NUMERICAL SIMULATION OF STRUCTURAL DEFORMATION UNDER SHOCK AND IMPACT LOADS USING A COUPLED MULTI-SOLVER APPROACH

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Abstract

Spatial discretization in numerical analyses is typically based upon a single method such as Lagrange, Euler, a mixture of Lagrange and Euler - ALE (Arbitrary Lagrange Euler), or meshfree Lagrangian - SPH (Smooth Particle Hydrodynamics). For the numerical simulation of the deformation of structures under shock and impact loadings, each of the different solution techniques has unique advantages and limitations. For many engineering problems involving shock and impact, there is no single ideal numerical method that is appropriate to the various regimes of a problem. An approach wherein different techniques may be applied within a single numerical analysis can provide the “best” solution in terms of accuracy and efficiency. This requires not only that multiple spatial discretizations be used within a single modeling process but also that interaction and coupling between these different methods be implemented. To demonstrate the effective use of such a coupled multi-solver approach, the results of four real-life examples are presented in this paper. These are: a.) airplane impact and subsequent failure and collapse of New York World Trade Center North Tower, b.) oblique impact on a steel-reinforced concrete slab, c.) underwater explosive loading on a submerged hollow metal cylinder, and d.) a pipe bomb explosion in a vehicle. These numerical simulations are performed with the nonlinear dynamic analysis computer code AUTODYN®. The correlation between the numerical results and the available experimental and observed data demonstrates that the coupled multi-solver approach is an accurate and effective analysis technique.

Keywords: Impact, Shock, Computational Simulation, Structural Safety.

1. Introduction

For structures under shock and impact loading, numerical simulations have proven to be extremely useful. They provide a rapid and less expensive way to evaluate new design ideas. Numerical simulation can supply quantitative and accurate details of stress, strain, and deformation fields that would be very expensive or difficult to reproduce experimentally. In these numerical simulations, the partial differential equations governing the basic physics principles of conservation of mass, momentum, and energy are employed. The equations to be solved are time-dependent and nonlinear in nature. These equations, together with constitutive models describing material behavior and a set of initial and boundary conditions, define the complete system for shock and impact simulations.

The governing partial differential equations need to be solved in both time and space domains. The solution over the time domain can be achieved by an explicit method. In the explicit method, the solution at a given point in time is explicitly expressed as a function of the system variables and parameters, with no requirement for stiffness and mass matrices. Thus the computing cost at each time step is low but may also require numerous time steps for a complete solution. The solution over the space domain can be obtained utilizing different spatial discretizations such as Lagrange, Euler, ALE, or meshfree methods. Each of these techniques has unique capabilities and limitations. Usually, there is not a single technique that is appropriate to all the regimes of a problem. For example, as will be discussed in greater detail later, numerical simulation of the dynamic response of a structure to an explosive detonation, can best be described using an Eulerian approach for the detonation and blast while the structural response is generally best modeled using a Lagrangian method. This leads to a requirement for a numerical technique that allows both Eulerian and Lagrangian solutions in a single simulation with coupling between the different techniques in space and time. Such an approach, wherein different methods may be applied within a single numerical analysis, can provide the “best” solution in terms of accuracy and efficiency.

In the present paper, Lagrange, Euler, ALE, and SPH methods, as well as coupled combinations of these methods, are described and applied to a plate structure impacted by a projectile. The pros and cons of each solution technique, as well as the advantages of the use of coupled methods, are elaborated. To further demonstrate the effective use of coupled multi-solver approach, the results of four real-life examples are presented in the paper. These are: a.) airplane impact and subsequent failure and collapse of New York World Trade Center North Tower, b.) oblique impact on a steel-reinforced concrete slab, c.) underwater explosive loading on a submerged hollow metal cylinder, and d.) a pipe bomb explosion in a vehicle. These numerical simulations were performed with the nonlinear dynamic analysis computer code AUTODYN. The correlation between the numerical results and the available experimental and observed data validates that the coupled multi-solver approach is an accurate and effective analysis technique.

2. Methods of Space Discretization

The spatial discretization is performed by representing the fields and structures of the problem using computational points in space, usually connected with each other through computational grids. Usually, the finer the grid is, more accurate the solution. The most commonly used spatial discretizations are Lagrange, Euler, ALE (Arbitrary Lagrange Euler - a mixture of Lagrange and Euler), and meshfree methods such as SPH (Smooth Particles Hydrodynamics).

2.1. Lagrange

The Lagrange method of space discretization, as described in [1], where the numerical grid moves and deforms with the material, is ideal for following the material motion and deformation in regions of relatively low distortion, and possibly large displacement. Conservation of mass is automatically satisfied and material boundaries are clearly defined. The Lagrange method is most appropriate for representing solids like structures and projectiles. The advantages of the Lagrange method are computational efficiency and ease of incorporating complex material models. The disadvantage of Lagrange is that the numerical grid can become severely distorted or tangled in an extremely deformed region, which can lead to adverse effects on the integration time step and accuracy. However, these problems can be overcome to a certain extent by applying numerical techniques such as erosion and rezoning.

2.2. Euler

The Euler method of space discretization, as described in [2], where the numerical grid is fixed in space while the physical material flows through the grid, is typically well suited for the description of the material behavior of severe deformations. The Euler method is generally used for representing fluids and gases, for example, the gas product of high explosives after detonation. To describe solid behavior, additional calculations are required to transport the solid stress tensor and the history of the material through the grid. The advantage of the Euler method is that large deformations or flow situations, by definition, do not result in grid distortions due to the fixed grid. The tradeoff is the extra computational work required to maintain material interfaces and to reduce numerical diffusion.

2.3. ALE (Arbitrary Lagrange Euler)

The ALE (Arbitrary Lagrange Euler) method of space discretization is a hybrid of the Lagrange and Euler methods. It allows redefining the grid continuously in arbitrary and predefined ways as the calculation proceeds, which effectively provides a continuous rezoning facility. Various predefined grid motions can be specified such as free (Lagrange), fixed (Euler), equipotential, equal spacing, and others. The ALE method can model solids as well as liquids. The advantage of ALE is the ability to reduce and sometimes eliminate difficulties caused by severe mesh distortions encountered by the Lagrange method and allows a calculation to continue efficiently. However, compared with Lagrange, an additional computational step of rezoning is employed, as described in [3, 4], to move the grid and remap the solution onto a new grid.

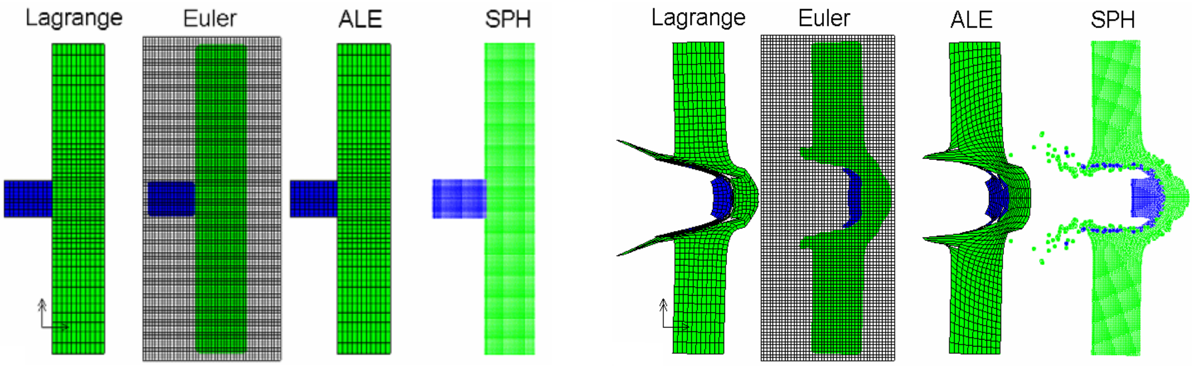
2.4. Meshfree Lagrangian Method – SPH (Smooth Particles Hydrodynamics)

The meshfree Lagrangian method of space discretization - SPH (Smooth Particles Hydrodynamics), initially was used in astro-physics [5]. It was implemented in AUTODYN [6] in 1995. The SPH particles are not only interacting mass points but also interpolation points used to calculate the value of physical variables based on the data from neighboring SPH particles, scaled by a weighting function. Because there is no grid defined, the SPH method does not suffer from grid tangling in large deformation problems. Compared with the Euler method, material boundaries and interfaces in the SPH are rather well defined and material separation is naturally handled. Therefore, the SPH method is very useful to simulate material behavior subject to severe deformation and distortion, for example, in hyper-velocity impact and for the cracking of brittle materials. However, the SPH method requires a sort of the particles in order to locate current neighboring particles, which makes the computational time per cycle more expensive than mesh based Lagrangian techniques – this can make meshfree methods less efficient than mesh based Lagrangian methods with comparable resolution.

2.5. Examples of Lagrange, Euler, ALE, and SPH Methods

To demonstrate the use of Lagrange, Euler, ALE, and SPH methods, a numerical simulation of an impact problem shown in FIGURE 1 is conducted. The steel projectile has a diameter of 7.5mm and weighs about 2.9g. It impacts 22.5mm thick aluminium plate at a velocity of 1000m/s. An erosion mechanism is applied to the Lagrange as well as ALE grids to eliminate the elements that become highly distorted.

All of these methods display similar impact damage on both the projectile and the target. The Euler method needs extra cells around the materials representing a void region into which deformed materials may flow. The ALE grid distorts less than the Lagrange grid because of equipotential rezoning where a node is re-positioned relative to its nearest neighbors. Compared with the Lagrange and the ALE, the SPH method maintains a well-defined material interface without the need to use erosion.



(a) before impact (b) after impact

FIGURE 1 **Examples of Lagrange, Euler, ALE, and SPH simulations on an impact problem.**

3. Coupled Multi-Solver Approach: Interaction and Coupling between Space Discretization Methods

Because the boundaries of ALE grids are Lagrangian in nature and the particles in SPH method move with the material, ALE and SPH are essentially a Lagrangian type of space discretization. The interaction between space discretization methods can then be categorized as Lagrange to Lagrange interaction or Euler to Lagrange coupling.

3.1. Lagrange/Lagrange Interaction

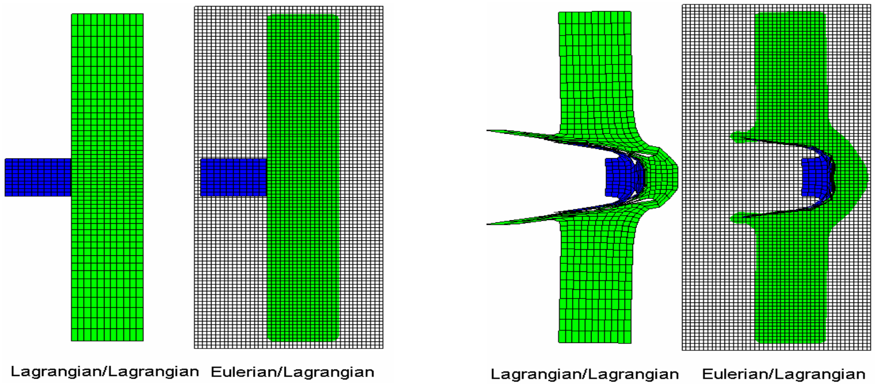
The interaction between two Lagrangian grids is called Lagrange/Lagrange interaction and is implemented using impact/slide surfaces. An interaction detection zone is automatically defined around each interacting Lagrangian face. Whenever a node enters into this detection zone it is repelled. This occurs for the interaction of each of the independent Lagrangian faces with each other, and with itself.

3.2. Euler/Lagrange Coupling

The interaction between Eulerian and Lagrangian grids is called Euler/Lagrange coupling, often used to simulate fluid/structure interaction. Lagrangian grids overlap the Eulerian grid and provide constraints to the flow of material in the Eulerian grid. At the Euler-Lagrange interface, the Lagrange grid acts as a geometric flow boundary to the Euler grid while the Euler grid provides a pressure boundary to the Lagrange grid. As the Lagrange grid moves or distorts, it covers and uncovers the fixed Euler cells. The coupled Euler/Lagrange technique allows complex gas-structure or fluid-structure interaction problems including large displacements and deformations of the structure, to be solved in a single numerical simulation.

3.3. Example of Lagrange/Lagrange Interaction and Euler/Lagrange Coupling

AUTODYN is a general-purpose computer program that is designed to solve non-linear engineering problems involving large deformation and strain of solid structures as well as fluid flow and gas dynamics [7]. Various spatial discretization solvers of Lagrange, Euler, ALE, Shell, Beam, Euler-FCT, Euler-Godunuv, and SPH, as well as the interaction and coupling among these solvers have been implemented in AUTODYN since 1987 [8]. To demonstrate the use of the coupled multi-solver approach, the same impact problem shown in the FIGURE 1 is computed again using Lagrange/Lagrange interaction where the projectile and target are modeled in Lagrange and using Euler/Lagrange coupling where the projectile is Lagrange and the target is Euler. The damage shown in FIGURE 2 has the similar extent as that in the FIGURE 1. It is noteworthy to point out that the constitutive models in AUTODYN are programmed independent of the solvers and so the same material behavior can be studied for all solver types.



(a). before impact (b). after impact

FIGURE 2 **Examples of Lagrange/Lagrange interaction and Euler/Lagrange coupling in the impact simulations.**

4. Examples of Coupled Multi-Solver Methods

To further demonstrate the effective use of the coupled technique, the results of four real-life examples of shock and impact numerical simulations are presented. These simulations were conducted using AUTODYN.

4.1. Impact and Collapse of New York World Trade Center North Tower

The AUTODYN model for this calculation includes the entire building of the New York World Trade Center North Tower and a Boeing passenger jet [9]. The model contains a total of 270,000 beam, shell, and Lagrange brick continuum elements. All of the columns, both at the building perimeter and inside the central core, are represented by beam elements, while each floor of the North Tower is represented by shell elements, with the floor boundary nodes joined with the nodes of the surrounding beam elements. The airplane is also represented by shell elements except that the jet fuel is represented by Lagrange continuum cells. Beam and shell solvers are of Lagrangian type in terms of spatial discretization. Thus Lagrange/Lagrange interaction is utilized in the simulation to allow the contact and sliding between the shell and beam elements. FIGURE 3 shows the AUTODYN-generated three-dimensional model of the North Tower and the airplane.

The complete numerical simulation consists of four stages. The first stage is the calculation to define the static equilibrium of the building under gravity. Then the airplane impacts the building to start the second stage of the simulation. This stage is used to evaluate damage from the airplane impact locally as well as throughout the building. Because of impact resistance, the airplane finally comes to rest inside the building with the burning jet fuel spread though several floors of the building. The third stage is to model the strength and stiffness reduction of the building resulting from the post-impact fuel fire. Once the local stiffness and strength has been reduced, the final stage begins, which is the progressive collapse driven by gravity of the weakened building.

The comparison of the impact damage between the AUTODYN simulation in [9] and the report by FEMA [10] is shown in FIGURE 4. The number of broken columns predicted by AUTODYN is exactly the same as those on the photo FIGURE 4(a) taken from the FEMA report [10]. The predicted damage area shown in dark color of FIGURE 4(b) on the building exterior face is also very similar to the observed damage area. In the AUTODYN simulation, in order to reduce the cost of computation with the use of symmetry, the airplane is assumed to fly parallel to the ground. So the perimeter columns are cut horizontally. The photo from [10], which was released after the simulation was completed, suggests that the airplane hit the building with some small angle of incidence because the damage was not perfectly horizontal. Simulation of the first 5 seconds of the progressive collapse shows that the building has almost collapsed to half of its height as shown in FIGURE 5. This closely matches the recorded accounts of the actual collapse.

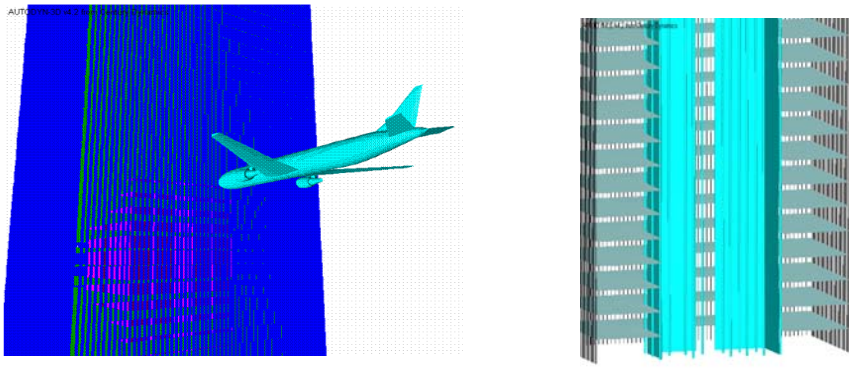

(a). outside of the building (b). inside of the building

FIGURE 3 AUTODYN models of the World Trade Center North Tower and the Boeing airplane.

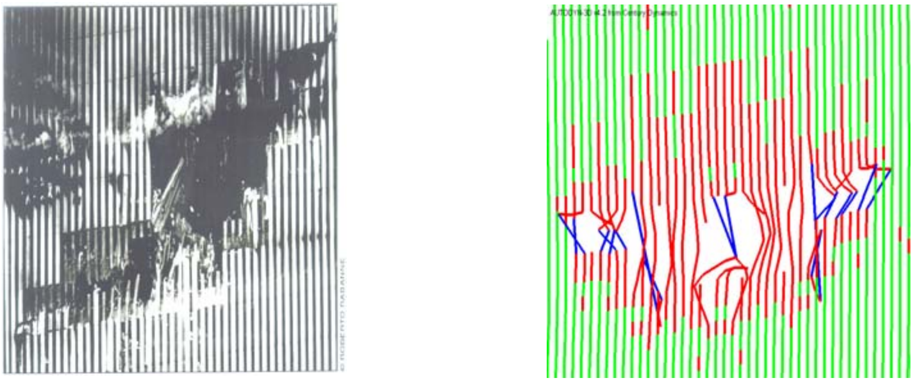
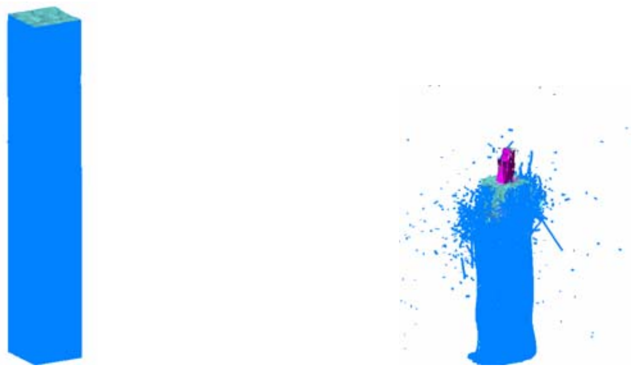

(a). FEMA Report [9] (b). AUTODYN Simulation [10]

FIGURE 4 The comparison of the impact damage between the AUTODYN simulation [9] and the observation [10].



(a) start (b) 5 seconds

FIGURE 5 **The comparison of the building at the start and 5s of the progressive collapse in AUTODYN simulation.**

4.2. Oblique Impact on a Steel-Reinforced Concrete Slab

In this example, a steel-reinforced concrete target was impacted obliquely by a 20kg kinetic energy penetrator at a velocity of 293m/s [11]. The penetrator had a caliber of 90mm with an ogive nose. The reinforced concrete target was a rectangular block 4.5m wide by 4.0m high, reinforced with 20mm diameter steel rebars. The target was set at an angle of 10° off normal in the lateral plane. Lagrange, SPH, and Beam solvers and Lagrange/Lagrange interaction among these solvers are applied in the AUTODYN simulation. The volume of concrete that experiences large distortion is represented using the meshfree Lagrangian SPH method. The volume of the concrete target which experiences only small deformation is represented by Lagrange method to speed up the computation. The SPH volume is joined to the Lagrange volume of the target. The concrete reinforcement is represented explicitly through beam elements which overlay the concrete discretization and are joined to appropriate nodes within the Lagrange mesh and SPH particles. The penetrator is represented by Lagrange grid. The final discretization of the penetrator and the concrete target is shown in FIGURE 6.

FIGURE 7 compares the distortion and subsequent cutting of the rebars between the observed and simulated data. The predicted penetrator/rebar interaction is in very close agreement with the experimental observation, where a similar distance separates the two vertical rebars and the uppermost rebar in the horizontal plane is bent and cut by the penetrator.

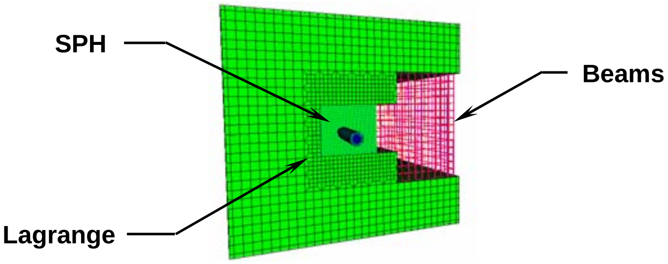
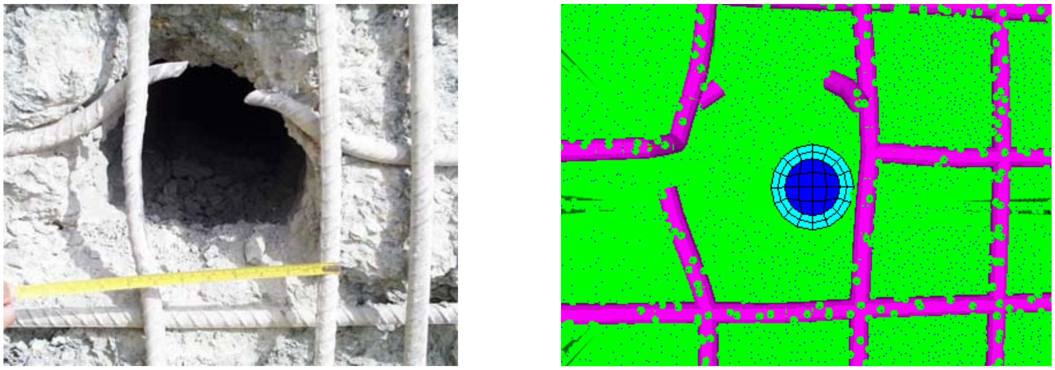


FIGURE 6 **Space discretization in the oblique impact concrete target [11].**



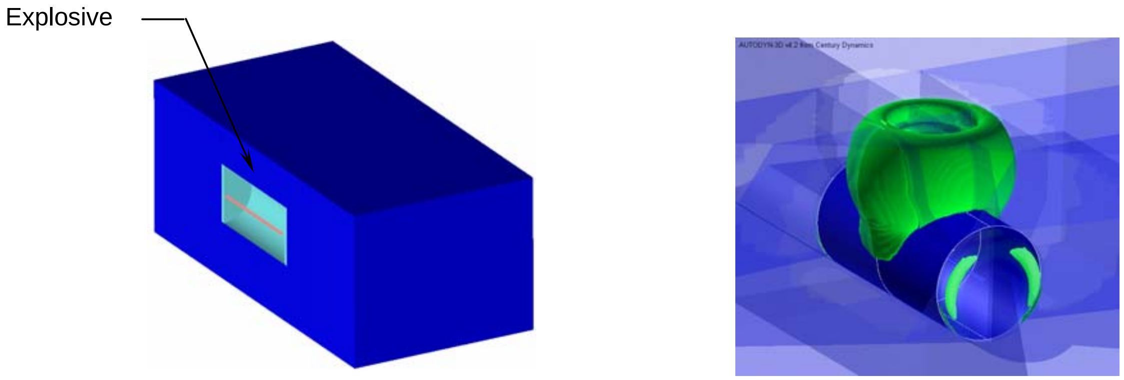
(a) experimental observation (b) AUTODYN simulation

FIGURE 7 Comparison of impact damage between experiment and AUTODYN simulation [11].

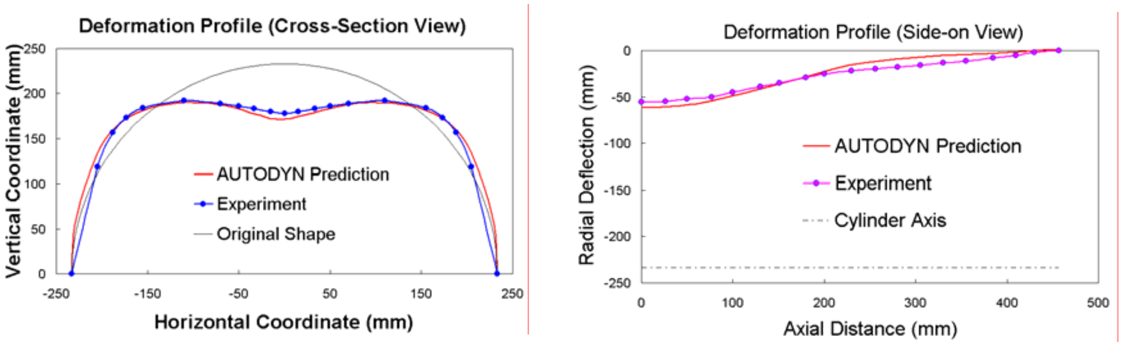
4.3. Underwater Explosive Loading on a Submerged Hollow Metal Cylinder

In this example, a submerged, hollow aluminium cylinder with a diameter of 457mm was subjected to the explosion of 11 grams of pentolite centered 89mm above the center of the cylinder and 216mm below the water surface [12]. The thickness of the cylinder is 5mm. A 50mm diameter, solid steel rod was mounted along the cylinder axis. The water is represented by Lagrange elements, while the cylinder and the rod are represented by shell and beam elements, respectively. The explosive is represented by Eulerian elements. The Lagrange/Lagrange interactions between the Lagrange, the shell, and the beam as well as the Euler/Lagrange coupling between the Euler and the Lagrangian grids are used in the simulation.

FIGURE 8(a) shows the cutaway picture of material location plot. Because of the higher sound speed in aluminum than in water, the pressure wave propagates faster through the solid cylinder than through the water as shown FIGURE 8(b). While the pressure wave through the solid cylinder has already reached the cylinder end, the pressure wave through the water has travelled about the half this distance. In the experiment [12], the permanent deformation profile of the cylinder was measured after the explosion. FIGURE 8(c) & (d) show the comparison of deformation profiles of the cylinder between the AUTODYN simulation and the experimental measurements. The deformation profile of the AUTODYN simulation is taken at 11ms after the explosion. Both the predicted side-view and cross-section profiles are in good agreement with the experimental measurements. The small discrepancies could be attributed to the dynamic elastic deformation that was not taken account of in the experimental measurements.



(a) initial material location (b) pressure contour plot after detonation

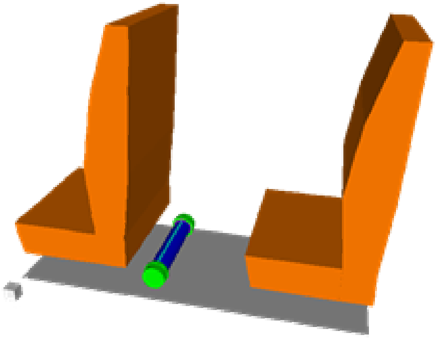


(c) deformation profile of cross-section view (d) deformation profile of side-on view

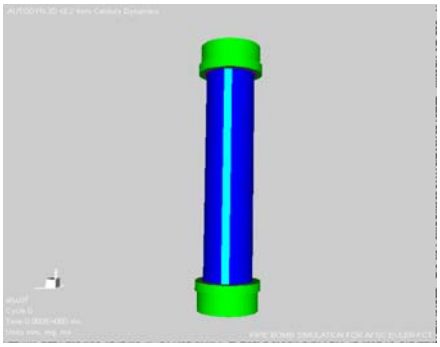
FIGURE 8 Example of underwater explosive loading on a submerged hollow metal cylinder.

4.4. Pipe Bomb Explosion in a Vehicle

This example is a pipe bomb being detonated on the floor of a vehicle. The interior detonation of the explosive and subsequent expansion of the detonation products is modeled with the Euler-FCT solver. The pipe and steel witness plate representing the car floor are modeled using the Lagrangian shell solver while two end caps are modeled by solid Lagrange elements. Both Lagrange/Lagrange interaction and Euler/Lagrange coupling are applied simultaneously in the simulation. FIGURE 9(a) shows the location of the pipe bomb in the vehicle. The initial material location plot is shown in FIGURE 9(b). After the explosion, the pipe ruptured with multiple fragments being created. These fragments then impacted the witness plate as shown in FIGURE 9(c). The impact damage to the plate compares well with the experimental result shown in FIGURE 9(d).



(a) location of the pipe bomb in a vehicle



(b) initial material location plot

(c) the predicted damage by AUTODYN (d) the damaged witness plate in the experiment

FIGURE 9 **Example of pipe bomb explosion in a vehicle.**

5. Conclusions

The four real-life AUTODYN impact and shock simulations demonstrate the successful use of the coupled multi-solver approach in AUTODYN. The correlation between the numerical results and the available experimental or observed data demonstrates that the coupled multi-solver approach is an accurate and effective analysis technique.

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