Evaluation of Debris Modeling Technique on Failure Simulation of Concrete Structures

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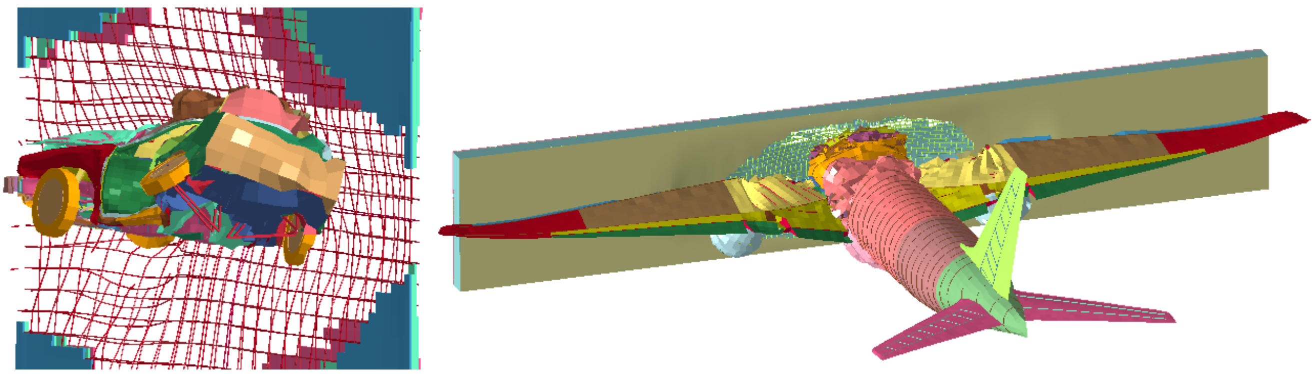
1 Introduction

It is a crucial issue to protect important buildings, especially nuclear power plants against large natural disaster or terrorist attack. Some examples of such kind of simulation are shown in Fig.1. Nuclear power plant is a concrete structure and highly accurate prediction of the failure modes, e.g., crack propagation, penetration and spalling is required at the impact of projectile. In reality, when concrete material is failed, the failed material is not deleted and piles up as debris instead. In the case of second impact or subsequent seismic load, existence of debris cannot be ignored since the impact force is loaded on the structure through the debris. Although many sophisticated failure models are implemented in LS-DYNA, the generation of the debris cannot be simulated when the failure models working with erosion capability are used since the failed elements are deleted. In contrast, ***DEFINE_ADAPTIVE_SOLID_TO_SPH/DES** keyword[1] provides the simulation technique considering the effect of the debris since the failed solid elements are replaced with the particles. In this presentation, the results obtained using different options in ***DEFINE_ADAPTIVE_SOLID_TO_SPH/DES** is compared and the possibility to use this capability for real problem on concrete structure is discussed.



(a) Impact of vehicle blown by tornado [2]   (b) Aircraft impact [3]

Fig.1: Examples of impact simulation on reinforced concrete structures

2 Debris modeling capability to be examined

LS-DYNA has an capability to model debris after failure of solid elements using the keyword ***DEFINE_ADAPTIVE_SOLID_TO_SPH/DES**. Difference of responses with several options on these keywords are compared. The model used for the research was originally constructed with hexahedral solid element only as a base model. And Solid-SPH and Solid-DES models were prepared based on the original model. Both of ***DEFINE_ADAPTIVE_SOLID_TO_SPH** and ***DEFINE_ADAPTIVE_SOLID_TO_DES** have the option NQ=N which generates N x N x N particles per solid element. NQ=1,2 and 3 are tested. The versions of LS-DYNA used in the test are as follows;

LS-DYNA R9.1.0 for Windows	SMP Double Precision	Revision: 113244
LS-DYNA R9.1.0 for Windows	SMP Single Precision	Revision: 113621
LS-DYNA R9.1.0 for Linux	SMP Double Precision	Revision: 113621
LS-DYNA R9.1.0 for Linux	SMP Single Precision	Revision: 113621

3 Analysis model

The geometry and dimensions of the model are shown in Fig.2. The keyword ***DEFINE_ADAPTIVE_SOLID_TO_SPH/DES** is applied on the solid elements shown as pink region. The impacvtor (rigid semisphere) with the mass of 500 kg and the initial velocity of 40m/s impacts the concrete block. Three DOF of all the nodes on the bottom of the block are constrained using ***BOUNDARY_SPC**. The contact definitions are as follows;

concrete solid – impactor : ***CONTACT_ERODING_SURFACE_TO_SURFACE**
concrete sph/des – impactor : ***CONTACT_AUTOMATIC_NODES_TO_SURFACE**
concrete sph/des – concrete solid : ***CONTACT_ERODING_NODES_TO_SURFACE**

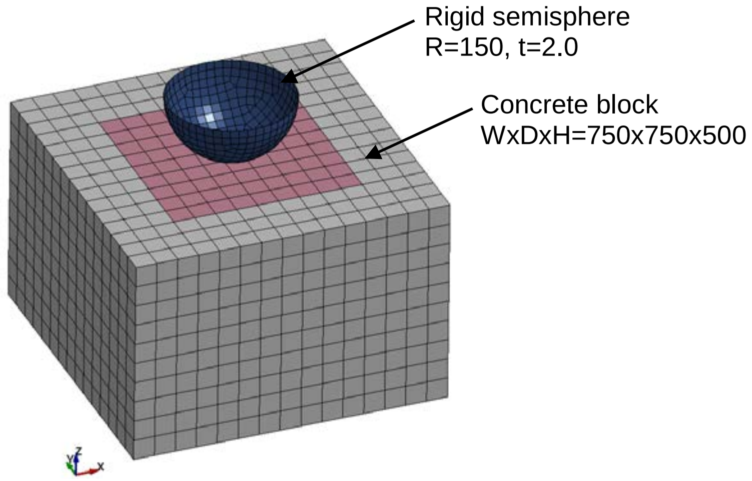


Fig.2: Model geometry and dimensions (unit : mm)

4 Material definition and additional computational condition

***MAT_CONCRETE_DAMAGE_REL3** is used for the concrete model. The uniaxial compressive strength is 24.5 MPa. The maximum shear strain of 0.04 is defined as the failure criterion on ***MAT_ADD_EROSION**. The SPH particles activated after the failure of the solid elements inherit the material properties of the concrete model. In contrast, the DES particles are generated as rigid body after the failure of the concrete solid elements. The SMP execution was performed with four CPUs and negative ncpu option (ncpu=-4) is specified on the command line to avoid inconsistency. In addition, ***DEFINE_ADAPTIVE_SOLID_TO_SPH** has another option ICPL and ICPL=0 is used in the simulation according to the description for debris simulation on the user's manual.

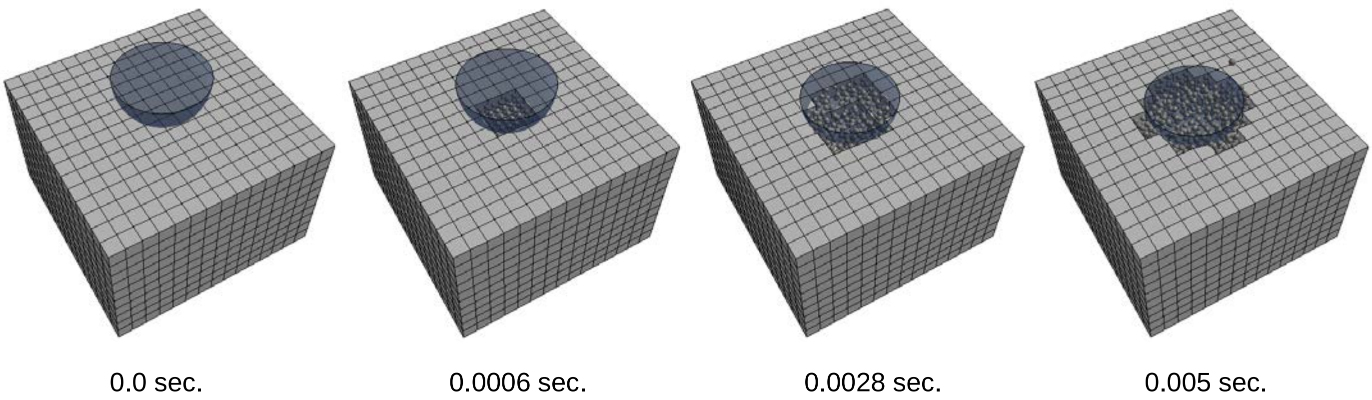
5 Results of simulation

In this computational experiment, 14 cases were executed on Windows and Linux. Similar results can be obtained on both of two platforms. So the results on Windows are presented here and summarized in Table 1. For the solid only case with single precision execution, "complex sound speed" error occurred. The cases of solid-SPH with single precision execution were terminated abnormally without any error messages. For solid-DES cases, NQ option didn't work correctly. Eight particles per solid element were generated regardless of the number of NQ. Some examples of the sequence of the erosion through the simulation are shown in Fig.3. In this figure, SPH shows the behavior like continuum, while DES particles scatters like discontinuous material. The contact force history are shown in Fig.4 (a). The contact force curves for each case is the summation of the contact forces between the original concrete solid elements and the impactor and between SPH/DES particles and the impactor. Also SPC reaction force history are shown in Fig.4 (b).

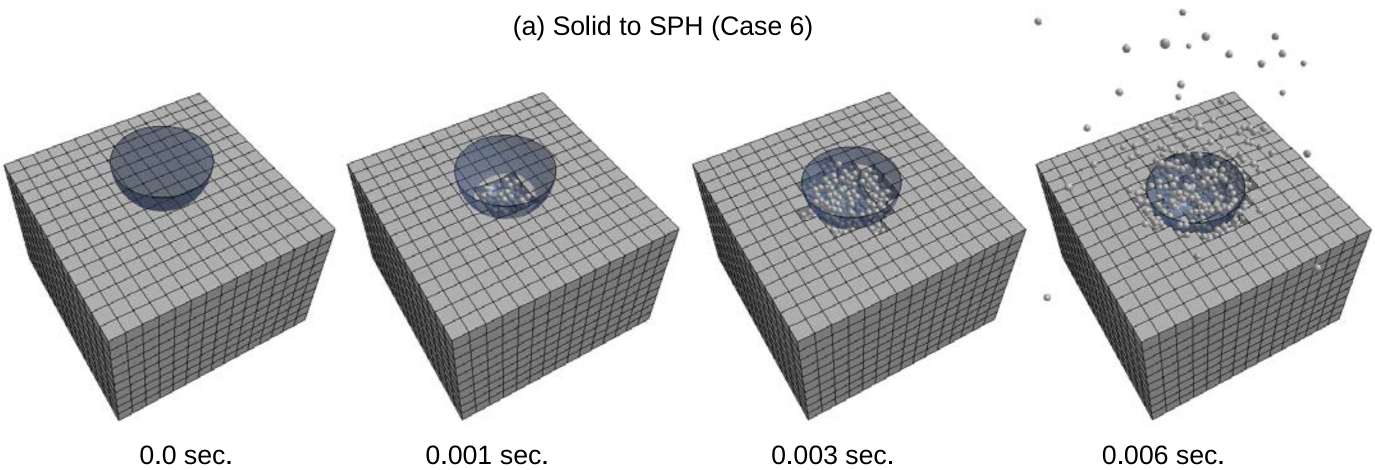
*Table 1: Summary of results**

Case	Model	NQ	Generated particles N x N x N	Precision	Termination	Energy balance	CPU time (s)
1	Solid	-	-	single	error	-	-
2				double	normal	OK	807
3	Solid to SPH	1	1 x 1 x 1	single	error	-	-
4				double	normal	OK	1270
5		2	2 x 2 x 2	single	error	-	-
6				double	normal	NG	1335
7		3	3 x 3 x 3	single	error	-	-
8				double	normal	NG	1679
9	Solid to DES	1	2 x 2 x 2	single	normal	NG	736
10				double	normal	NG	701
11		2	2 x 2 x 2	single	normal	NG	675
12				double	normal	NG	806
13		3	2 x 2 x 2	single	normal	NG	1147
14				double	normal	NG	1260

* Windows 7 64 bit, Intel CORE i7 3.60 GHz, four CPU execution



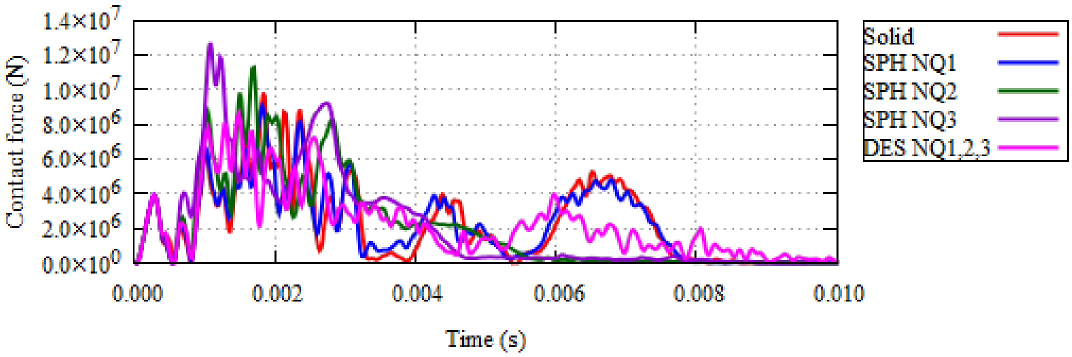
(a) Solid to SPH (Case 6)



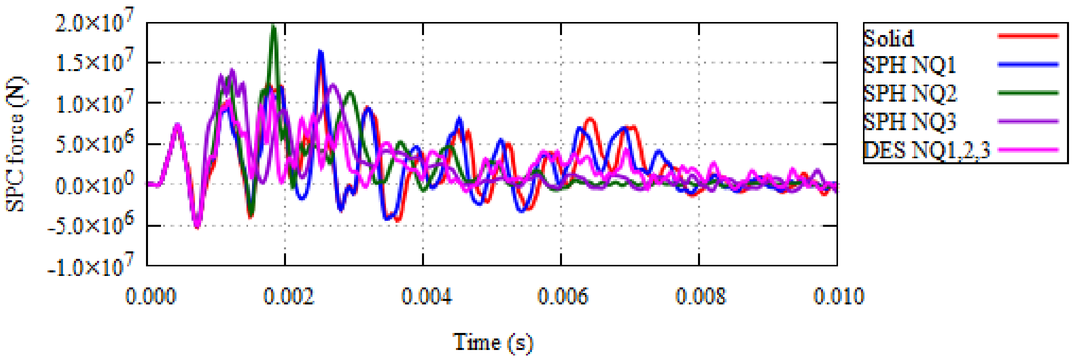
(b) Solid to DES (Case 12)

Fig.3: Examples of eroding sequence

The displacement and velocity history of the impactor and the energy balance of each case are shown in Fig.5 and 6.

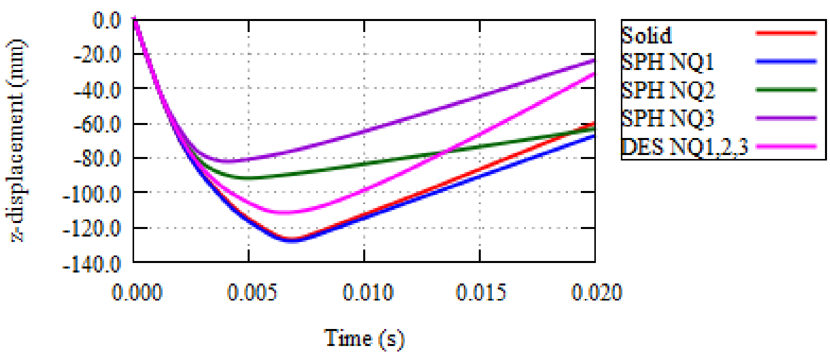


(a) Contact force between concrete and impactor history

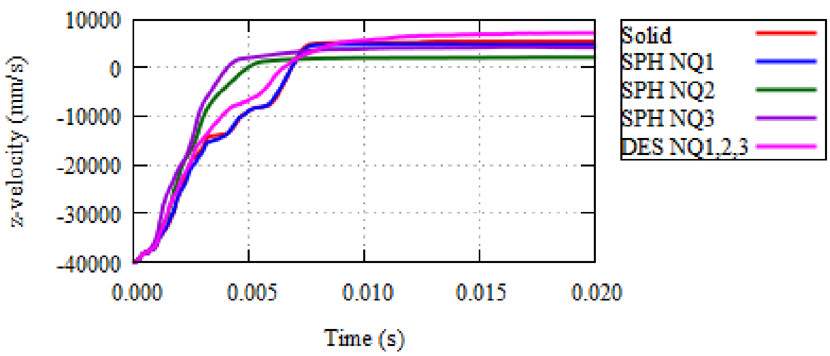


(b) SPC reaction force history

Fig.4: Contact force and SPC reaction force histories from double precision cases

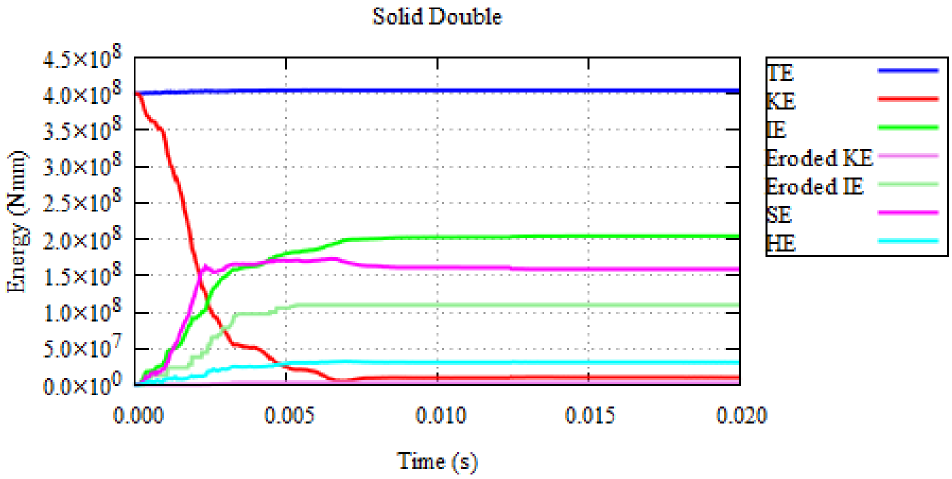


(a) Displacement

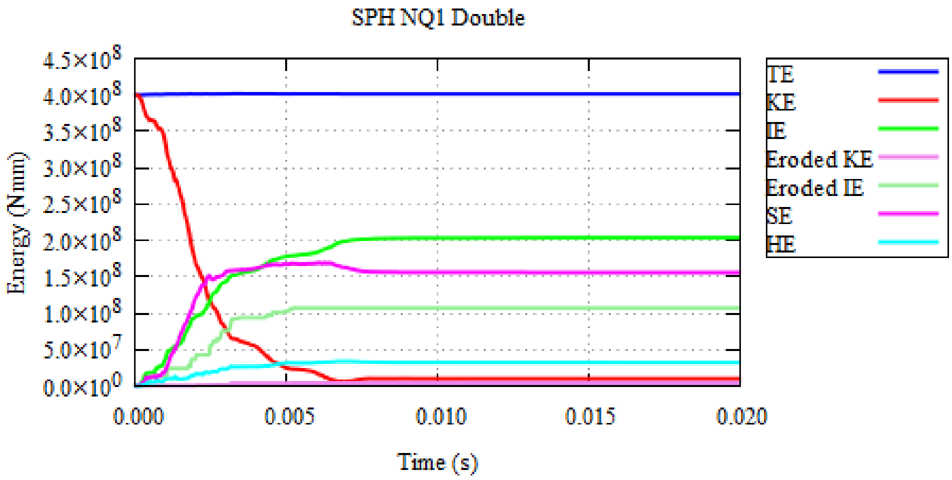


(b) Velocity

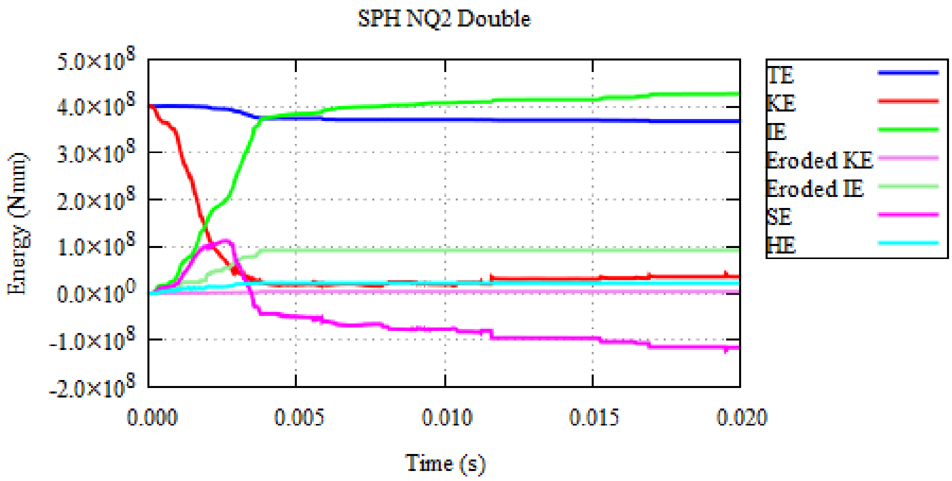
Fig.5: Displacement and velocity histories of impactor from double precision cases



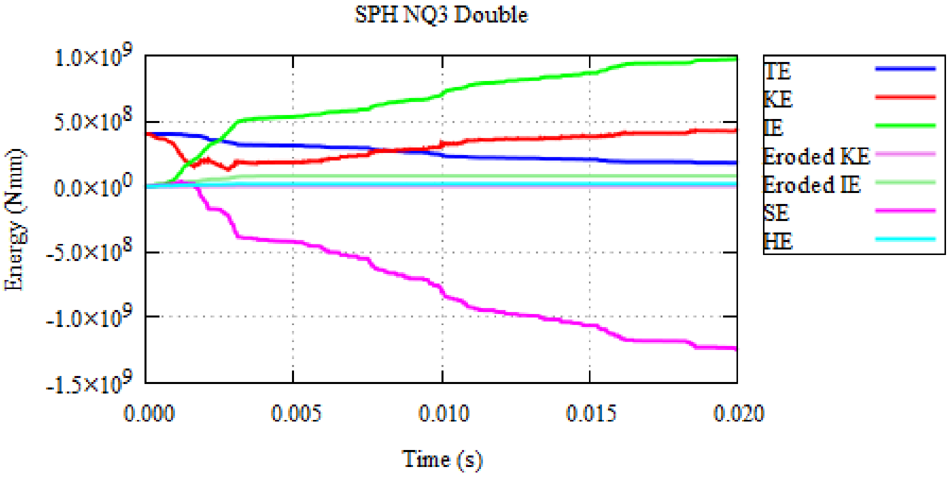
(a) Case 2 : Solid model, Double precision



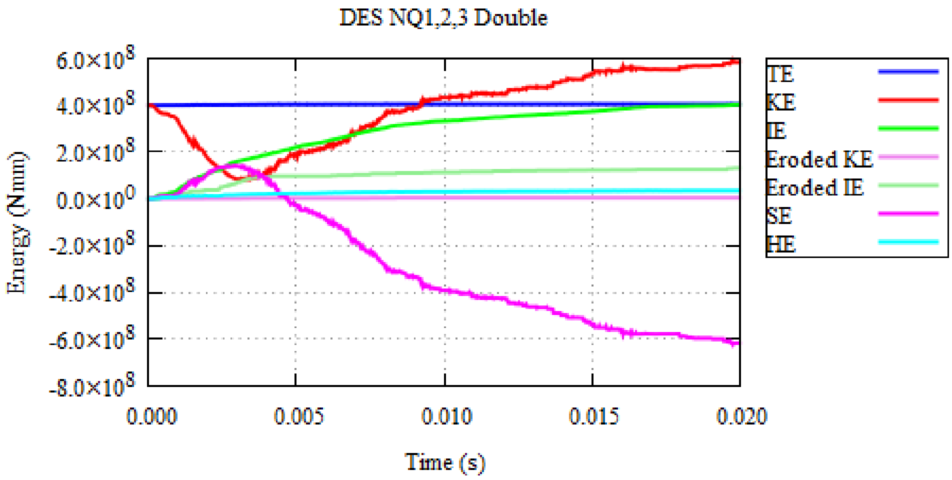
(b) Case 4 : Solid-SPH model, NQ=1, Double precision



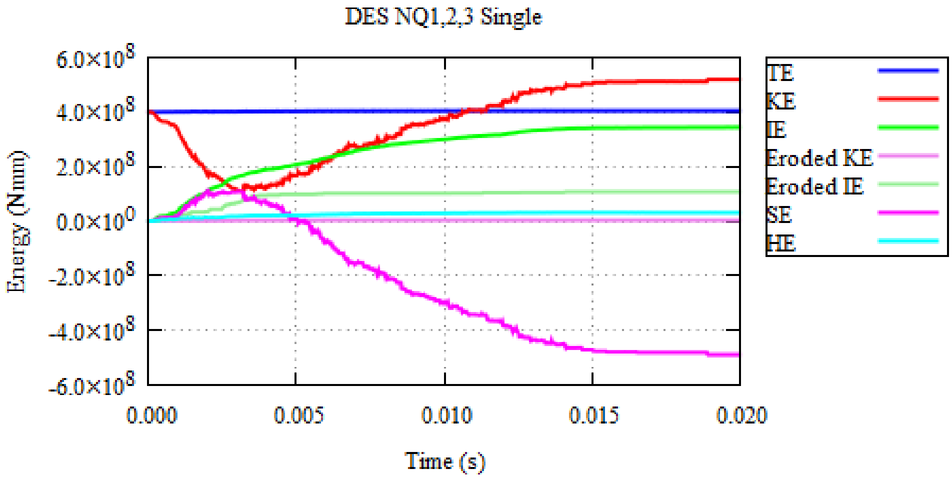
(c) Case 6 : Solid-SPH model, NQ=2, Double precision



(d) Case 8 : Solid-SPH model, NQ=3, Double precision



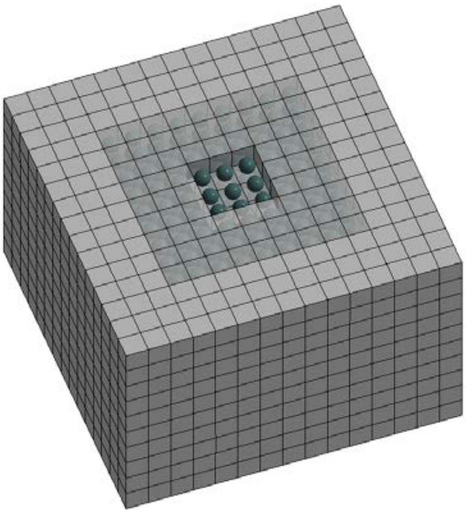
(e) Case 10,12,14 : Solid-DES model, NQ=1,2,3, Double precision



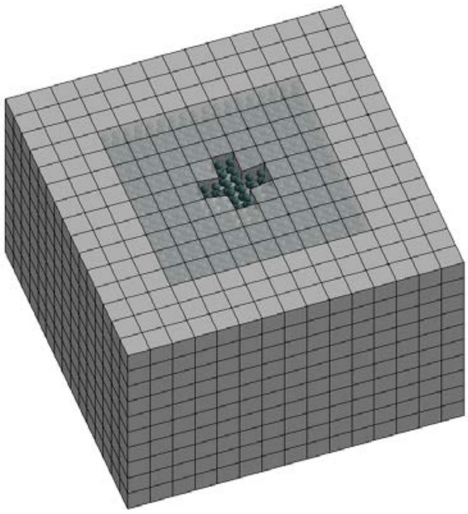
(f) Case 9,11,13 : Solid-SPH model, NQ=1,2,3, Single precision

Fig.6: Energy balance (TE;Total Energy, KE;Kinetic Energy, IE;Internal Energy, SE;Sliding Interface Energy, HE;Hourglass Energy)

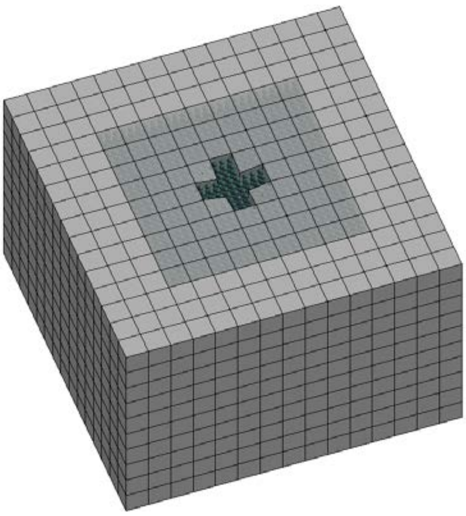
Figure 4 and 5 show the difference of results obtained from each analysis case. Large negative sliding interface energy can be seen in Fig.6. The sliding interface energy comes from the contact between the generated particles and solid elements of concrete material. It suggests that some improvement for the definition of the contact is required. SPH particles are activated as one, eight and 27 particles per solid element according to the value of NQ. These particles are generated at initial state in the simulation as shown in Fig.7 (a), (b) and (c). While DES particles are generated when solid element are deleted as shown in Fig.7 (d).



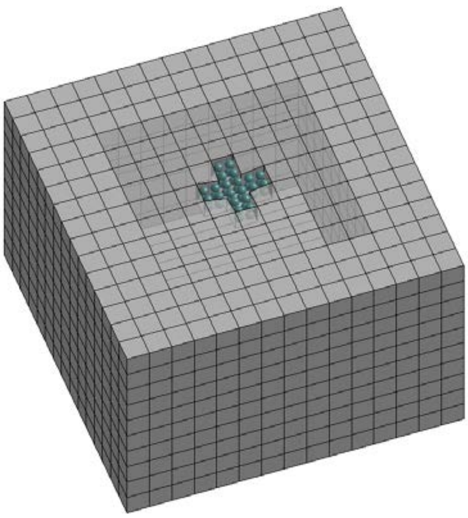
(a) Solid-SPH, NQ=1



(b) Solid-SPH, NQ=2



(c) Solid-SPH, NQ=3



(d) Solid-DES, NQ=1,2 and 3

Fig.7: Generated particles just after the erosion of solid elements

6 Summary

The capability of the keywords **`*DEFINE_ADAPTIVE_SOLID_TO_SPH/DES`** implemented in LS-DYNA are examined. It is considered that this feature is very important and useful to model accumulation of debris caused by the failure of concrete material. The difference of the results under several analysis condition, e.g., particle type, number of generated particles, can be seen. Most reliable analysis condition should be determined by the comparison with real experiment in the future. LS-DYNA R9.1.0 SMP on Windows and Linux are used in this paper.

Reference

[1] LS-DYNA keyword User's Manual LS-DYNA R9.0 08/29/16 (r:7883), LSTC, 2016
[2] Madurapperuma, M., Niwa, K.: " Analysis of Reinforced Concrete Walls due to Impact of Vehicles during Tornadoes ", JSOL LS-DYNA & JSTAMP Forum, 2015
[3] Madurapperuma, M., Niwa, K.: " Analysis of Aircraft Impact on Reinforced Concrete Structures Using SPH for Modeling Non-Structural Components ", JSOL LS-DYNA & JSTAMP Forum, 2016