE_TO_SURFACE`** keyword. The parameters used in the contact card is shown in Fig.8.

```
*CONTACT_ERODING_SURFACE_TO_SURFACE_ID
$#     cid                                                                 title
        50
$#    ssid      msid     sstyp     mstyp    sboxid    mboxid       spr       mpr
       922       101         2         2                             0         0
$#      fs        fd        dc        vc       vdc    penchk        bt        dt
      0.25      0.10      10.0       0.1      30.0                 0.0  1.000E20
$#     sfs       sfm       sst       mst      sfst      sfmt       fsf       vsf
       1.0       1.0                           1.0       1.0       1.0       1.0
$#    isym    erosop      iadj
         0         1         1
$#    soft    sofscl    lcidab    maxpar     sbopt     depth     bsort    frcfrq
         2       0.1         0     1.025       3.0        35         1         1
```

Fig.8: Contact card sample parameters.

When using discrete element spheres as fragments, the interaction between the spheres and the target is modeled with two different methods, one of which is **`*DEFINE_DE_TO_SURFACE_COUPLING`**. The other one is the traditional **`*CONTACT_ERODING_NODES_TO_SURFACE`**. The difference between these approaches is explained by Karajan et.al. [4]. Both keywords with sample parameters are given in Fig.9 and 10 respectively.

```
*DEFINE_DE_TO_SURFACE_COUPLING
$#   desid    surfid    destyp   surftyp
       922     10101         0         1
$#   frics     fricd      damp     bsort      lcvx      lcvy      lcvz     wearc
      0.01      0.01      0.05         1         0         0         0       0.0
```

Fig.9: Discrete element to surface coupling (method 1)

```
*CONTACT_ERODING_NODES_TO_SURFACE_ID
$#     cid                                                                 title
        50
$#   surfa     surfb  surfatyp  surfbtyp   saboxid   sbboxid      sapr      sbpr
       922     10101         4         3         0         0         0         0
$#      fs        fd        dc        vc       vdc    penchk        bt        dt
       0.0       0.0       0.0       0.0      30.0         0       0.01.00000E20
$#    sfsa      sfsb      sast      sbst     sfsat     sfsbt       fsf       vsf
       1.0       1.0       0.0       0.0       1.0       1.0       1.0       1.0
$#    isym    erosop      iadj
         0         1         1
$#    soft    sofscl    lcidab    maxpar     sbopt     depth     bsort    frcfrq
         1       0.1         0     1.025       3.0        33         1         1
```

Fig.10: Discrete element to surface coupling (method 2).

6 Simulation Results and Verification

During the simulations, LS-DYNA® R14 version with AVX2 and Intel® MPI is used on Linux system with 120 cores for S-ALE and Lagrangian combination and 24 cores with discrete element method and PBM combination. The MPP decomposition is done accordingly for each method. The possible effect of different decompositions to the final results is not investigated in this study.

6.1 PBM with Discrete Element Method Combination Results

While using this combination, **`*CONTACT_ERODING_NODES_TO_SURFACE`** method gives the following dispersion on the target plate as depicted in Fig.11.

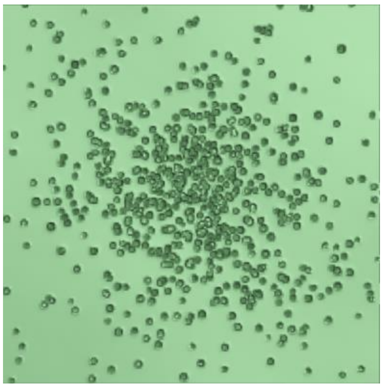

Fig.11: Fragment dispersion on target plate with PBM.

When **`*DEFINE_DE_TO_SURFACE_COUPLING`** keyword is utilized for fragment and target interaction, the contact between these two could not be captured. The discrete element spheres passed through the target without any interaction. The reason for this could not be identified and planned to be investigated in future studies.

6.2 S-ALE & Lagrange Combination Results

The dispersion of particles on the target plate is obtained four different cases. The cases are shown in Table 1.

Table 1. Load Cases

	Coarse Sphere Mesh	Fine Sphere Mesh
Default Sphere Position	1.1	2.1
Gravity Loaded Sphere Position	1.2	2.2

At first glance, the FSI forces are compared for these load cases. The impulse generated by the forces applied on the fragments in X direction is shown in Fig.12.

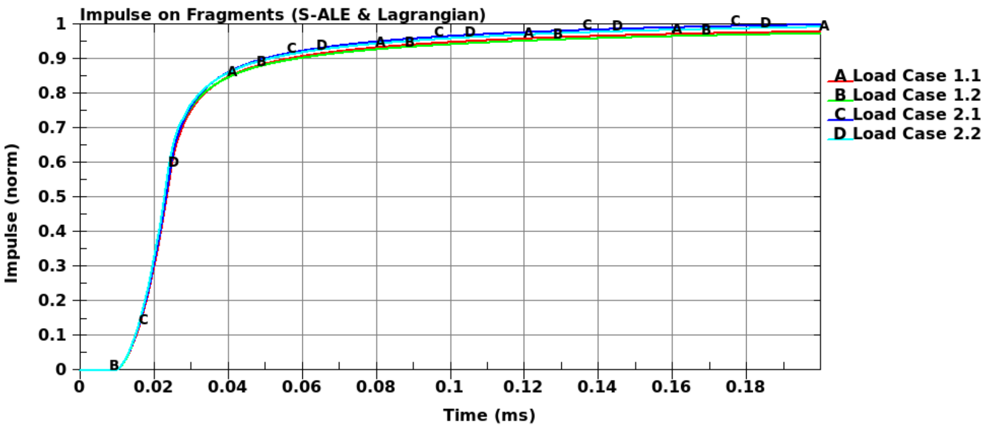

Fig.12: Impulse on fragments (S-ALE & Lagrangian)

It is obvious that the mesh size of the fragments is not significantly affecting the impulse generated by the explosive. However, when the dispersions are investigated, there are some differences observed which are shown in Fig.13.

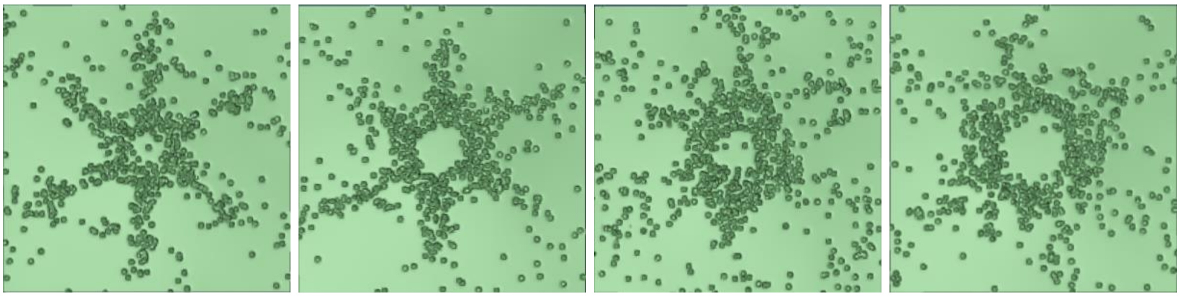

Fig.13: Load Case results (from left to right 1.1, 1.2, 2.1, 2.2)

When the fragments are positioned in default way, the dispersion seems to be concentrated in the center and due to the mesh size difference, the fine sphere mesh results in a denser sphere collision on the target plate. When the spheres are positioned with gravity first, the dispersion results changed in a way that coarse sphere mesh results in a different dispersion than the fine sphere mesh results. For all the cases, the center displacement is obtained with respect to time as follows. As it can also be seen in Fig.14 that the center displacement is higher when fine mesh fragments are used.

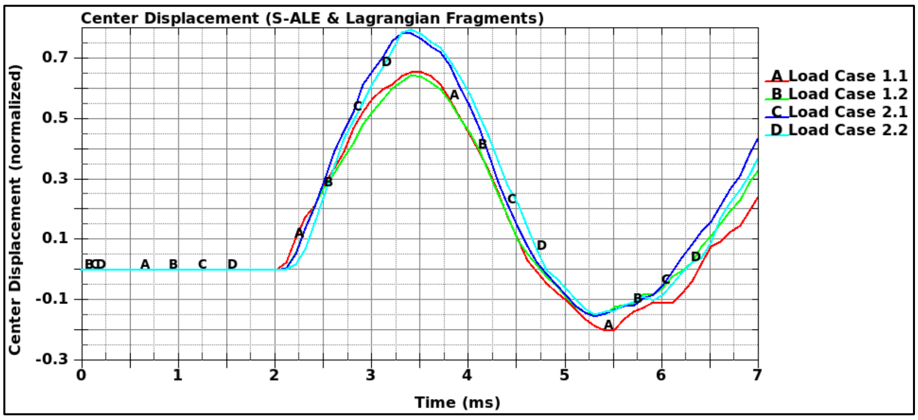

Fig.14: Center displacement (normalized) of target plate.

The field test result in terms of fragment distribution on target plate is shown in Fig.15.

Fig.15: Fragment dispersion on target plate.

It is observed that the deformation of the target plate is captured with a reasonable accuracy with the combination of S-ALE method for explosive and classical Lagrangian approach for the fragmentation spheres. It can also be seen that the dispersion in the central part of the plate is captured in better visual accuracy with the PBM and discrete element method combination. However, when the center plate displacement is compared, it is obvious that S-ALE and Lagrangian combination has a higher impulse applied on the target plate. This issue can also be related with the fact that PBM method is producing less accurate results in close-in range explosions than the ALE method [5]. This fact can be supported by the center displacement results represented in Fig.16.

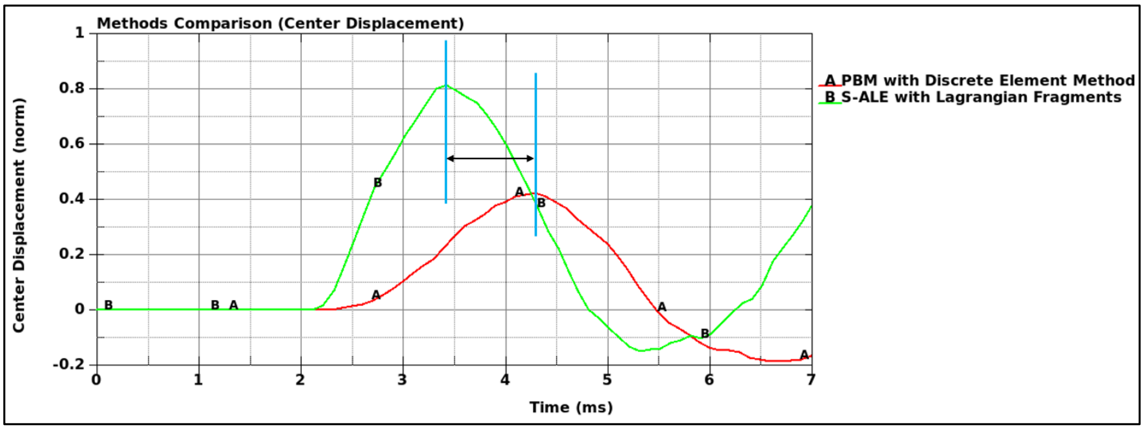

Fig.16: Center displacement comparison between methods.

7 Summary and Future Work

This work delves into the modeling of a relatively new threat posed by directional focused fragmentation charges, employing two distinct approaches. A reasonable level of accuracy is achieved for both dispersion and the final plastic deformation of the plate while using the S-ALE method for the explosive in combination with the classical Lagrangian approach for fragment spheres. However, it should be noted that this combination requires significantly more computational time than the use of PBM with the discrete element method. In the following studies, a closer examination of PBM will be undertaken, and parameter sets for the discrete element method will be investigated to enhance their accuracy to a level comparable to that achieved by the S-ALE and Lagrangian combination.

8 Literature

[1] Chen, H.: "LS-DYNA® Structured ALE (S-ALE) Solver", 14th LS-DYNA® International Users Conference, 2016, Detroit, USA.

[2] Teng, H., Wang, J.: “Particle Blast Method (PBM) for the Simulation of Blast Loading”, 13th LS-DYNA® International Users Conference, 2014, Detroit, USA.

[3] LS-DYNA® Keyword User’s Manual R14@ad6b3a9c5, Ansys, 2023.

[4] Karajan, N. et.al, “Interaction Possibilities of Bonded and Loose Particles in LS-DYNA®”, 9th European LS-DYNA Users Conference, 2013, Manchester, UK.

[5] Schwer, L. et.al, “LS-DYNA Air Blast Techniques: Comparisons with Experiments for Close-in Charges”, 10th European LS-DYNA Conference, 2015, Würzburg, GERMANY.