Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Fluid Structure Interaction (FSI) Analysis during Explosion using Numerical Technique

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Abstract

Fluid-structure interaction (FSI) is a intricate multi-physics problem that occurs in a variety of domains. The blast wave propagation and its impact on the structure is an ongoing research. Experimental study of blast wave propagation and its impact on the structure is difficult to perform, so a numerical study is an alternative approach to study this phenomenon. This research is on study of FSI during explosion using C4 as a detonation in geometric domain. The mesh of 2D domain of the fluid and aluminium structure are created using blockMesh for three different cases. blastSolids4Foam solver has been used inorder to perform two way FSI during explosion. Three different 2D cases have been simulated with the structure on the either side of the domain. Because of the reflection of blast wave, the intensity of blast wave behind the first structure is higher in multiple structure than the single structure. The pressure at the different probe location on fluid domain and the deflection at the tip of the solid structure for three cases has been recorded. The maximum x-displacement is found to be 0.1m and 0.148m for case I and case II but the intensity of displacement decrease with the combination of both cases to 0.08m and 0.12m on the solid structure which can be compared with case I and case II respectively.

Keywords

Fluid–structure interaction (FSI), blast wave propagation, numerical simulation, blastSolids4Foam

1. Introduction

FSI stands for Fluid-Structure Interaction, which is a specialized field within computational engineering and physics.FSI incorporates the study of the dynamic interaction between a fluid and a solid structure where both the fluid and the structure affect each other's behavior, It also includes study of how forces, pressures, and velocities within a fluid affect the deformation and motion of nearby solid structures along with the modeling and simulation and conversely.

Different explosives are being used in the military for a very long time, although there have been several explosion-related accident due to a lack of attention paid to the security of explosive materials during storage and transit. When a high order explosion is started, an extremely quick chemical reaction known as an exothermic reaction happens. Explosive substances that are solid or liquid are transformed into hot, dense, and high-pressure gases throughout the reaction process. When explosive materials first start to expand, they do so quickly in order to attain equilibrium with the air around them and create a shock wave[1].

Explosive blasts continue to result in losses in both civilian and military settings, therefore it's crucial to understand how blast loading interacts dynamically with structure, how to reduce shock, and, most importantly, how to recognize the mechanisms that cause blast trauma. It will describe how to simulate the Fluid-structure interaction (FSI) employing a coupling approach for treating the fluid as a moving medium by a moving mesh using the ALE formulation, as well as how to handle the structure on a deformable mesh using a Lagrangian formulation.[2].

2. Literature Reviews

The explosive is oxidized and the detonation area increases by the detonation velocity in the initial phase, causing the shock front to compress the surrounding air. The shock wave front has a high velocity, greater than the speed of sound. The shock front has a very narrow width.and has an expanding character. When the shock front hits the structure, the structure absorbs the properties of the wave and its energy. Thus, the impact on the surface of the structure can be reduced when it moves to the next point after the next time interval. The force generated by the shock directly affects the human life in the close range[3].

When the blast wave strikes the structure surface, the blast pressure will interlock and reflection phenomenon will appear.The blast wave velocity and its energy will decrease due to the negative velocity and energy.The force due to the reflected wave can cause a high damage on the structure surface.If the geometry is not rough or the blast propagate in the open space, there will not be reflection.The blast wave pressure can cause more effect on the structure causing an addition of the pressure[4].

The explosion wave propagates outward and puts forces on the vertical wall, causing the structure to distort. Simultaneously, due to vertical wall displacement, Changes in the computational domain of detonation wave propagation, impacting detonation wave propagation. They have a relationship and engage with one other. The explosion wave spreads. outward and combines with the vertical wall, forming a vortex in the upper right corner resulting the change in pressure and the blast wave velocity. The detonation process depicted in the numerical simulation results is compatible with Beyer's [5] detonation propagation method.

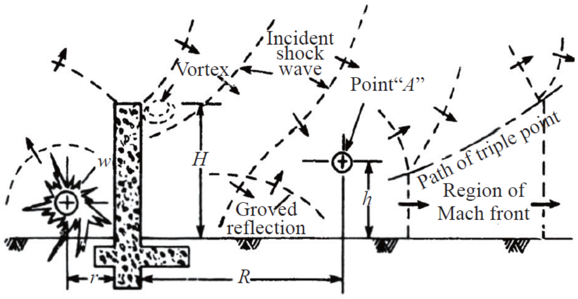

Figure 1: A sketch of detonation process [1]

Internal explosions severely harm the linings of buildings and result in numerous fatalities and immeasurable economic damages.In this study, numerical simulations are used to analyze a severe gas explosion that took place inside a highway tunnel in Chengdu, China. With dimensions that match those of the actual prototype and by taking into account fluid-structure interaction (FSI) effects, a five-part fully coupled numerical model is created.Following that, a thorough modeling procedure is described and verified by comparison with empirical formulas. This study examines the tunnel's effective stresses and dynamic reactions, as well as the strength and propagation characteristics of a blast shock wave[6].

A collection of algorithms for the numerical simulation of the gas dynamics of explosions can be found in the BLAST software, which is based on the Euler solver. If the wave velocity of detonation and the energy release mechanism are fully imposed in the solid explosive, a simple ideal gas model simulates the detonation of a high explosive. It has also been tested how a blast wave will interact with the structure. The explosion is 2.5 meters high and 10 meters from the building. Blast over pressure have been documented. This software for explosions, it is said, exhibits numerical simulation of explosion processes and explains its use[7].

The Eulerian-material formulation was utilized in the numerical simulation of the air blast to validate it for high pressure wave propagation and to compare the examples with experimental findings. A fixed mesh and an Eulerian formulation are used to model the high explosion process. The mesh is fixed, in contrast to traditional Lagrangian methods, and the material flows through the mesh. A pressure wave with hard wall reflection and a pressure wave with free propagation have both been put to the test.In the split technique, we used second-order algorithms for the advection algorithm that follows the Lagrangian phase. For both simulations, the pressure impulses calculated by time-integrating the pressure time history are quite similar. Major explosion physical phenomena can be observed and good agreements between experimental data and the pressure transient in the explosion are obtained[8].

2.0.1 blast wave propagation

The explosion generates hot gasses that expand and displace the area they inhabit. As a result, a layer of compressed air known as the blast wave forms in front of this volume of gas. It holds a large portion of the energy produced upon explosion. The blast wave's effect is mostly determined by the type of explosion and the distance between the explosion source and the target. (so-called "stand-off distance"). The positive phase occurs when the pressure of the blast wave rapidly rises above the surrounding air pressure. After a brief period of time, the pressure may decrease below the ambient pressure, signaling the start of the negative phase. During this part of the process, a partial vacuum is created, pulling in air and being accompanied by intense suction waves that carry debris far away from the blast area. The positive stage has less time but a greater strength than the negative one. Furthermore, as the distance develops, so does the duration of the shock wave's positive phase, resulting in less peak intensity and a longer lasting shock pulse. One of the most essential elements in defining the reflected wave is the peak positive pressure (P+) in Megapascals (MPa), which is affected by a variety of explosion-related variables. Numerous analytical solutions for characterizing explosion waves have been created in recent decades and may be found in the literature. Furthermore, an extensive number of additional parameters enter into the empirical depiction of a limited explosion pulse that might interact with the ground or damaged surfaces.

BlastFoam is a freely available solver for simulating explosion.The two situations It contains an explosion tube and two charge detonators. Initially, gas using the van der Waals EOS and water using the Stinened gas EOS separated at the domain's center. The multi-phase and detonation dynamics of the complicated issue are demonstrated by the two-charge detonation instance. C-4 and TNT are both exploded in air, with C-4 having a single point explosion in the center of a circular domain and TNT having detonation points in three evenly spaced locations inside a rectangular domain. As a consequence, we can infer that blastFoam can be employed in our research for explosive dynamics modeling.[9].

3. Methodology

3.1 Study design

The approach behind the explosive dynamics will be carried out by using CFD software. After modeling geometry on OpenFoam, the meshing will be created using blockMesh. On solving the mesh using the boundary condition and the numerical scheme, we can obtain the result of the FSI simulation. Last stage in the research is to extract the data and information systematically and analyzing the different scenario to get meaningful result.

3.2 Geometry and Case Setup

Geometry has been created on blockMesh with the dimension of 7m on x axis and 4m on y axis. The location of detonation is -1 m along x-axis from origin and 2 m above the origin i.e. (-1,2). And, spherical detonation of C4 with radius 0.1 m is consider for the simulation. The solid structure is composed up of aluminium with the density of 2700 Kg/m3 and the poisoon's ratio of 0.27. The thickness of the structure is 0.5m in every three different cases. The three cases with different

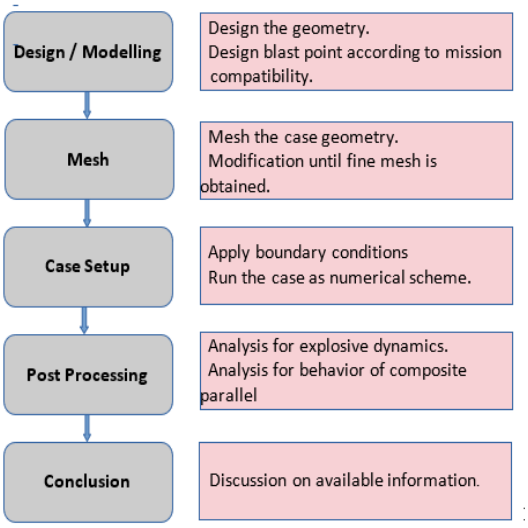

Figure 2: Work flow of numerical simulation

structure have been taken using the Solid4Foam software: case I, case II and Case III with the different structure which are mentioned below:

Case I: The domain of size 7m*4m with two flaps each with 1 m height on both side of 2D domain has been taken, where the vertices of both lower and upper flaps from origin -0.05 to 0.05 along x- axis separated by 2m height. The red color rectangular section shows the solid structure and the remaining region is defined as fluid domain.

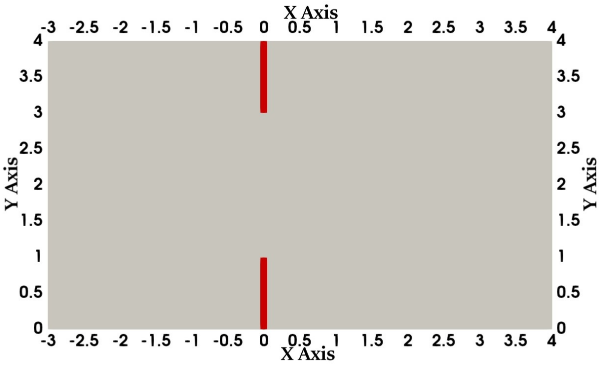

Figure 3: Geometry of case I

Case-II: Here, lower face of lower flap of 1 m height has coordinates of 1.05 to 1.15 along x-axis. The distance between upper face of lower flap and fixed wall is 0.5 m where upper face of fixed wall is with 1.5 m height. The upper face of fixed wall and lower face of upper flap has 0.5 m separation. The height of upper flap is 1 m.

Case-III: This is the case with combined domain including the above Case I and Case II where first domain and second domain have been combined with the unchanged location and coordinates.

3.3 Mesh

blockMesh and snappyHexMesh are the open software package of an OpenFOAM for meshing. snappyHexMesh is useful for the complex geometry and curvature. Since the research include 2D geometry,block mesh will be used to generate the structured mesh. The blockMesh tool creates grading and curved edge parametric meshes. The domain geometry is broken down into a collection of one or more three-dimensional hexahedral blocks.Each geometry block is specified by eight vertices, one at each corner of a hexahedron. The mesh is apparently specified as the number of cells in each direction of the block, providing blockMesh with enough information to produce the mesh data. BlockMesh was employed individually in the fluid and solid domains. The number of cell on x direction and y direction defined on the each solid structure are 10 and 50 respectively for all three cases. The number of cells on the fluid domain are 31825, 30341 and 31025 for three consecutive cases. The mesh for three different case are shown below:

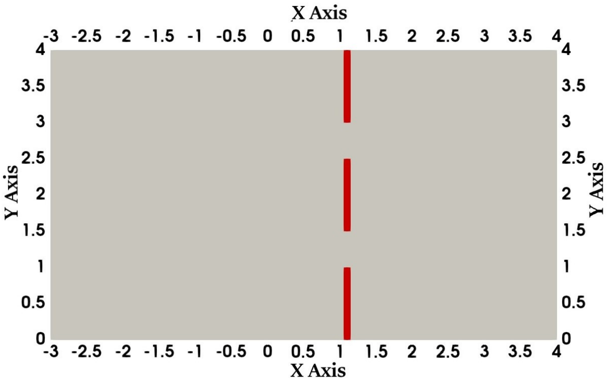

Figure 4: Geometry of case II

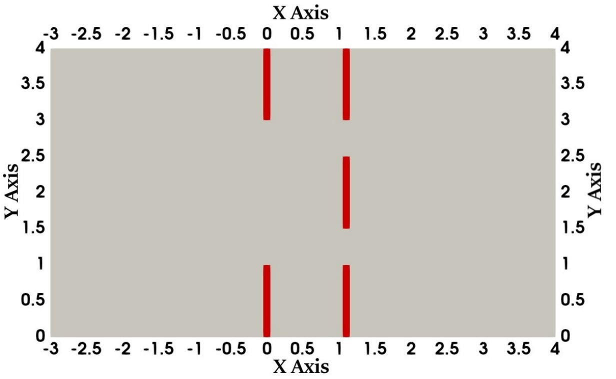

Figure 5: Geometry of case III

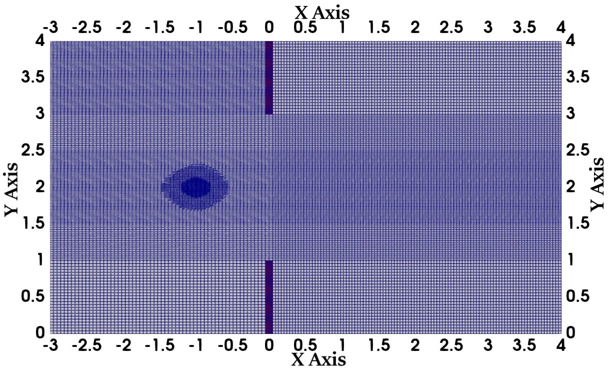

Figure 6: Block Mesh of case I

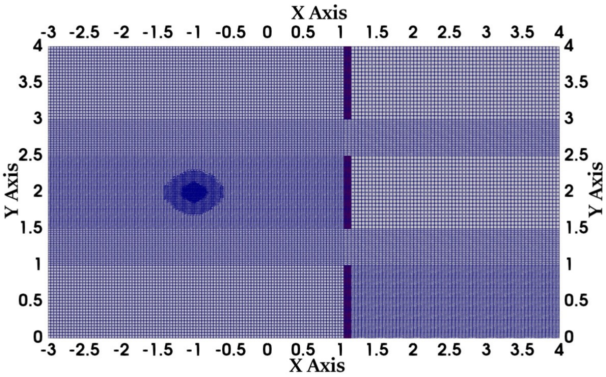

Figure 7: Block Mesh of case II

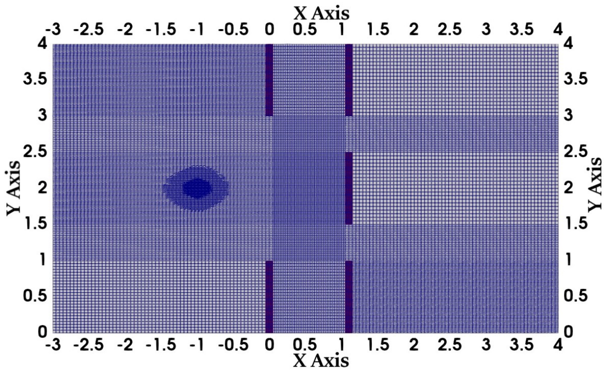

Figure 8: Block Mesh of case III

3.4 OpenFOAM

It is a free and open-source program for solving complicated fluid flows incorporating chemical processes, turbulence, and heat transport, as well as solid dynamics and electromagnetic fields. For dealing with the research problem, an infinite number of processors may be provided for an endless number of tasks in OpenFOAM, as well as the flexibility to generate boundary conditions and solvers.Following the meshing of the issue, multiple solvers can be utilized to solve the needed problem. In OpenFOAM, several applications for CFD simulations are coded, including in-compressible or compressible flow, multiphase flow, heat transfer, comustion, electro-magnetism, turbulence modeling, and solid mechanics, among others, Examples include icoFoam,rhoSonicFoam,and simpleFoam.

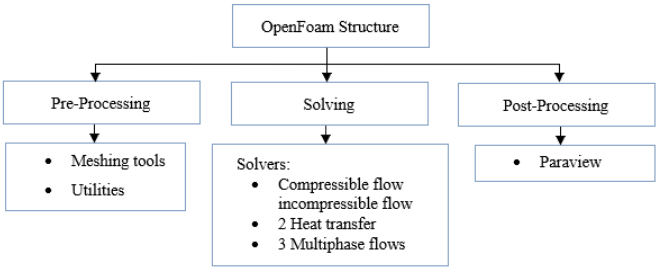

Figure 9: Structure of OpenFOAM

3.4.1 Solver

blastsolids4foam solver will be used which is in the blastFoam to run the FSI simulation under explosion. Synthetik Applied Technologies' blastFoam is an open-source toolkit based on openFoam that can successfully address multi-phase compressible flow issues in high-explosive detonation, explosive safety, and airblast.

3.4.2 Post Processing

The ParaView which is inbuilt in OpenFoam has been used for the post processing to visualize and analyze the result.

3.5 Coupling method of FSI

A numerical simulation technique that examines the simultaneous interaction of a fluid and a solid structure is the coupled method of Fluid-Structure Interaction (FSI) analysis. The governing equations for the fluid dynamics and structural mechanics are solved concurrently in this techniques,allowing precise depiction of the mutual effect and dynamic interaction between the fluid and the structure. The coupled approach is one of the most advanced and accurate FSI analysis techniques, and it is widely employed in a variety of engineering applications. Fluid-structure interaction (FSI) may be simulated in two ways: monolithically by solving the flow and structural equations simultaneously, and partitionedly by using separate solvers for the flow and structural equations.The performance of a partitioned quasi-Newton approach, which solves the coupled problem using nonlinear equations corresponding to the interface position, is compared to that of a monolithic Newton algorithm.various structural configurations with the an incompressible fluid are solved,and the ratio of the time for the partitioned simulation to the time for the monolithic simulation when convergence is obtained is determined to be between 1/2 and 4[10].

FixeRelaxationCoeffs coupling which is monolithic type has been used to transfer information between solid and fluid interface with the relaxation factor of 0.4.

3.6 Numerical technique

The Navier-Stokes equations, which are the fundamental governing equations of fluid dynamics, may be simplified to the following forms: U is a vector of conservative variables that includes volume fraction, mass, momentum, and energy, F is a vector of fluxes that correspond to the conservative variables, and S is a vector of source terms.

$$\partial_t U + \nabla \cdot F = S \tag{1}$$

$$U = \begin{pmatrix} \alpha_1 \\ \alpha_1\rho_1 \\ \alpha_2\rho_2 \\ \rho u \\ \rho E \end{pmatrix} F = \begin{pmatrix} \alpha_1 u \\ \alpha_1\rho_1 u \\ \alpha_2\rho_2 u \\ \rho u * u + \rho I \\ (\rho E + p)u \end{pmatrix} S = \begin{pmatrix} \alpha_1 \nabla \cdot u \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

$$\sum \lim_{i} \alpha_i = 1 \qquad \text{and} \qquad \rho = \sum \lim_{i} \alpha_i \rho_i \tag{3}$$

Where, α the mixture density, u mixture velocity, E total energy, p pressure, p_i, α_i and are the density and volume fraction of each phase respectively. When the explosive component detonates, the pressure release follows the equation of state, which takes into account the mixture's internal energy, densities, and volume fraction. The five-equation model is used to solve the simulation of a collection of extremely compressible materials, each regulated by a distinct equation of state (EOS). Based on the work of JWL EOS, the equations of state are cast in Mie-Gruneisen form and can properly explain the thermodynamics of detonation products and unreacted high explosives.

$$P = A\left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \omega \rho e \quad (4)$$

Where, P is the pressure [MPa], $A, B, R_1, R_2, and\omega$ are material constants, V is the ratio ρ_{sol}/ρ, where ρ_{sol} is the density of the solid explosive, e is the internal energy per unit mass [11].

4. Result and Discussion

The initial shock wave produced by the explosion. This indicates the sudden release of energy resulting in a high-pressure wave propagating through the fluid. The pressure reaches at maximum value during the explosion.The gradual decay in pressure following the initial spike indicates the dissipation of the blast wave over the time.The decay is influenced by factor such as fluid viscosity, turbulence and the interaction with the structure. The pressure graph shows that pressure fluctuation caused by reflections of the blast wave from surfaces or interaction nearby structure. The simulation has been carried out with 8 core processor.

4.1 Pressure

Case I: Two probe locations such as A(0,1.1,0) and B(0.55,0.55,0) were defined on the fluid domain and the pressure distribution on that location has been recorded. The maximum pressure at location A is appeared as 11.85 Mpa at 0.0002 second and location B is 6 Mpa at 0.0004 second. The location A is just above the top of the structure surface. Due to the deflection of structure part the pressure flucation and rise has been appeared at 0.0012 second which result with the second peak. Location B is at the downside of the structure so the pressure intensity is relatively lower than the location A.

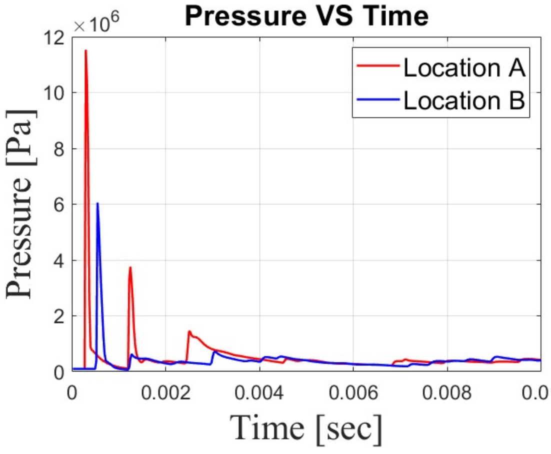

Figure 10: Pressure at position A and B for case I

Case II: Three probe locations such as C(1.05,1.1,0), B(0.55,0.55.0) and D(1.55,0.8,0) were defined on the fluid domain where the location B is common point on case I and case II. The peak pressure after explosion are 22.3 Mpa, 19 Mpa and 4 Mpa on consecutive location. But in location B we can see that the pressure rise immediately in 0.0005 second then tries to return back to atmospheric pressure. But reflection wave has been appeared resulting the increase in pressure as the blast wave strikes the structure and reaches the maximum at location B. The small fluctuation on the pressure at each location due to the effect of deflection of flap.

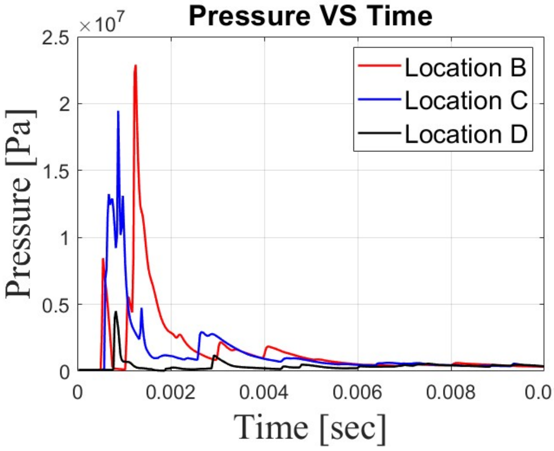

Figure 11: Pressure on different location at case II

Case III: All the point located on case I and case II has been recorded as the case III is the combination of case I and case II. As we can see that the peak pressure is nearer to 12 Mpa in figure 11 but due to the combination the pressure increased and reached to 12 Mpa on location A. Due to the reflection of blast wave between case I and case II, the maximum fluctuation appear in location B which is in between the two cases. In location C, the increment of the pressure wave has been appeared causing the back pressure flow of blast.

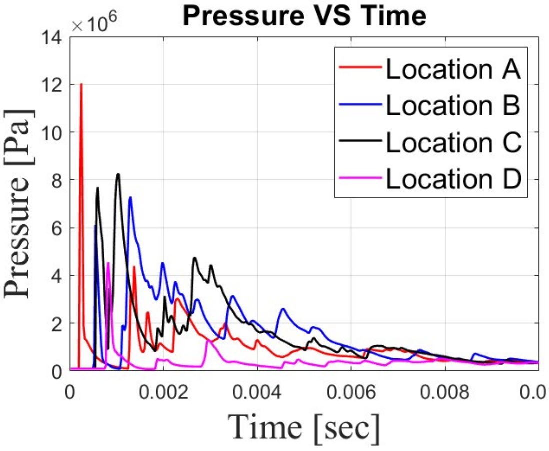

Figure 12: Pressure on different location at case III

4.2 Displacement

Due to the blast wave the aluminium solid structure vibrate along x axis as the base of the aluminium plate is considered as wall. While vibration occurs at the tip of the solid structure, small change in the direction to y-axis also appeared.

Case I : The maximum x-displacement is found to be 0.1m at

0.0025 second approximately then the oscillation phenomenon has been appeared. The displacement occurs at the negative x axis direction up to -0.055 meter at 0.0095 second. The graph shows that the intensity of displacement decays over time as the structure vibrate and return back to original position. The maximum deflection at y direction is 0.0049 meter. When the blast strikes the surface is start to move along x axis as we have simulated on 2D domain, then the decrement has been appeared. When it moves to the negative x direction then the displacement along y direction has been increased. The x-displacement and y-displacement on the tip of the solid structure is shown below:

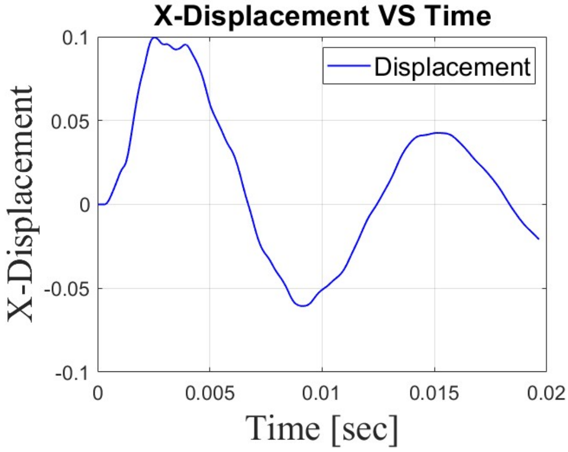

Figure 13: X-displacement on the tip of flap for case I

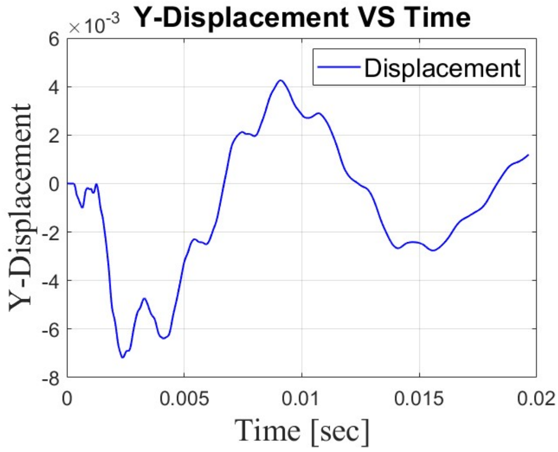

Figure 14: fig:Y-displacement on the tip of flap for case I

Case II: The middle solid structure is defined as wall but other two structure shows the displacement. The maximum x-displacement is found to be 0.148m approximately.The structure then return back and the oscillating phenomenon has been appeared. The detonation center for the second flap is far than second flap so the maximum deflection on the tip of the first flap should deflect more than the second flap. The space between the structure is less in second case compared to the first case, then the blast wave reflect back from the middle walled structure which results more displacement in second flap. The x-displacement and y-displacement on the tip of the solid structure is shown below:

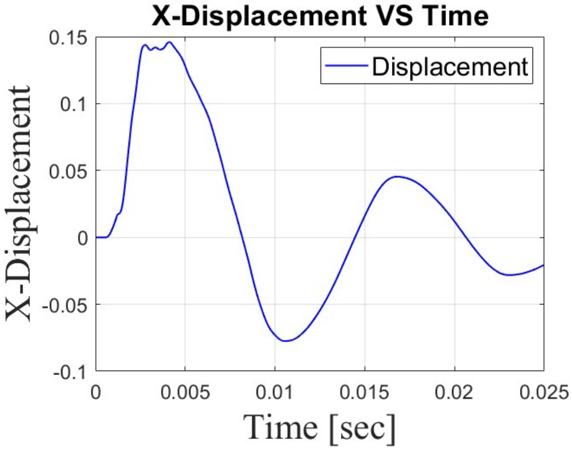

Figure 15: X-displacement on the tip of flap for case II

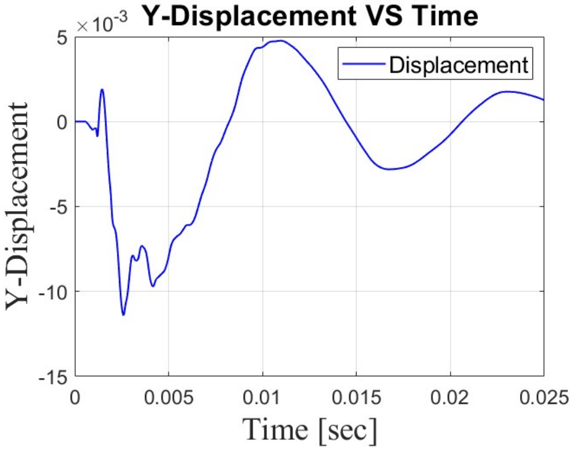

Figure 16: Y-displacement on the tip of flap for case II

Case III: The displacement for the first and second column of flap at the tip has been recorded and found that the displacement intensity has been significantly decreased with the combination of both the cases. The maximum deflection at the tip of the first flap reached to the 0.08m approximately which is less than case I and 0.12m on second flap also less than case II. The deflection also decays over the time which represent that the aluminium material will oscillate and try to remain in its original position.

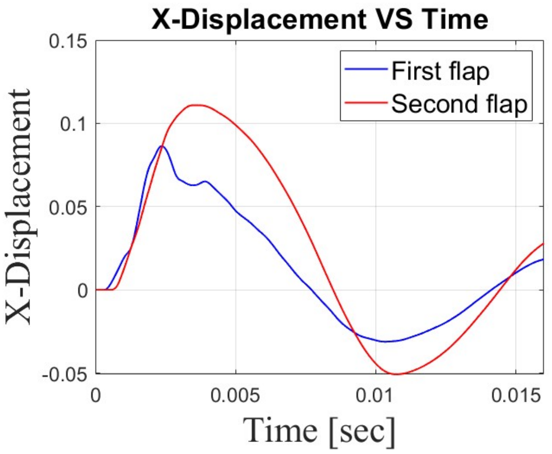

Figure 17: X-displacement on the tip of flap for case III

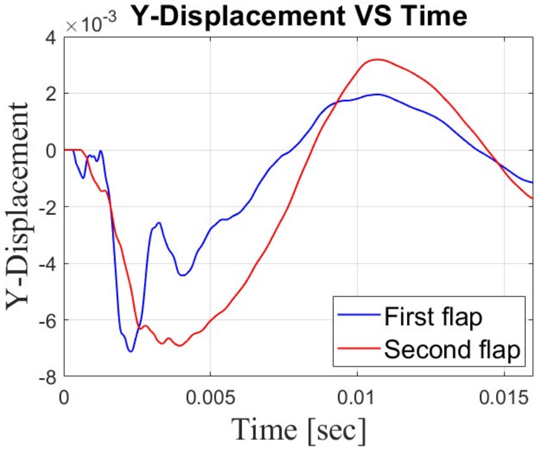

Figure 18: Y-displacement on the tip of flap for case III

Conclusion

The numerical simulation for the Fluid-structure interaction due to the explosion of C4 in 2D domain with three different cases was conducted using solids4Foam. The pressure decay over the time and the intensity of the blast wave has been recorded. The common location at case I, case II and case III will have different pressure intensities. Due to the reflection of wall structure, the intensity at common point is higher in case II although the case II is far from the detonation center. The effect of blast wave resulting the deflection and the pressure intensity increased due to the deflection on case II and the decreases in case III as the combination of case I and case II shows the FSI phenomenon during explosion of C4.

Acknowledgments

The authors are thankful to Er. Bhakta Bahadur Bhandari and Er. Salim Maharjan for their valuable suggestions and ideas. The authors express their sincere gratitude to Assistant Professor Er. Prajwal Raj Shakya, Head of Department, Department of Automobile and Mechanical Engineering and Assistant Professor Er.Sunil Adhikari, Coordinator, M.Sc. in Mechanical Design and Manufacturing, Thapathali Campus, IOE.

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